Combining attention: a novel way of conceptualizing the links between attention, sensory processing, and behavior

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Published online: 8 August 2014 © The Psychonomic Society, Inc. 2014

Abstract Many everyday behaviors appear to require both the interpretation of incoming sensory information and the maintenance of a current task goal. This intuitive notion suggests that combining attentional control processes might reflect a fundamentally novel way in which attention supports complex behavior. Using an established paradigm, here we show that joint recruitment in multiple attention control systems leads to corresponding combined increases in behavior and underlying sensory processing of attended targets. Moreover, our data also revealed that the nature of the combined effect depends on a flexible allocation of attentional resources to individual component processes, which change dynamically as a function of task demands. Together, these data provide a new conceptual framework for characterizing the role of attention in behavior and suggest important extensions to the prevailing theories of attention.

Keywords Attention · Complex behavior

Introduction

Consider the following example. After failing to find the way to your hotel in a foreign city, you ask a passerby for directions; they point to the map you are holding, and you follow their finger tracing the correct route. Successful completion of this task depends on the involvement of two attentional mechanisms, one that supports behavior by interpreting behaviorally relevant sensory information (i.e., automated attention elicited by the finger point’s direction; Ristic & Kingstone 2012; Ristic et al. 2012) and another that supports behavior by maintaining the current goal (i.e., endogenous attention engaged by the goal of getting to the hotel; Jonides 1981). Intuitively then, complex behaviors may depend on the ability of attentional control systems to combine the meaning of the sensory cues with the present goals of an individual.

This idea dovetails with a recent proposal that, in addition to the two well-known modes of attentional control (i.e., exogenous orienting elicited by sensory properties of the cues and endogenous attention elicited by current goals; Jonides 1981; Posner 1980), attention could also be engaged independently by stimuli that carry different types of selection history (Anderson et al. 2011b; Awh et al. 2012). In this framework, attentional control systems are seen as operating in a coordinated independent fashion, supporting the notion that attentional control systems may combine. However, while this prediction holds for situations in which different types of sensory information are used to engage each attention system independently, it is at present unclear if a single cue, whose sensory properties afford processing in multiple attention control systems, would also have an ability to engage attentional systems in a combined manner. Stimuli that are relevant for behavior, like common symbols, might be especially good candidates due to their capacity to elicit activity in the control systems engaged by the cue’s typical meaning (i.e., automated attention) and those that support explicit goal-directed behaviors (i.e., endogenous attention).

The first aim of this study was to test whether multiple attention control systems combine when they are engaged jointly by a single behaviorally relevant cue. In this effort, we measured the effects of automated and endogenous attention on behavior and target processing when they were engaged in isolation relative to when they were engaged in combination. To test this first aim, we capitalized on data showing that, when elicited in isolation, both automated and endogenous attention result in facilitation of response times and lead to increased sensory processing of attended targets.
While automated attention facilitates behavior (Ristic & Kingstone 2012; Ristic et al. 2012) and underlying sensory processing of target events (Eimer 1997; Tipper et al. 2008) by directing attention in accordance with overlearned associations between behaviorally relevant stimuli and the events in the environment, endogenous attention facilitates behavior and sensory processing by directing attention in accordance with internal goals (e.g., Hawkins et al., 1990; Hopfinger, Buonocore, & Mangun, 2000; Jonides, 1981). Thus, if attention systems combine to jointly affect behavior and sensory processing, the performance in this combined condition should reflect at least an additive combination of the two isolated components.

The second aim was to characterize the nature of attentional resource allocation during combined attention. Past studies support the notion that automated and endogenous orienting normally draw on distinct and independent pools of attentional resources (e.g., Berger et al. 2005; Ristic et al. 2012). However, while this finding holds for situations in which each system is engaged using two different cues, it is at present unknown how those resources may be distributed when multiple attention systems are engaged by the same cue. One possibility is that combined attention may continue to reflect a summation of the resources available to each component process. This may occur for example when the task demands an optimal engagement of resources available to each component and allows for each process to develop fully, similarly to when attention systems are engaged using different sensory information. This outcome would suggest independence between resources available to component systems during combined orienting. Another possibility is that combined attention may depend on flexible pooling of resources available to each component system, as they are accessed simultaneously by the same cue. These resources may then be allocated to the combined effect dynamically as a function of task demands. Such flexible allocation may occur when a larger amount of resources is required to engage one component process, for example when the task demands an increased deployment of resources towards the endogenous system. Such an outcome would suggest that combined attention involves a cross talk between individual attention systems, because in this case they are engaged in concert by a single cue and in support of a common goal.

Our last aim was to assess if attentional systems combine only under conditions when both component processes are directed toward processing of target events at a common spatial location. Due to everyday behavioral relevance of arrow cues, it would be reasonable to expect that combined attention might reflect a domain-specific system that is engaged in situations when automated and endogenous orienting converge spatially onto the same location. However, it is also plausible that combined attention might reflect a general mechanism responsible for integrating the information conveyed by the cue with the current goals. If this is true, one would also expect to observe combined attention effects under conditions when the two component processes diverge spatially, i.e., they are directed toward processing of target events occurring at two different spatial locations.

