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An Adaptive View of Attentional Control

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Although humans can voluntarily direct their attention to particular stimuli, attention can at times be involuntarily allocated to stimuli and such attentional capture can result in unproductive distraction. A challenge to any comprehensive theory of attention is to explain how involuntary mechanisms of attentional control and their potential to produce distraction are ultimately reflective of an adaptation. Traditional arguments on this topic have appealed to a generalized cost-benefit accounting. Specifically, the cost of misallocating attention to the kinds of stimuli prioritized by involuntary mechanisms of attentional control over the long run is argued to be small in comparison with the potentially life-altering cost of failing to attend to such stimuli, which involuntary mechanisms of attentional control guard against. Our understanding of these mechanisms has undergone a revolution in recent years, findings from which point to a much more sophisticated adaptation that systematically maximizes benefits associated with automating the control of attention while minimizing unwanted distraction. In this review, I provide an updated model of the adaptive nature of involuntary mechanisms of attentional control, outlining concrete principles governing the management of specific costs and benefits. I conclude that distraction does not in general constitute a failure of attentional control but rather reflects the joint product of these adaptive principles.

Public Significance Statement
What we direct our attention to is not always under our control. Processes governing the involuntary control of attention can sometimes lead to distraction, which poses a fundamental challenge for the ability to account for these processes as reflective of an adaptation. This review article offers an updated cost-benefit framework for the control of attention that explains the ways in which involuntary mechanisms of attentional control provide unique advantages while minimizing the costs of distraction.

Keywords: selective attention, attentional capture, selection history, human performance, adaptation

Attention functions as the filter through which we experience the world around us. Attention is intrinsically selective, determining which among competing percepts are represented in the brain when representational capacity is limited (Desimone & Duncan, 1995). That is to say, attention plays a powerful role in determining what a person "sees;" this is especially true when there is more present in the environment than can be perceived at any one moment, which is typically the case in naturalistic scenes (e.g., Rensink et al., 1997). A crucial function of attention is to selectively process information in a manner that is adaptive, promoting survival and wellbeing.

Distraction can be costly. From distractions in the classroom that impede learning (e.g., Taneja et al., 2015) to driving-related distraction linked to motor vehicle crashes (e.g., Strayer & Drew, 2004) to failures to recognize hazards in work environments that can lead to injury or even death (e.g., Namian et al., 2018), there is significant public interest in mitigating distractions. Abnormal attention plays a role in a variety of psychopathologies; for example, attention-deficit-hyperactivity disorder, schizophrenia, depression, and addiction, among others (see Anderson, 2021, for a review). Addressing the

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challenges brought about by distraction and abnormal attention requires a deep understanding of *why* attention functions as it does and how this functioning can go awry.

Apart from voluntarily mechanisms of attentional control whereby observers selectively attend to information volitionally in the service of accomplishing their task goals (Wolfe et al., 1989); for example, selectively attending to red objects when trying to find apples in the produce section of a grocery store, attention can also be directed to certain objects involuntarily. The involuntary allocation of attention is typically referred to as *attentional capture*, and in scientific studies of attention it is measured in the form of a decrement in attentional performance attributable to the presence of a task-irrelevant stimulus. That is to say, attentional capture is empirically defined with respect to the distraction it can cause. Although the adaptive nature of voluntary attentional control is intuitive, attentional capture demands a more nuanced line of reasoning to account for the phenomenon as reflective of an adaptation.

Attentional capture is now widely believed to be the product of three distinct influences on *attentional priority*, which reflects the degree of attentional bias applied to a stimulus in perceptual processing. The first is the goals of the observer, which result in stimuli that share featural overlap with an intentionally prioritized (typically, target) stimulus capturing attention in a phenomenon referred to as *(goal-)contingent attentional capture* (Folk et al., 1992; although see Belopolsky et al., 2010; Lien et al., 2010; Luck et al., 2021, for controversy concerning the specific mechanisms by which attentional capture is modulated by goals). Returning to the prior example, searching for red apples might result in distraction from red objects that are unrelated to apples, such as a person in a red shirt. The second is the physical salience of stimuli (Theeuwes, 1992, 2010); when a physically salient stimulus captures attention, this is referred to as *stimulus-driven attentional capture*. For example, a bright flashing billboard might distract the attention of a driver trying to focus on the road in front of them. More recently, *selection history*, or the prior experiences of an individual that collectively exert an influence on attentional priority (Awh et al., 2012), has been proposed as a third factor governing the involuntary allocation of attention. Such prior experience includes pairings between stimuli and reward (e.g., Della Libera & Chelazzi, 2009; Le Pelley et al., 2015) that can produce *value-driven attentional capture* (attentional capture attributable to the reward history of stimuli; Anderson et al., 2011; Anderson, 2013), pairings between stimuli and aversive outcomes (e.g., Schmidt et al., 2015), and repeated selection of a stimulus as a target (Kyllingsbaek et al., 2001; Qu et al., 2017; Shiffrin & Schneider, 1977). For example, a prepared food item might come to capture attention once it has been learned to be tasty and filling, or perhaps a person's smartphone once it has been learned to provide a gateway to enjoyable information content. Emotionally valent stimuli have also been shown to capture attention under certain conditions (Mulckhuyse, 2018; Öhman & Mineka, 2001; Vuilleumier, 2005); for example, a face exhibiting terror, a predator bearing teeth, or an erotic image, although the mechanisms underlying such attention allocation are debated (Brown et al., 2020; Öhman & Mineka, 2001; Vromen et al., 2016).