To test these ideas, in Experiment 1 we measured performance in three conditions: automated attention, endogenous attention, and combined attention. By using an easy and a difficult target discrimination task within each condition, we assessed the effects of increasing task demands on the resulting commitment of attentional resources to target performance using behavior [i.e., reaction times (RT)], and sensory processing (i.e., accuracy). In Experiment 2, we examined whether automated and endogenous systems also combined when these two component processes diverged in space using a counterpredictive cuing design.

Experiment 1

Recent data show that stimuli that are important for behavior, like common symbols, engage attention in an automated fashion (Ristic & Kingstone 2012; Ristic et al. 2012). Mirroring the attentional bias of stimuli with prior selection history (Anderson et al. 2011b; Awh et al. 2012), automated orienting has been found to operate independently from both traditional exogenous (Posner 1980; Posner & Cohen 1984) and endogenous (Jonides 1981) attention. According to additive factors logic, then, combining two independent systems should result in their joint effect (Sternberg 1969). Classic studies typically support this idea and report an additive relationship between exogenous and endogenous control systems under conditions when each system is engaged using a different sensory cue (e.g., Berger et al. 2005). However, it is at present unknown whether attention systems may also combine when they are engaged by the same sensory cue. Within this framework, an additive or a superadditive relationship between the two components would support the idea of combined attention, indicating that a single cue engaged multiple attention systems. Alternatively, an underadditive relationship between the two components would suggest that a single cue was unable to engage multiple attention systems in concert but instead facilitated their interference.

In Experiment 1, we tested (1) whether a single behaviorally and task relevant cue could engage multiple attention control systems; (2) if the combined effect affected behavior and perceptual processing of attended targets in a predictable manner; and (3) the nature of attentional resource distribution.
to individual automated and endogenous systems during the combined effect.

**Methods**

**Participants**

Forty-four observers participated. Twenty-two \((n = 22)\) were assigned to each easy and difficulty target discrimination condition.

**Apparatus and stimuli**

Participants viewed the trial sequence on a 16-in (40.64 cm) monitor from an approximate distance of 57 cm. All stimuli were black line drawings presented against a white background (Fig. 1a). Arrows \((3.5^\circ \text{ of visual angle})\) were comprised of a straight line \((2.5^\circ)\) with an arrowhead and an arrow tail. A square \((3.5^\circ \times 3.5^\circ)\) and a circle \((3.5^\circ)\) served as symbolic cues. The target was a \(2^\circ \times 1.5^\circ\) checkerboard, with individual squares \((0.5^\circ \times 0.5^\circ)\) filled sequentially in the easy target discrimination task and at random in the difficult target discrimination task (Fig. 1a). Targets were masked with a rectangle \((2^\circ \times 1.5^\circ)\) depicting a complex line pattern (Fig. 1a). Attentional cues were shown at fixation while the target and the mask were presented peripherally along the horizontal meridian with an eccentricity of 6.2\(^\circ\).

**Design**

Task difficulty (easy vs hard target perceptual discrimination) was manipulated between subjects. Attention condition (automated, endogenous, combined), cue validity (cued vs uncued), which allowed us to examine the effects of attention on target processing, and stimulus onset asynchrony (SOA; 100, 300, 600, 900 ms), which allowed us to examine the spatial profile of attentional effects, were manipulated within subjects.

Cues could indicate either left or right target locations. We engaged automated attention in isolation using a spatially uninformative arrow (Hommel et al. 2001; Ristic et al. 2002; Tipples 2002). We engaged endogenous attention in isolation using a shape symbol, which informed participants about the likely target location (Ristic & Kingstone 2009). Finally, we engaged combined attention using a spatially predictive arrow, which required the engagement of automated orienting in facilitating the processing of the arrow cue and endogenous orienting in facilitating the maintenance of cue predictability.

In the automated condition, the arrow did not predict the location of the target \((P = 0.5)\). In the endogenous and combined conditions, the cues predicted the location of the target \((P = 0.8)\). Shapes indicated a likely target location with the square cue predicting the likely target occurrence on the right, and the circle cue predicting the likely target occurrence on the left of fixation.\(^1\) Arrows indicated the likely target location by their direction. On each trial, participants were asked to discriminate between the two target stimuli (Fig. 1a). For each participant, and in a counterbalanced fashion, one stimulus image was designated as a ‘target’ and the other one as a ‘non-target’. Participants discriminated between ‘target’ and ‘non-target’ images by pressing either the ‘b’ or ‘h’ keys on the keyboard, with this key-response assignment counterbalanced between participants.\(^2\) As in previous studies (e.g., Berger et al. 2005; Ristic et al. 2012), task difficulty was manipulated by increasing the complexity of target discrimination within each attention condition.

**Procedure**

A cuing task was used to elicit and measure attention (Posner 1980). Trials started with a presentation of a fixation cross, which was replaced by a cue after 675 ms. Following 100, 300, 600 or 900 ms, a target was shown for 150 ms and immediately replaced by the mask. The cue and the mask remained on the screen until participants responded or 2,700 ms had elapsed. Intertrial interval was 650 ms. Attention conditions were blocked and presented in a random order across participants while cue direction, target location, and SOA times were intermixed and presented equally often within each attention condition. Responses were measured from target onset. Participants were informed about the cues’ spatial information, were asked to maintain central fixation, and to respond as fast and as accurately as possible. Each attention condition contained 512 trials divided equally across eight blocks. Ten practice trials were run at the start of each condition.

**Results**

Participants performed with an average accuracy of 93 % in the easy target discrimination and 74 % in the difficult target discrimination condition. Response errors, which were removed from analyses (anticipations RTs < 150 ms, timeouts RTs > 1,500 ms, and non-assigned key presses) were rare and did not exceed 2 % in any condition.

\(^1\) Participants also completed a condition in which the shape did not inform about the target location. Task-irrelevant shapes did not influence attention (RT & Accuracy: all Fs < 1), confirming that spatially predictive shape condition provided a measure of endogenous attention in isolation.

\(^2\) Our results did not vary either as a function of target type (‘target’ vs ‘non-target’) or key assignment (‘b’/‘h’ vs ‘h’/‘b’ corresponding to target/non-target responses; RT & Accuracy: all Fs<2.5, ps > 0.12).
A. Example Task Sequences

B. Reaction Time and Accuracy Results

C. Magnitudes of Orienting

Fig. 1  a–c Example task sequences and results. a Example experimental sequences for automated, endogenous, and combined attention conditions as well as target stimuli manipulated in easy and difficult perceptual discrimination tasks (note: stimuli are not drawn to scale). b Interparticipant mean correct reaction times (RTs) and accuracy data plotted as a function of attention condition, perceptual discrimination difficulty, stimulus onset asynchrony (SOA), and cue validity. c Magnitude of the combined attention effect relative to the magnitudes of isolated automated and endogenous components as a function of perceptual discrimination difficulty for RT and accuracy measures. Gray line Projected additive effect of automated and endogenous orienting. Error bars Standard error of the difference between the means.
and cue validity (cued vs uncued targets; within-subjects variables) using three separate mixed effects ANOVAs.

Automated attention

As illustrated in Fig. 1b, spatially uninformative arrows produced typical automated orienting effects (e.g., Ristic et al. 2002; Tipples 2002). Revealing attentional orienting, faster and more accurate responses were found when discriminating cued relative to uncued targets [cue validity, RT: F(1,42)=13.1,  \( \eta^2_p = 0.24 \); Accuracy: F(1,42)=10.7,  \( P < 0.01, \eta^2_p = 0.20 \)]. Revealing the effectiveness of task difficulty manipulation, overall RTs were significantly slower [F(1,42)=54.7,  \( P < 0.0001, \eta^2_p = 0.56 \)] and less accurate [F(1,42)=56.4,  \( P < 0.0001, \eta^2_p = 0.57 \)] in the difficult relative to the easy task. Finally, revealing a typical foreperiod effect, RTs shortened overall as SOA time increased [F(3,126)=25,  \( P < 0.0001, \eta^2_p = 0.37 \)]. The magnitude of automated orienting (cued vs uncued) grew with lengthening SOA times [cue validity x SOA; RT: F(3,126)=6.4,  \( P < 0.001, \eta^2_p = 0.13 \); Accuracy: F(3,126)=3.7,  \( P = 0.05, \eta^2_p = 0.08 \)] and as indicated in Fig. 1b with task difficulty for accuracy but not for RT [task difficulty x cue validity; RT: F<1; Accuracy: F(1,42)=9.9,  \( P < 0.01, \eta^2_p = 0.19 \); task difficulty x cue validity x SOA; RT: F<1; Accuracy: F<2,  \( P > 0.07 \)].

To verify the presence of attentional effects in each task condition, we next analyzed easy and difficult tasks separately using repeated measures ANOVAs with cue validity and SOA included as factors. When the task was easy, automated orienting was reliable in RT [cue validity; F(1,21)=33.5,  \( P < 0.0001, \eta^2_p = 0.61 \)] and increased in magnitude as SOA time lengthened [cue validity x SOA; F(3,63)=6.7,  \( P < 0.001, \eta^2_p = 0.24 \)]. Automated orienting was not reliable in accuracy [cue validity; F<1; cue validity x SOA, F=1] due to overall very high performance accuracy. When the task was difficult, automated orienting was reliable in both RT and accuracy [cue validity; RT: F(1,21)=4.4,  \( P < 0.05, \eta^2_p = 0.17 \); Accuracy: F(1,21)=11,  \( P < 0.01, \eta^2_p = 0.34 \)] with both effects growing in magnitude with increasing SOA time [cue validity x SOA; RT: F(3,63)=3,  \( P < 0.05, \eta^2_p = 0.12 \); Accuracy: F(3,63)=3.4,  \( P < 0.05, \eta^2_p = 0.14 \)].

Thus, replicating and extending past reports, we observed typical automated attention effects in behavior i.e., RT (e.g., Tipples 2002) and additionally revealed mirroring effects in sensory processing of the target, i.e., accuracy. Comparison of automated effects across task difficulty revealed that the magnitude of automated orienting held steady across difficulty conditions in RT but increased in magnitude across difficulty in accuracy, as no reliable effects were observed in the easy task.