A burden placed on any theory of attentional control is to explain how automatic influences on attention, which are prone to producing distraction, are in fact ultimately reflective of an adaptation. This review seeks to address this challenge head-on. In line with the bulk of the research on the topic and the real-world implications introduced above, the review is written with a particular focus on attentional capture in the context of visual information processing in humans.

The Cost-Benefit Framework for Attentional Capture and Its Limitations

An at times implicit and frequently glossed-over argument in the scientific literature on attentional capture is that the cost of attending to the kinds of stimuli that capture attention—even when they are known to be task-irrelevant—exceeds the potential costs of failing to attend to such stimuli. Automatic modes of attentional control are thought to guard against these costs. For example, a physically salient stimulus, such as an abrupt onset (e.g., Yantis & Jonides, 1984) or looming motion (e.g., Franconeri & Simons, 2003), might indicate the sudden appearance of a predator from hiding, which an observer would be advantaged to quickly orient to regardless of what they might be trying to focus on at the moment it appears. Likewise, a reward-associated stimulus might signal an immediate and fleeting opportunity to acquire a valuable resource, whereas an aversively conditioned stimulus may signal an acute threat that should be quickly acted upon. As the traditional argument goes, the momentary distraction caused by having attention automatically oriented to such stimuli is little in proportion to the potentially life-altering cost of failing to attend to such stimuli at a critical moment, and so the brain evolved a mechanism for automating such attention allocation (e.g., Anderson, 2013; Öhman & Mineka, 2001). By this account, involuntary mechanisms of attentional orienting can be thought of as an insurance policy against costly failures to attend. This is particularly pertinent to the influence of physical salience and selection history on the control of attention. Contingent attentional capture leans on a different but related argument that by automating attentional control, an individual can expend less cognitive effort in rapidly localizing task-relevant stimuli, the value of which exceeds the cost of occasional misallocation of attention (e.g., Leber & Egeth, 2006a, 2006b).

Although intuitively appealing, such arguments are ultimately simplistic and shallow generalizations that do not easily lend themselves to rigorous hypothesis testing. Perhaps more saliently, they raise more questions than they answer, and their line of reasoning quickly runs into fundamental interpretive challenges. Is the human perceptual system really that seemingly indiscriminate when it comes to the automatic allocation of attention? For example, physical salience seems like a very rough proxy for survival-relevance, and which stimuli are rewarding or threatening can vary with context (e.g., a food item on a plate or countertop vs. in the dirt on the ground; a fire in one's bedroom vs. a campfire for roasting marshmallows). Likewise, if the cost of distraction was great enough under certain conditions, would observers really be unable to cope with such demands in resisting attentional capture? Could humans not have adapted a system of attentional control that balances costs and benefits with more nuance, and if so, what would the factors governing that balance be? At least in the context of value-driven attentional capture, more pronounced attentional capture by previously reward-associated stimuli is associated with drug dependence (Anderson, 2016; Anderson et al., 2013), risky and impulsive behavior (Anderson, Kronemer, et al., 2016), and impaired value-based decision-making (Itthipuripat et al., 2015), so it seems like an oversimplification to assume that robust attentional capture is in and of itself a good thing. The extent to which attentional capture by physically salient stimuli could misguide attention could also quickly become unwieldy unless bounded by adaptive principles concerning when and the manner in which physical salience guides attention (Theeuwes, 1992, 2010).

A Revised Model of Adaptive Attentional Control

As research on attentional capture has progressed, our understanding of the mechanisms governing and modulating the involuntary allocation of attention has grown considerably. Here, I synthesize some of the key findings in this area in an effort to provide a more comprehensive case for the adaptive nature of involuntary mechanisms of attentional control. The proposed account goes beyond general statements about the actual magnitude of the cost of misallocating attention versus failing to attend that might exist in the real world, and instead articulates specific principles by which automating the control of attention maximizes benefits to the individual while minimizing costs: what some of those benefits are and how they are realized, coupled with an accounting of how the misallocation of attention (distraction) is guarded against (see Table 1). The argument is not that attentional capture is itself an adaptation, but that such involuntary orienting reflects the joint consequence of these adaptive principles of information processing and how they are actualized in the control of attention.

In the research discussed, the costs of attentional capture are typically operationalized in terms of performance decrements in finding a searched-for stimulus (e.g., Anderson et al., 2011; Theeuwes, 1992), often in the context of response time or accuracy in target report. The experiment tasks generally use simple stimulus displays and these costs are not in and of themselves substantial. However, the presence of these costs powerfully proves the point that under certain circumstances a person cannot help but pay some attention to a stimulus they know they have no reason to attend to, even when doing so is to their objective detriment. The costs of such distraction are likely greater, and may under certain conditions be substantially greater (e.g., distraction while driving), in real-world environments. As will be argued, adaptive mechanisms of attentional control minimize these costs in specific ways. In defining the benefits of attentional capture as a mechanism, the focus is on processes that make the orienting of attention and subsequent response to a behaviorally relevant stimulus more efficient, particularly with respect to the cognitive demands required to support these processes. The benefits discussed here go significantly beyond historical arguments concerning how likely behaviorally relevant stimuli are to be missed in the real world—a benefit that, as mentioned above, does not straightforwardly lend itself to rigorous hypothesis testing.