Endogenous attention

Figure 1b shows that endogenous orienting in isolation was also reliable in both RT and accuracy measures, showing faster and more accurate responses for cued, i.e., predicted relative to uncued targets [cue validity; RT: F(1,42)=15.1,  \( P < 0.001, \eta^2_p = 0.26 \); Accuracy: F(1,42)=14.3,  \( P < 0.001, \eta^2_p = 0.25 \)]. Participants were also overall slower [F(1,42)=36.8,  \( P < 0.001, \eta^2_p = 0.47 \)] and less accurate [F(1,42)=47.2,  \( P < 0.001, \eta^2_p = 0.53 \)] in the difficult task. Overall RTs shortened as SOA time lengthened [i.e., the foreperiod effect; F(3,126)=21.3,  \( P < 0.001, \eta^2_p = 0.33 \)] and the magnitudes of orienting predictably grew with increasing SOA time [cue validity x SOA; RT: F(3,126)=3.8,  \( P < 0.05, \eta^2_p = 0.08 \); Accuracy: F(3,126)=3.8,  \( P < 0.05, \eta^2_p = 0.08 \)]. Unlike automated attention, however, task difficulty modulated the magnitude of endogenous attention in both RT and accuracy. In RT, the magnitude of endogenous orienting varied as a function of task difficulty and SOA [task difficulty x cue validity x SOA; F(3,126)=4.7,  \( P < 0.01, \eta^2_p = 0.10 \); two way interactions cue validity x task difficulty and cue validity x SOA both Fs>3.8,  \( ps < 0.05 \), both \( \eta^2_p > 0.08 \)] showing a larger increase with increasing SOA in the difficult task. In accuracy, the magnitude of endogenous orienting varied with SOA and difficulty separately [cue validity x SOA; F(3,126)=3.8,  \( P < 0.05, \eta^2_p = 0.08 \); cue validity x task difficulty; F(1,42)=14.6,  \( P < 0.001, \eta^2_p = 0.26 \); task difficulty x cue validity x SOA; F<1.5,  \( P > 0.3 \)] indicating once again that attention effects increased with SOA during the difficult task.

To verify that endogenous effects were reliable in both easy and difficult tasks, we next examined each condition separately using repeated measures ANOVAs with cue validity and SOA included as factors. When the task was easy, reliable endogenous orienting was observed in RT but not in accuracy [RT: F(1,21)=8.9,  \( P < 0.01, \eta^2_p = 0.3 \); Accuracy: F<1], due to ceiling effects in this easy task. While the magnitude of orienting held steady with SOA in RT [cue validity x SOA; F<1], in accuracy, endogenous orienting was temporarily present at 600 ms SOA only [cue validity x SOA; F(3,63)=2.8,  \( P = 0.5, \eta^2_p = 0.12 \); 600 ms SOA cued vs uncued, t(21)=2.1,  \( P < 0.05 \); all other SOAs ts<<1,  \( ps > 0.3 \), paired, two-tailed t-tests]. When the task was difficult, endogenous orienting was reliable in both RT and accuracy [RT: F(1,21)=11.2,  \( P < 0.01, \eta^2_p = 0.35 \); Accuracy: F(1,21)=15.4,  \( P < 0.001, \eta^2_p = 0.42 \)]. The magnitude of orienting increased reliably with lengthening of SOA time in RT [F(3,63)=5.5,  \( P < 0.01, \eta^2_p = 0.21 \)] and trended towards an increase in magnitude with SOA in accuracy [F(3,63)=2.5,  \( P = 0.7 \)].

Thus, isolated endogenous attention elicited using a symbolic shape cue was significant in both easy and difficult tasks (e.g., Muller & Rabbitt 1989). When the two effects were compared across difficulty conditions, an expected growth in magnitude with increases in task difficulty was observed (e.g., Berger et al. 2005).
Combined attention

The data for the critical combined condition are plotted in Fig. 1b. Attention effects emerged in both RT and accuracy [cue validity; both Fs>50, ps<0.0001, both \( \eta^2_p > 0.54 \)] and showed a robust foreperiod effect [F(3,126)=21.6, \( P < 0.0001 \), \( \eta^2_p = 0.34 \)]. As before, the difficult task resulted in lower RTs and lower accuracy overall [both Fs>34, ps<0.0001, both \( \eta^2_p > 0.45 \)] while the magnitude of attentional orienting grew with SOA [cue validity x SOA; RT: F(3,126)=7, \( P < 0.001 \), \( \eta^2_p = 0.14 \); Accuracy: F(3,126)=8.7, \( P < 0.001 \), \( \eta^2_p = 0.17 \)] and with task difficulty [task difficulty x cue validity; RT: F(1,42)=9.6, \( P < 0.01 \), \( \eta^2_p = 0.19 \); Accuracy: F(1,42)=58.7, \( P < 0.0001 \), \( \eta^2_p = 0.58 \)]. A three-way interaction between task difficulty, cue validity, and SOA was reliable in accuracy indicating a more pronounced increase in attentional facilitation of sensory processing with SOA time [F(3,126)=7.3, \( P < 0.0001 \), \( \eta^2_p = 0.15 \)] relative to RT measure in which the magnitudes of orienting for easy and difficult tasks remained stable across SOA intervals [task difficulty x cue validity x SOA; F(3,126)=1.7, \( P > 0.16 \)]. Separate analyses of easy and difficult conditions returned reliable combined orienting effects for each task [cue validity; RT easy and difficult both Fs>35, ps<0.0001, \( \eta^2_p > 0.62 \); Accuracy easy: F<1; Accuracy difficult: F(1,21)=60, \( P < 0.0001 \), \( \eta^2_p = 0.74 \)], which both increased across SOA intervals [cue validity x SOA; RT easy and difficult both Fs>3.3, ps<0.05, \( \eta^2_p > 0.14 \); Accuracy easy F<1; Accuracy difficult: F(3,63)=9.8, \( P < 0.001 \), \( \eta^2_p = 0.32 \)]. Thus, attentional effects were observed in the combined condition.

Analysis of orienting magnitudes

The critical test, however, involves a comparison of the magnitude of the combined effect with the sum of isolated automated and endogenous components. We reasoned that if a single behaviorally relevant cue could access multiple control systems, the combined effect should reflect at least an additive combination of the two isolated components.

An inspection of Fig. 1c shows precisely this outcome. The magnitude of combined attention in RT (i.e., uncued RT-cued RT) and accuracy (i.e., correct–incorrect) always surpassed the magnitudes of isolated measures of automated and endogenous attention\(^3\) and reflected either their additive or a superadditive combination. To confirm this, we ran repeated measures ANOVAs that compared the magnitude of the combined effect with an additive sum of isolated automated and endogenous magnitudes as a function of SOA for each difficulty condition separately. When the task was easy, the combined effect reflected a superadditive combination of automated and endogenous attention [combined vs additive; F(1,21)=5.3, \( P < 0.05 \), \( \eta^2_p = 0.20 \)], which grew overall with SOA [F(3,63)=4.5, \( P < 0.05 \), \( \eta^2_p = 0.17 \)] but did not vary across SOA [magnitude x SOA; F<1], as shown in Fig. 1c. When the task was difficult, however, the combined effect reflected an additive combination of automated and endogenous attention [combined vs. additive, both RT and Accuracy Fs<1], which also overall grew with SOA [both RT and Accuracy Fs>9.3, ps<0.0001, both \( \eta^2_p > 0.26 \)] but did not vary across SOA [magnitude x SOA, both RT and Accuracy Fs<1].

Discussion

We examined three questions in Experiment 1. First, we tested if a single behaviorally relevant and task relevant cue was capable of eliciting combined attention. The data confirmed this hypothesis. While typical orienting effects emerged for the isolated components of automated and endogenous attention, the magnitude of the combined effect surpassed both of these individual measures and reflected either their additive or a superadditive combination. Thus, a single cue engaged multiple attention systems without interference. Furthermore, this combined effect occurred only when a behaviorally relevant arrow served as a fixation stimulus and not when an arbitrary shape cue was used, which elicited typical endogenous effects.

Second, we examined if the combined effect affected behavior and perceptual processing of targets. The data supported this hypothesis as well. We found that combining automated and endogenous attention resulted in the facilitation of both RT and accuracy for attended (i.e., cued) targets. This shows that, in addition to affecting the speed of target identification, combined attention also led to theoretically predicted increases in the underlying perceptual processing of target’s features. These data dovetail with the results from past studies, which have similarly demonstrated that exogenous, endogenous, and automated attention increased both speed (Jonides 1981; Posner 1980; Ristic & Kingstone 1997) and accuracy, i.e., perceptual sensitivity of target processing (e.g., Eimer 1997; Hawkins et al. 1990; Hopfinger & Mangun 1998; Luck et al. 1994) and as such do not agree with proposals (e.g., Prinzmetal et al. 2005) that different attention control systems affect speed and accuracy of target processing in discrete ways (see also Carrasco 2011).

Finally, we examined the distribution of attentional resources during combined attention. We reasoned in the Introduction that combined attention may involve flexible pooling of resources available to individual component systems,
especially when task demands are placed disproportionately on one component process. This is exactly what our data suggested. When the task was easy, automated and endogenous attention combined in a superadditive manner. When the task was difficult, automated and endogenous attention combined in an additive manner. As suggested by Fig. 1c, this difference in the nature of the combined effect, i.e., a superadditive vs an additive relationship, appeared to be driven by the amount of resources allocated to the endogenous system as the task increased in difficulty. Indeed, when we analyzed the magnitudes of isolated automated and endogenous orienting as a function of task difficulty, we found that the magnitude of automated orienting remained stable across task difficulty [task difficulty; F<1] while the magnitude of endogenous orienting increased with task difficulty [task difficulty; RT: F(1,42)=7.1, P<0.05, η²_p=0.14; Accuracy: F (1,42)=15, P<0.001, η²_p=0.26]. This suggests that the total amount of resources devoted to the combined attention reflects the extent to which individual components’ resource pool is exhausted by the task demands. That is, the systems may combine in a superadditive fashion under conditions when there are plenty of resources available to both automated and endogenous attention, i.e., when the task is easy. However, the systems may combine in an additive fashion when the task necessitates a full allocation of resources to each component, i.e., the task is difficult. Furthermore, the change in the nature of the combined effect from an easy to a difficult task appears to be driven by an increased demand on the endogenous system, as automated orienting drew on the same amount of resources regardless of task demands and held steady across the difficulty manipulations, as it is typical for less controlled processes (see also Jonides 1981).

In sum, the data from Experiment 1 indicated that attentional control systems combined when a single behaviorally relevant and task relevant cue, like an arrow, directed automated and endogenous attention towards the same spatial location. This combined effect reflected a superadditive combination of the two component systems when the task was easy and their additive combination when the task was difficult, indicating flexible resource allocation during combined attention, and an increased deployment of attentional resources towards the endogenous system with increases in task difficulty.