Principles of Benefit Maximization

For attentional capture to be convincingly adaptive, as a mechanism it should confer specific, quantifiable benefits that go beyond merely ensuring that a particular type of

Table 1
Comparison of the Proposed Theoretical Model With Traditional Models of How Involuntary Mechanisms of Attentional Control Can Be Characterized as Reflective of An Adaptation

Predictions	Traditional accounts	Proposed new account
Benefits	Helps ensure stimuli that are pertinent to survival are quickly detected and do not go unnoticed	In addition to traditional benefits, adaptive principles make orienting and responding to behaviorally relevant stimuli a more efficient process than alternative mechanisms of attending
Costs	Prone to distraction by behaviorally irrelevant stimuli that resemble survival-relevant stimuli	Specific processes are built into the attention system that minimize the costs of distraction associated with involuntary mechanisms of attentional control
Relationship	Costs are tolerated in light of benefits, with the net effect being overall adaptive	Working together, the proposed principles collectively produce a highly adaptive system for orienting

stimulus is not ignored. The principles underlying these benefits could then be used to make specific predictions about the conditions under which the capture of attention would be expected. Furthermore, distinctions can be made concerning how attention involuntarily prioritizes stimuli in the interest of adaptive behavior, with different modes of orienting supporting specific adaptations. Recent findings in the attentional capture literature offer important insights that speak directly to these issues.

Offloading Attentional Demands

Perhaps the most intuitive benefit afforded by mechanisms of involuntary attentional control is offloading attentional demands. Active visual search requires the maintenance of a representation of the searched-for stimulus or *target template* in either working memory or activated long-term memory (Woodman et al., 2013), which is metabolically demanding. Such goal-directed attention requires sustained cognitive effort and is significantly slower in its time course than the rapid orienting response that reflects attentional capture (Theeuwes, 2018).

When given the option in a highly demanding visual search task, individuals frequently fail to adjust their *attentional control settings*, or the attentional priorities established in the service of performing a task, to search for the easiest target to find given the distribution of stimuli in a search array (e.g., Irons & Leber, 2016, 2018). It appears that the act of reevaluating and recalibrating attentional control settings is not a frequently adopted strategy that people use to maximize performance. Instead, it has been shown that individuals have a strong tendency to persist in attentional control settings that have previously proven useful in successfully identifying the target, even when such attentional control settings produce avoidable distraction once task parameters change (Leber & Egeth, 2006a, 2006b; Leber et al., 2009).

Collectively, these findings suggest that individuals have a tendency to settle on attentional templates that work in localizing a prioritized stimulus (e.g., the target), and default to maintaining such attentional priorities if they still allow for target identification. In doing so, they tolerate some measure of associated distraction in exchange for the ability to avoid the cognitive effort involved in recalibrating attentional control settings. Once fully automated, the process of orienting to a familiar target no longer even requires an active target template (Kyllingsbaek et al., 2001; Qu et al., 2017; Shiffrin & Schneider, 1977), reducing the metabolic demand associated with the control of contingent attentional capture (Folk et al., 1992; see also Woodman et al., 2013). In this way, the human attentional system systematically offloads attentional demands as evidence accumulates that the biases it implements are useful in localizing prioritized stimuli, first settling on a target template to persistently maintain in activated long-term memory (Woodman et al., 2013) and then fully automating such orienting and eliminating the reliance on an active template altogether (Kyllingsbaek et al., 2001; Shiffrin & Schneider, 1977; Qu et al., 2017). Thus, it appears that the attentional system trades off an increasing proclivity toward otherwise avoidable distraction with a reduction in total energy expended in the service of visual search. This same principle can be applied to the influence of reward history and punishment history on the control of attention (e.g., Anderson et al., 2011; Schmidt et al., 2015), with mechanisms of involuntary orienting eliminating the demands associated with actively monitoring for such important signals.

Implicit Learning

Related to the issue of offloading attentional demands is the issue of leveraging *implicit learning*, or learning that is below the threshold for conscious awareness. This applies to contingent attentional capture as well as the influence of selection history on attention. In the case of contingent attentional capture, attention will be preferentially allocated to stimuli that share a feature with a more frequent target even though participants are not aware of an imbalance in the frequency of different target stimuli (Cosman & Vecera, 2014). A similar bias is evident toward the location at which a target has been more likely to have appeared in the past (Jiang, 2018; Jiang et al., 2013), and contextual guidance by the arrangement of nontargets to a likely target location has long been argued to rely, at least in part, on mechanisms of implicit learning (e.g., Chun & Jiang, 2003; Colagiuri & Livesey, 2016). In the case of selection history, substantial evidence indicates that individuals can develop a bias to orient to previously reward-predictive and previously punishment-predictive stimuli even when they are unaware of the relationship between particular stimuli and outcomes (e.g., Grégoire & Anderson, 2019; Hopkins et al., 2016; Leganes-Fonteneau et al., 2018).

This unconscious element of involuntary attentional control is adaptive in that it allows an individual to leverage the benefits of learning before such learning reaches the level of awareness needed to explicitly configure an attentional template. Indeed, such an influence of implicit learning on the involuntary control of attention entirely obviates the need to ever even reconfigure goal-contingent attentional control at all; thereby, providing another means of offloading attentional demands. It also requires less active engagement during periods where important information can be learned, relying on automatic mechanisms of associative learning (e.g., Kim & Anderson, 2019a; Sali et al., 2014) and statistical learning (e.g., Li & Theeuwes, 2020; Zhao et al., 2013) rather than more laborious mechanisms of explicit hypothesis testing. That attentional capture is shaped by implicit learning dovetails with the fact that attentional capture is itself a largely unconscious process that places minimal demands on processing resources (Theeuwes, 2018), with unconscious processing potentially reflecting a core feature of what makes attentional capture adaptive.

Need-Specific Mechanisms of Prioritization

When it comes to contingent attentional capture and stimulus-driven attentional capture, the purpose that these mechanisms serve are intuitively distinct. The former is configurable and leverages knowledge of currently pertinent stimuli, whereas the latter is adapted for detection of the unexpected and lacks stimulus specificity. When it comes to the influence of selection history on attention, however, the apparent purpose of such bias is multifaceted, likely reflecting the diversity of learning experiences and underlying mechanisms that constitute selection history. More specifically, mechanisms of involuntary attentional orienting on the basis of selection history can serve at least two distinct categories of function. The first is detection of a potentially important signal, such as one that signifies the presence of a threat, and the second is automating patterns of orienting that have proven effective in accomplishing task goals. Although there is intrinsic overlap, the former is concerned principally with orienting to a signal that can appear unpredictably and the latter with optimizing attention under familiar and predictable conditions.

Recent evidence suggests that the attention system is sensitive to this distinction and has evolved two distinct mechanisms of involuntary orienting to support the two corresponding needs. When a stimulus repeatedly signals the need to orient attention in a certain way in the service of completing a task, it will come to involuntarily trigger this orienting response (e.g., Qu et al., 2017; Shiffrin & Schneider, 1977). Conversely, if a stimulus reliably predicts a reward or punishment, a bias to orient to such signals will develop (e.g., Anderson & Britton, 2020; Bucker & Theeuwes, 2017; Le Pelley et al., 2015). A variety of dissociations indicate such selection history-dependent effects are subserved by different learning systems, with the former reflecting stimulus—response learning and the latter reflecting stimulus—outcome associative learning (Anderson & Britton, 2019; Anderson & Kim, 2018a; Anderson et al., 2017; Kim & Anderson, 2019a, 2019b, 2020). In this way, the involuntary control of attention is optimized for both the detection of informative signals and the automated repetition of a cue-triggered orienting response, with a dedicated circuit optimized for the support of each of these needs. There is some evidence that the influence of statistical learning on the involuntary orienting of attention may be subserved by a third distinct mechanism of selection history-dependent attentional control (Kim & Anderson, 2021), although such findings are too preliminary to convincingly distinguish its influence from the two mechanisms previously discussed and more research is needed on the matter.

Interestingly, and consistent with the principle of parsimony in the coupling of involuntary attentional control to biological needs, learning from reward and punishment appear to influence the control of attention via a common underlying mechanism. Behaviorally, reward learning and punishment learning typically have comparable effects on the orienting of attention (Anderson & Kim, 2018c; Watson et al., 2019). Compellingly, the neural correlates of attentional capture by previously reward-associated (see Anderson, 2019) and previously punishment-associated stimuli appear indistinguishable (Kim et al., in press). Given that each type of stimulus serves as a valent signal for a biologically significant outcome, the brain leverages a mechanism for assigning attentional priority to such stimuli that shapes the orienting response in the same way regardless of whether the associated outcome is positive or negative; whether the outcome associated with a stimulus is positive or negative is not informative with respect to whether the stimulus should be attended, and as such the attention system does not discriminate on the basis of such information.

Attentional Capture and the Facilitation of Behavior

Although the need to orient to signals for reward and punishment may itself be valence-independent (Kim et al., in press), the behavioral response demanded by the stimuli associated with these two types of outcomes is diametrically opposed. Reward-associated stimuli signal the need for approach behavior while punishment-associated stimuli signal the need for avoidance behavior. A truly adaptive system of involuntary attentional orienting will be sensitive to this distinction, with the associated orienting response serving to facilitate the appropriate behavior.

In the case of attentional capture by previously reward-associated stimuli, there is good evidence that actions are automatically biased in favor of the behavioral response associated with the reward cue (Anderson, 2017; Anderson, Folk, et al., 2016; Kim & Anderson, 2019c). That is, involuntary attentional orienting to reward cues facilitates cue-associated actions. Although it is less clear in the case of attention to punishment-associated stimuli, a tendency toward avoidance or inaction triggered by such stimuli has been suggested (Carsten et al., 2019; Chen & Bargh, 1999; Guitart-Masip et al., 2014). Although the mechanisms by which an involuntary orienting response and a corresponding behavioral response are linked remain to be clarified, it appears that the valence of the eliciting stimulus determines how behavior is affected by reward and punishment cues, and that the corresponding orienting response facilitates such behavior in a way that, like the orienting response itself, is to some degree automated.