While this interpretation is consistent with our data, one might argue that there might be a difference in how arrow and shape cues affect endogenous attention, such that the combined effect may simply reflect a larger contribution of endogenous orienting elicited by a familiar arrow cue relative to an unfamiliar shape cue. Two lines of evidence from our data argue against this interpretation. First, this account predicts that arrow and shape cues differed in the ease of cue interpretation. If so, extracting the cue-target relationship from a symbolic shape cue should take a longer time relative to the same process engaged by a familiar arrow cue. Thus, endogenous orienting elicited by the shape cues should be initially delayed relative to the combined effect elicited by arrows; however, the two effects should eventually converge as a function of the SOA time. Our data do not support this prediction. Looking at Fig. 1c, one can see that the magnitudes of endogenous and combined attention closely mirrored one another across SOA times, without ever converging. That is, while the combined effect emerged in a larger magnitude early, due to rapid engagement of automated orienting, both effects peaked at 600 ms SOA, and held steady thereafter. Consistent with this observation, and as indicated before, no interactions between combined orienting magnitudes and SOA times were observed (all Fs < 1). Second, if the ease of cue interpretation differentially afforded the development of endogenous orienting during the combined condition, the endogenous component elicited by the arrow cue should be larger in magnitude than the endogenous component elicited by the shape cue. Furthermore, one might also predict that this difference might be especially pronounced in the easy task when participants are presumably less motivated to utilize the unfamiliar shape cue relative to the familiar arrow one (e.g., see Davis & Gibson 2012). If so, the magnitude of the estimated endogenous component elicited by the arrow cue during the combined effect (i.e., combined–automated) should surpass the magnitude of the isolated endogenous component elicited by the shape cue, with this difference especially pronounced in the easy task. Our data did not support this prediction either. When we compared the magnitudes of the estimated endogenous component derived from the combined condition (i.e., combined effect magnitude–automated effect magnitude) with the magnitude of isolated endogenous orienting as a function of SOA for RT and accuracy and for each task difficulty condition using four separate repeated measures ANOVAs, no differences in the magnitudes of the two endogenous effects emerged (estimated vs isolated endogenous effect magnitude; all Fs < 1). Taken together then, these two lines of evidence argue firmly against the alternative explanation that the arrow and shape cues differentially affected the development of endogenous attention.

Experiment 2

In Experiment 2 we addressed the final question of whether attentional systems combined even when the two component systems were directed to two different spatial locations. To do so, we employed a counterpredictive cuing design, which was coupled with a difficult target discrimination response from Experiment 1. There are two main advantages of this design. First, it allowed us to directly test the question of whether combined attention emerged similarly when the two component processes were directed to two different locations in
space by employing the same cue to elicit both types of orienting within the same participants. In our counterpredictive design, participants were asked to orient endogenously in the opposite direction from the arrow cue, i.e., away from it. The performance for targets occurring at those predicted locations was a measure of endogenous attention. However, on a subset of trials, the target also appeared at the location indicated by the arrow. The performance for targets occurring at those cued locations was a measure of automated attention. Combined attention reflected the sum of endogenous and automated effects. The effect of each automated and endogenous orienting was assessed relative to performance for targets that occurred at two additional locations that were neither predicted nor cued. As such, this four-location cuing task allowed for an unambiguous assessment of both automated and endogenous orienting against the common baseline. Given the existing data showing that automated and endogenous orienting occur in parallel when a similar counterpredictive task is coupled with a simple target detection response (Friesen et al. 2004; Tipples 2008), here we expected that the combined measure would also approximate an additive relationship between automated and endogenous components.

Second, the counterpredictive Experiment 2 also allowed us to further test the flexible resource allocation hypothesis. In particular, the data from Experiment 1 suggested that increases in task difficulty demanded increases in the allocation of attentional resources towards the endogenous system. In Experiment 2, we further increased the demands on the endogenous system without changing the complexity of target’s perceptual discrimination by asking participants to orient endogenously away from the arrow’s direction. Because all other task parameters were kept on par with Experiment 1, any differences in attentional resource allocation during combined orienting between Experiments 1 and 2 reflected changes in the attentional resource allocation to the endogenous component. Note that the change in the number of possible target locations from Experiment 1 to Experiment 2 is unlikely to explain the potential difference in combined attention between the two experiments. This is because the data from Experiment 1 in which an easy task was employed within a two-location cuing paradigm fully replicated the data reported by Ristic and Kingstone (2006) in which an easy task was employed within a four-location cuing paradigm. As such, any differences in the combined effect between Experiments 1 and 2 reflect the added demand on the endogenous component rather than the change in the number of possible target locations.

The key comparison thus involved the contrast between the magnitude of the combined effect from Experiment 2, when automated and endogenous effects diverged across two spatial locations, and the magnitude of the combined effect from Experiment 1, when automated and endogenous effects converged on to the same spatial location. This comparison yields two meaningful outcomes. The first is that the magnitude of combined attention from Experiment 2 is smaller than the magnitude of combined attention from Experiment 1. This would indicate that the effects of automated and endogenous attention interfered when they were directed to opposing spatial locations in Experiment 2, producing an underadditive combination. This outcome would demand an interpretation that combined attention depended on a spatial convergence of constituting components. The second possible outcome is that the magnitude of combined attention from Experiment 2 is equal or larger than the magnitude of combined attention from Experiment 1. Both results would suggest that automated and endogenous attention combined when the two systems diverged across different spatial locations (Experiment 2) and when they converged onto the same spatial location (Experiment 1) without interfering. In turn, both outcomes would suggest an interpretation that combined attention did not depend on a spatial convergence of constituting components, but instead reflected a general mechanism for integrating the information coming from the sensory systems with the present goal states.