Concerning attentional capture by physically salient stimuli and contingent attentional capture, two cases of involuntary attentional control in which the eliciting stimulus is not necessarily valent, the orienting response may still have adaptive consequences for behavior. The allocation of attention has long been hypothesized to include an alerting component, which may serve to facilitate more rapid information processing (Fan et al., 2005; see also Yantis & Jonides, 1984). At the same time, the process of attentional capture has been hypothesized to contain a "circuit-breaker" component (Corbetta & Shulman, 2002), allowing for the rapid reconfiguring of attentional priorities (and the information available for decision-making) in the event of changing task demands. In these ways, the involuntary orienting of attention not only shapes how an individual processes information, but also actively facilitates the execution of adaptive behavior signaled by stimuli in the environment.

Principles of Cost Minimization

Perhaps even more important for an adaptive theory of attentional control are mechanisms by which the cost associated with attentional capture can be mitigated. To the degree that individuals can reduce the extent to which attention is captured when there is greater certainty concerning the likelihood that capture would result in unwanted distraction, the cost of misallocating attention afforded by automatic mechanisms of attentional control could be more easily managed. Recent research indicates multiple modulatory factors and considerations that serve in this interest.

Context-Dependent Modulation of Attentional Control

One of the principle ways in which the cost of misallocating attention can be minimized is by configuring attentional priority such that which stimuli capture attention depends on which stimuli are most important in the current context. This is particularly pertinent to the role of selection history and which prior learning experiences are brought to bear in influencing selection. There is now substantial evidence that how attentional capture is influenced by selection history is quite sensitive to contextual factors. In the case of value-driven attention, if a stimulus is associated with reward in one context but not in another, attentional capture by that stimulus will be specific to when it appears in the context in which it was rewarded (Anderson, 2015a, 2015b; see also Anderson & Kim, 2018a, 2018b). Likewise, attentional capture by aversively conditioned stimuli is context-specific (Grégoire et al., in press). At the same time, if context is not diagnostic of whether a particular stimulus predicts a reward during learning, there is a tendency to generalize such learning to attention allocation in a novel context (Anderson et al., 2012). A parallel tendency has been observed with respect to spatial attentional biases (Liao & Anderson, 2020b) and semantically related stimuli (Grégoire & Anderson, 2019). In this way, individuals exploit prior learning about the boundary conditions concerning the pertinence of a stimulus while defaulting to generalizing their learning in the absence of evidence against such generalization. If a stimulus is explicitly not predictive of a valent outcome in a particular context, it will not capture attention in that context, reducing the likelihood of counterproductive distraction.

This same principle applies to the influence of task demands on attentional capture and the adoption of an attentional control setting. Individuals will either search for a specific feature or for the most physically salient stimulus (singleton detection mode) based on the effectiveness of such priorities in localizing the target in a given context, even if they are unaware of the link between context and the heterogeneity of the search display (Cosman & Vecera, 2013). Given the relationship between the target and distractor features, individuals adjust their attentional control settings to more efficiently ignore target-similar distractors that can appear in the task context (Geng et al., 2017).

State-Dependent Modulation of Attentional Control

Another important way in which unproductive attentional capture could be mitigated is via state-dependent modulation. To the degree that the kind of stimuli that capture attention can be modulated by the state of an individual, stimuli that are more or less pertinent to the considerations particular to that state could be correspondingly prioritized. Such state-dependent modulation of attentional capture has been well-studied in the context of anxiety. Specifically, threatening stimuli capture attention more robustly for anxious individuals (Bar-Haim et al., 2007). Similarly, attentional biases for food-related stimuli are more pronounced when an individual is hungry (e.g., Gearhardt et al., 2012), and the magnitude of distraction caused by drug-related stimuli is related to drug craving (Field et al., 2009).

More recent research suggests that such state dependence reflects a broader principle of attentional control that is not limited to threat-related and consumable stimuli. A state of threat or negative arousal generally accentuates attentional capture by physically salient stimuli (Kim & Anderson, 2020b; Lee et al., 2014; Sutherland & Mather, 2012). Individuals with elevated stress-related symptoms are also more susceptible to stimulus-driven attentional capture (Esterman et al., 2013). Such findings fit nicely with historical arguments that attentional capture by physically salient stimuli might reflect an adaptive mechanism of attentional control that promotes detection of a potential threat, and takes this an important step further by demonstrating that the magnitude of this bias to some degree scales with the internal state of the individual as it relates to threat. Such threat-dependent modulation of attentional bias does not come at a concomitant cost in the ability to voluntarily deploy attention efficiently in a broader sense (Kim et al., 2021), further supporting its adaptive nature.

At the same time, when in an anxious or threatened state, one could argue that the prospect of procuring reward should be deprioritized, with attentional priorities emphasizing surviving rather than thriving. A pair of recent studies demonstrates this diametrically opposite effect of anxiety on attentional bias: when an individual is in an anxious state, previously reward-associated stimuli are more easily ignored as task-irrelevant distractors (Kim & Anderson, 2020a, 2020b). Such evidence suggests a fine-tuning of involuntary mechanisms of attentional orienting on the basis of the state of the individual—at least in the case of anxiety—both enhancing the attentional priority of some classes of stimuli and reducing the priority of others to reflect what the current state indicates is most important. Such evidence also suggests that anxiety-dependent effects on the control of attention are not reducible to increased distractibility due to anxiety-related fatigue or impairments in cognitive control.

The attentional state of a person also has implications for susceptibility to attentional capture. Stimulus-driven attentional capture can be significantly reduced when attention is spatially focused in advance of a physically salient distractor being presented (e.g., Yantis & Johnston, 1990). Likewise, stimulus-driven attentional capture is generally reduced under conditions of high perceptual load (e.g., Lavie, 1995). This is less true for previously reward-associated stimuli, which have demonstrated the ability to robustly capture attention despite spatially focused attention (Munneke et al., 2016); this suggests generally high attentional priority for reward-related stimuli, which might help to ensure that unexpected reward opportunities do not go undetected.

Signal Suppression and Learning to Ignore

In situations in which attentional capture is frequent and counterproductive, an adaptive system of attentional control would be expected to be capable of reducing the magnitude of such distraction via suppressive mechanisms. That is, if the costs of attentional capture clearly outweigh the benefits *in a particular situation*, an adaptive attention system will be sensitive to this imbalance rather than rely solely on generalizations concerning the cost-benefit ratio *averaged over all situations*. This is related to the concept of context-dependence described above, although in this case suppressive mechanisms are leveraged to mitigate distraction rather than the individual more finely tuning which stimuli are prioritized given the continencies associated with the context.

Recent findings indicate that statistical learning plays a strong modulatory role with respect to the influence physical salience on the involuntary orienting of attention. If a physically salient distractor appears more frequently in a particular location, attentional capture by this distractor will be reduced when it appears in this frequent location (e.g., Britton & Anderson, 2020; Wang & Theeuwes, 2018; Wang et al., 2019), reflecting proactive spatial suppression of the high-probability distractor location (Wang et al., 2019). Likewise, distractors more frequently appearing in a particular color are more easily ignored (Failing et al., 2019; Stilwell et al., 2019; Vatterott & Vecera, 2012), and individuals are even sensitive to the confluence of spatial and feature-based contingencies, more efficiently ignoring distractors whose feature-by-location combination is particularly probable (Failing et al., 2019). In this way, otherwise frequent distraction is effectively mitigated.

The frequency with which salient distractors are encountered in general also plays an important role in the involuntary control of attention. The more frequently a physically salient stimulus is encountered, the more efficiently such stimuli are ignored, in a manner that cannot be explained by intertrial priming (Geyer et al., 2008; Sayim et al., 2010). It appears that involuntary attentional orienting to task-irrelevant but physically salient stimuli is subject to habituation (Turatto & Pascucci, 2016). Even knowing the probably that a salient distractor will be encountered in advance of a given trial is sufficient to reduce the frequency of stimulus-driven attentional capture (Moher et al., 2011). In this way, when the prospect of distraction by salient stimuli is particularly pronounced, the degree to which physically salient stimuli are automatically prioritized by the attention system can be adjusted downward.

A mechanism of signal suppression has been identified in the control of attention by which the attentional priority afforded to physically salient stimuli can be reduced (Gaspelin et al., 2015; Gaspelin & Luck, 2018). Particularly when a diagnostic feature of the target is useful in guiding goal-directed attention and the features of physically salient distractors are familiar and to some degree predictable (Luck et al., 2021), the engagement of this mechanism of suppression can largely eliminate attentional capture from even occurring. Signal suppression provides an attentional process through which the cost of distraction can be managed; it does not appear to reflect the influence of strategic attentional control but rather an influence of selection history on the control of attention (Luck et al., 2021). This mechanism also appears to be particularly adapted to the influence of physical salience on the control of attention; reward-associated stimuli, which may be particularly pertinent to survival, have demonstrated a tendency to be resistant to such signal suppression (Pearson et al., 2020).

Value-driven attention poses a particularly interesting and diagnostic test case for the concept of a cost-benefit principle governing the involuntary control of attention in specific situations. In one part of a typical experiment paradigm, attending to particular stimuli is met with a reward in an initial learning phase. Then, in a subsequent part of the task, previously reward-associated stimuli are made irrelevant to the task and attending to them is no longer of any benefit (e.g., Anderson et al., 2011; Anderson & Halpern, 2017). In this sort of situation, there is no cost to attending to previously reward-associated stimuli in terms of reward outcome, only a small decrement in the speed and accuracy of visual search. Similarly, in paradigms in which a task-irrelevant distractor predicts reward, reward is received on the majority of trials even if the distractor is covertly attended (e.g., Le Pelley et al., 2015), with an at most small cost to attending to such distractors and clear information value in monitoring for their presence. This raises the question of whether, were there a more substantial cost to attending to reward-associated stimuli, could individuals in fact suppress attention to such stimuli.

A recent study provides a straightforward demonstration of this very cost-benefit principle in modulating the involuntary control of attention. When a very fast and accurate response to the target is required to obtain a reward in the presence of a reward-associated distractor, precluding the ability to both orient to the reward-associated stimulus and receive the reward it is associated with, individuals will come to more efficiently ignore reward-associated distractors (compared with neutral distractors matched for physical salience; Grégoire et al., 2020). That is, reward-predictive stimuli can be deprioritized by the attentional system, resulting in the more efficient ignoring of such stimuli compared with neutral stimuli. The typical finding of increased distraction by reward-associated stimuli was then replicated with this aspect of the reward contingencies removed from the task, allowing both the orienting of attention to reward-predictive distractors and the receipt of reward (Grégoire et al., 2020). Thus, value-driven attention can be thought of as an adaptive response to the relationship between the costs and benefits of attending to reward-related stimuli; when the costs of attending to such stimuli are great enough in terms of reward, individuals can in fact learn to more efficiently ignore reward-related stimuli. It is not the case that reward-associated stimuli necessarily capture attention in an obligatory fashion and/or are immune to suppressive mechanisms of attentional control.