Thus, if combined attention does not depend on the spatial convergence of the constituting components, the magnitude of the combined effect observed in Experiment 2 should either approximate or exceed the magnitude of the combined effect observed in Experiment 1. This is exactly what our data indicated.

Methods

Participants, stimuli, design and procedure

Thirty \((n = 30)\) additional participants completed the same task as in Experiment 1 difficult target discrimination condition, except: (1) there were now four possible arrow directions and target locations (left, right, up, and down); and (2) arrow direction was counterpredictive of target location, such that the target appeared on the opposite side as indicated by the arrow in 81\% of trials, as shown in Fig. 2a. Automated orienting occurred on trials in which the target appeared at the location indicated by the arrow (i.e., 6.25 \% of trials; Friesen et al. 2004; Hayward & Ristic 2013; Tipples 2008) while endogenous orienting occurred on trials in which the target appeared at the location opposite to the arrow’s direction (i.e., 81 \% of trials; Friesen et al. 2004; Tipples 2008). Both automated and endogenous attention were assessed relative to the common condition in which the target occurred with an equal probability of 6.25 \% at one of the two remaining not-predicted and not-cued locations (i.e., NP-NC trials, 6.25 \%; Friesen et al. 2004; Hayward & Ristic 2013; Tipples 2008).
Each participant was informed about the counterpredictive cue-target contingency, and completed 1,024 experimental trials divided equally across eight testing blocks.

Results

Participants performed with an average accuracy of 70% while response errors, which were removed from analyses (anticipatory RTs < 150 ms, timeouts RTs > 1,500 ms, and responses made using the non-assigned key presses) accounted for 2.55% of data.

First, to establish the presence of isolated effects, we examined automated and endogenous attention as a function of cue validity and SOA in RT and accuracy (i.e., cued vs NP-NC for automated attention; predicted vs. NP-NC for endogenous attention; cf. Hayward & Ristic 2013) using two separate repeated measures ANOVAs.

We found that automated orienting was muted under these attentionally taxing conditions, as shown in Fig. 2b [RT: F<1; Accuracy: F(1,29)=2.6, P>0.1; all other effects Fs<2.6, ps>0.05]. In contrast, endogenous orienting was robust. Participants were faster and more accurate in discriminating the targets occurring at predicted locations [RT and Accuracy both Fs>61, ps<0.0001, both η²_p>0.67]. The magnitude of endogenous orienting grew with lengthening of SOA times [cue validity x SOA; RT and Accuracy both Fs>23, ps<0.0001, both η²_p>0.44] and a typical foreperiod emerged as well [F(3, 87)=16.8, P<0.0001, η²_p=0.37]. Thus, under these very taxing conditions in which participants were asked to perform a difficult perceptual target discrimination task and to maintain a complex cue-target contingency, automated orienting became suppressed while endogenous orienting persisted, and, as it is typically found, grew with SOA.

To test if combined attention was limited to situations when multiple attention systems converged onto the same spatial location, we next compared the magnitude of the spatially divergent combined attention (i.e., the sum of the isolated magnitudes of spatially divergent automated and endogenous effects) obtained in the present Experiment 2 with the magnitude of the spatially convergent combined attention obtained in Experiment 1. A mixed effects ANOVA with experiment (Experiment 1; Experiment 2) included as a between-subjects factor and SOA included as a within-subjects factor was run. Both RT and accuracy analyses returned no reliable differences in the magnitude of the combined effect across the two experiments [Experiment 1 vs Experiment 2; RT: F(1,50)=3.5, P>0.05; Accuracy: F<1; all other effects and interactions, F<1]. Thus, automated and endogenous orienting combined additively. If anything, this nonsignificant difference in the magnitudes of the combined effect trended towards reflecting a larger magnitude of combined attention in Experiment 2 relative to Experiment 1, as shown in Fig. 3. To remind, we reasoned that only an outcome showing an underadditive relationship between automated and endogenous orienting in Experiment 2 would indicate that attentional systems did not combine. Our data argue strongly against this notion. Instead, they show that attentional systems combined in an additive fashion under conditions when the two component processes diverged across different spatial locations (Experiment 2) and when they converged onto the same spatial location (Experiment 1). As such, this finding supports the conclusion that combined attention does not depend on the spatial convergence of individual components.

One might note here that, unlike Experiment 1, automated orienting was muted in Experiment 2. Endogenous orienting

A. Task Conditions

B. Reaction Time and Accuracy Results

![Fig. 2](https://example.com/fig2.png)