Beyond the Initial Allocation of Attention

The costs associated with attentional capture need to be understood in the broader context of sustained information processing. More simplistic accounts of the adaptiveness of attentional capture as a mechanism emphasize an hypothesized fleeting nature of the cost of misallocating attention, but it is possible that such initial capture of attention could actually have downstream benefits for information processing. Specifically, it would be more adaptive if attentional capture could actually facilitate the sustained ignoring of a stimulus in the event that the eliciting stimulus is in fact task-irrelevant. A recent study of attention to threat-related stimuli suggests this might be the case (Britton & Anderson, 2021). Fixating stimuli rendered in a particular color resulted in electric shock during a visual foraging task. Although such stimuli initially captured covert attention, after the first fixation shock-associated stimuli remained significantly less likely to be fixated through the duration of the trial over multiple subsequent fixations (Britton & Anderson, 2021). This contrasts with attention to found targets in multiple-target search, which robustly elicit return fixations (Cain et al., 2013), indicating that initial attentional priority does not necessarily lead to sustained ignoring but sustained ignoring is possible when it is necessary to avoid punishment. Similarly, when a physically salient stimulus is known to be task-irrelevant in advance, it can be more rapidly and efficiently rejected than a less salient nontarget (Geng & DiQuattro, 2010).

In this way, the act of initially rejecting an attended stimulus can facilitate subsequent ignoring, which has been referred to as "search and destroy" (see Moher & Egeth, 2012), offering one additional mechanism by which attentional capture can be made to be more adaptive. The influence of physical salience on the computation of attentional priority has long been understood to be short-lived, evident particularly in the earliest stages of visual information processing (e.g., van Zoest et al., 2004). In general, automatic influences on the computation of attentional priority seem to predominantly affect the "initial sweep" of the visual field, particularly adapted for the rapid detection of an unexpected stimulus, and beyond this initial sweep not only are the stimuli that capture attention generally not difficult to ignore, but the sustained ignoring of such stimuli might actually be in some cases facilitated.

Specifically in the case of reward learning, it has also been shown that the ability to maintain an attentional bias for a learned predictor of reward does not preclude the ability to reshape momentary attentional priorities on the basis of current value. In the event that the currently reward-associated stimulus changes unexpectedly, individuals are able to adapt to preferentially attend to the currently valued stimulus over the previously valued stimulus even if their long-term value-based biases have not yet adjusted as revealed by a subsequent task probing attentional processing of task-irrelevant stimuli (Liao & Anderson, 2020a). In this way, recently experienced value and value learned over the long-term separately bias attention, a distinction supported by neuroanatomy (Kim & Hikosaka, 2013); this allows for rapid adjustments in value-based attentional priority without requiring that more chronic value-based biases that have a history of serving an adaptive function be abandoned in the process.

The Cost-Benefit Framework Revisited

Theoretical accounts of involuntary mechanisms of attentional control have historically done little to explain how such mechanisms could be considered as reflective of an adaptation despite the distraction that they can cause. Indeed, the cost associated with involuntary mechanisms of attentional control is the bedrock of their empirical definition in the scientific study of attention. How can it be that attention is so explicitly fallible, yet reflective of an adaptive mental process?

The cost of attentional capture is conspicuously small in typical attention experiments (often on the order of milliseconds in time to localize a target), and such distraction generally does not preclude the ability to find a searched-for stimulus within a relatively short timeframe. Coupled with speculation concerning the potentially life-altering consequence of ignoring certain stimuli in critical but unanticipated situations, arguments in favor of the adaptiveness of involuntary mechanisms of attentional control have appealed to this apparent imbalance in the cost-benefit ratio (e.g., Anderson, 2013). These sorts of high-level cost-benefit arguments, however, still allow for—and could even be said to argue in favor of—a rampant propensity for distraction. Although the cost to any single instance of distraction attributable to attentional capture may be small, repeated distraction poses a fundamental challenge to theories of attentional control, especially when the cost of such distraction can be readily anticipated. At the same time, perhaps the benefits afforded by involuntary attentional capture are to some degree underappreciated and go beyond merely alerting an individual to a potentially important source of information that must then be subjected to effortful cognitive processing.

In this review, I highlight several dimensions of attentional control that, working together, allow for the involuntary control of attention to be much more adaptive than a simple cost-benefit framework for the process as a whole would allow. According to the proposed view, involuntary attentional biases address specific needs rapidly and automatically, in a manner that provides distinct advantages over more controlled and deliberate mechanisms of information processing. A variety of processes and support mechanisms serve to mitigate the cost of distraction that involuntary mechanisms of attentional control can give rise to. With the proposed principles of benefit maximization and cost minimization working together, a more convincing case for attentional capture as reflective of an adaptation can be made. Rather than reflecting a largely indiscriminate application of a generalized cost-benefit principle, as historical views on the issue have argued, I counter here that the involuntary control of attention is instead reflective of a rather sophisticated set of adaptations.

Limitations and Outstanding Questions

Certain examples of attentional capture appear, at least on the surface, to be explicitly maladaptive in the context in which they are measured. For example, individuals develop a bias to orient toward a signal for reward even when they are only ever rewarded for looking away from the stimulus (Kim & Anderson, 2019a). Participants can develop a bias to orient toward a stimulus associated with electric shock even though doing so ironically makes shock more likely (Nissens et al., 2017) or actually triggers it (Anderson & Britton, 2020). How can an adaptive view of attentional control account for such patently suboptimal orienting responses? In this context, it is important to note that these and similar experiments utilize task structures designed to carefully probe the involuntary nature of the orienting response that are quite atypical with respect to structures present in the real world (see Anderson, 2018). In most naturalistic situations, it is advantageous to rapidly orient to a reward-associated or punishment-associated stimulus to assess the situation and decide how to act, but rarely is it advantageous to direct attention away from such stimuli. More broadly, such findings underscore the notion that attentional capture is not itself an adaptation per se but rather reflects a consequence of adaptive principles of information processing.

In this review, costs and benefits are typically contextualized with respect to quantifiable performance metrics in an attention task, in keeping with relevant empirical studies. In the real world, such costs and benefits must be anchored with respect to both ontogeny (i.e., considerations that arise during the course of individual development) and phylogeny (i.e., selection pressures over generations). Precisely how the costs and benefits of mechanisms of involuntary orienting measure up under naturalistic considerations, and whether phylogeny or ontogeny plays a more pivotal role in the shaping of the human attention system, are important questions for future investigation.

Reconceptualizing Attentional Capture and the Nature of Distraction

Distraction is not uncommonly characterized as a *failure* of attentional control. A quick literature search on “failure” and “attention[al] control” will yield a plethora of hits relevant to distraction and the related phenomenon of mind wandering. When attentional processes produce distraction, which intrinsically has some nonzero cost associated with it, it is easy to think of the attention system as having “failed” the person; this is especially true when the person actively tried to, but could not, avoid distraction. According to the model forwarded in this review, distraction in many (arguably most) circumstances is by no means a failure of attentional control. It is rather exactly what an adaptive system of information processing should do.

Maladaptive attention is of course a very real problem, exemplified by psychopathological disturbances in which attention is implicated (e.g., Anderson, 2021) and distraction that directly leads to injury or death (e.g., Namian et al., 2018; Strayer & Drew, 2004). The proposed account offers an interpretative lens through which to understand such phenomena. In these and related situations, it may be the case that a fundamentally adaptive system has, given the experiences and contexts to which the individual has been exposed, developed a pattern of orienting that is situationally maladaptive. Likewise, the seemingly rampant propensity for distraction associated with the proliferation of digital technologies is not reflective of a degradation of attentional control in young people, as is frequently suggested in popular media; rather, such technology is interfacing with a highly adaptive attentional system with befitting consequences, and these consequences carry social and occupational implications. In such cases, it would be misguided to try to "fix" the attention system of the individual. Instead, it may be more advantageous to work to reshape the biases of the attention system, leveraging a knowledge of the principles by which this system functions; the adaptive principles discussed in this review offer a starting point for thinking about how one might go about that challenge.

Toward an Integrative and Unifying Framework for the Control of Attention

Over the past couple of decades, considerable effort has been undertaken to develop theoretical models of attention that fractionate the mental process, highlighting dissociations and introducing distinctions. This includes long-standing debates contrasting goal-contingent and stimulus-driven priorities (e.g., Folk et al., 1992; Luck et al., 2021; Theeuwes, 1992, 2010), distinctions between the dorsal and ventral attention network (Corbetta & Shulman, 2002), models of habit-like influences on attention (e.g., Jiang, 2018), the introduction of a trichotomy view of attentional control contrasting the influence of goals, salience, and selection history (Awh et al., 2012), and subsequent mechanistic distinctions within the domain of selection history (e.g., Kim & Anderson, 2019a, 2021). Such distinctions are meaningful and should certainly be incorporated into models of attentional control. What is currently lacking in the field, however, is a corresponding effort to bind these disparate components of attentional control together under a common overarching framework that can explain why they collectively function and interact in the ways that they do.

Although we have quite a bit of ground to cover here as a field, I think a refined cost-benefit framework for the adaptive control of information processing could go a long way toward providing a more unified model of attentional control that could be juxtaposed with the increasingly fractionated models actively under development. This starts with the core principle of reinforcement learning as applied to a cost-benefit accounting of when and what to prioritize by attention. For example, contingent attentional capture could be explained as a specific case of a mental representation (in this case, a target template held in active memory) biasing information processing. With experience, individuals learn that automatically prioritizing such information produces greater benefits than costs when considering the principles discussed in this review, and so the attention system will undergo learning-dependent change to facilitate such prioritization in the future. A similar concept could be applied to attentional prioritization of physically salient stimuli, including the principles that mitigate the extent of unproductive distraction discussed earlier.

Goal-contingent, stimulus-driven, and selection history-dependent attentional capture in all its varieties are all presumably adaptations of an evolved system of information processing, and the pieces are coming into place to begin thinking deeply about what their common threads might be. It is my hope that the framework introduced in this review will provide a productive foundation upon which we can begin the process of constructing a comprehensive and unified account of the control of attention. A theoretical account along these lines would have the potential to obviate seemingly unending debates contrasting the relative strength and contribution of different mechanisms of attentional control (see, e.g., Luck et al., 2021), fundamentally changing the tone of the conversation in the field of attention and the lens with which prior and subsequent observations concerning the nature of attentional control are interpreted.

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