Fig. 2 a,b Example task sequences and results for Experiment 2. a Experimental conditions and target probabilities (note: stimuli are not drawn to scale). b Interparticipant mean correct RTs and accuracy data plotted as a function of attention condition, perceptual discrimination difficulty, SOA, and cue validity. Error bars Standard error of the difference between the means.
on the other hand was robust with its magnitude approximating an additive combination of automated and endogenous effects. The magnitude of this combined effect continued to approximate the magnitude of the combined effect from Experiment 1, which included reliable contributions from both automated and endogenous components. We believe that this result exemplifies the proposed flexible allocation of attentional resources during combined attention. That is, while the magnitude of the combined effect in Experiment 2 approximated the magnitude of the combined effect in Experiment 1, the allocation of attentional resources towards the constituting components changed between the two experiments. In contrast to Experiment 1 in which attentional resources were directed to each automated and endogenous system, in Experiment 2, resources available to those two systems appear to have been pooled towards the endogenous system, with a consequence of a suppressed automated orienting. Importantly, and highlighting the notion that this result reflects pooling of attentional resources available to individual automated and endogenous systems, and not endogenous orienting in isolation, the magnitude of this endogenous component in Experiment 2 was larger than (1) the magnitude of the isolated endogenous effect from Experiment 1 difficult task \[RT: F(1,50)=10, P<0.001, \eta^2_p=0.17; \text{Accuracy: } F(1,50)=11, P<0.01, \eta^2_p=0.18,\] and (2) the magnitude of the estimated endogenous component derived from the combined effect in Experiment 1 difficult task \[i.e., \text{combined – automated; RT: } F(1,50)=9.6, P<0.01, \eta^2_p=0.16; \text{Accuracy: } F(1,50)=8, P<0.01, \eta^2_p=0.14.\] Thus, the magnitude of the endogenous orienting in isolation and approximated the magnitude of an additive sum of automated and endogenous effects, i.e., combined attention.

Flexible resource allocation

To delineate the nature of resource allocation to individual components during combined attention, we also examined the changes in the overall magnitudes of orienting (i.e., collapsed across SOA times) for combined, endogenous, and automated attention as a function of task difficulty. One-way ANOVAs were performed for each attention condition with task difficulty (i.e., Experiment 1 easy task; Experiment 1 difficult task; Experiment 2) included as a between-subjects variable.

Figure 3 illustrates the magnitudes of combined, endogenous, and automated attention as a function of task difficulty along with an estimated additive effect of automated and endogenous components. First, it shows that the magnitude of combined attention grew linearly with increasing task difficulty, with an average gain of 43 ms in RT \[F(2,71)=10.7, P<0.0001, \eta^2_p=0.23\] and a corresponding 9.75 % gain in accuracy \[F(2,71)=22.3, P<0.0001, \eta^2_p=0.38\]. The reliable growth in the magnitude of orienting occurred between the easy and difficult tasks in Experiment 1 (RT and Accuracy: both ts(42)<−3.1, ps<0.01, unpaired t-tests, two tailed) and between the easy task in Experiment 1 and Experiment 2 (RT and Accuracy: both ts(50)>4.6, ps<0.0001; Experiment 1 difficult vs Experiment 2; RT: t(50) = 1.9, P = 0.07; Accuracy: t < 1). Second, Fig. 3 also shows a similar increase in the magnitude of endogenous orienting, which grew at a rate of approximately 58 ms in RT \[F(2,71)=18.3, P<0.0001, \eta^2_p=0.34\] and 8% in accuracy \[F(2,71)=26.6, P<0.0001, \eta^2_p=0.43\] across difficulty conditions. Here, a reliable growth in the magnitude of orienting occurred between each difficulty condition (RT: all ts > |2.7|, ps < 0.05; Accuracy: all ts > |3.8|, ps < 0.001). Finally, and in contrast to these data, Fig. 3 shows that the magnitude of automated orienting held steady in
Experiment 1 but decreased in magnitude only under extreme demands for endogenous resources in Experiment 2 [RT: $F(2,71)=3$, $P=0.05$, $\eta^2_p=0.07$; Accuracy: $F(2,71)=4.7$, $P<0.05$, $\eta^2_p=0.11$]. In RT, automated orienting decreased reliably from Experiment 1 (Experiment 1 easy vs difficult, $t(42)=-3.15$, $P<0.01$) and decreased marginally from Experiment 1 difficult task to Experiment 2 [$t(50)=-1.8$, $P=0.07$; Experiment 1 easy vs Experiment 2, $t(50)=1.3$, $P>0.2$].

This final analysis illustrates the flexible allocation of attentional resources during combined attention. When increases in task difficulty were optimal, (i.e., a change from an easy to a difficulty task in Experiment 1), combined attention included about the same amount of attentional resources allocated to automated processes while the contribution of endogenous resources increased with task demands. When fewer endogenous resources were taken up by the task, as in Experiment 1 easy task condition, the systems combined in a superadditive manner whereas when more endogenous resources were taken up by the task, as in Experiment 1 difficult task, the systems combined in an additive manner. When task difficulty was extreme however, as in Experiment 2, a reallocation of all available resources towards the endogenous system appeared to take place resulting in a suppression of other, less controlled (i.e., automated) processes (see also Yantis & Jonides 1990). Importantly however, the combined effect persisted despite changes in resource allocation to individual component processes.

General discussion

Inspired by an observation that many daily tasks may require attentional control systems to combine rather than to act in isolation, we investigated if attentional systems combined under experimental conditions in which sensory information and participants’ intentions were relevant. Specifically, we examined whether automated attention, which is engaged by behaviorally relevant cues like arrows, and endogenous attention, which is engaged by participants’ intentions combined to influence behavior and perceptual processing of attended targets. Four lines of evidence supported this hypothesis. First, we demonstrated combined attention by showing that the magnitude of orienting in the combined condition (i.e., in which a behaviorally relevant cue was made task relevant) always surpassed the individual magnitudes of isolated automated and endogenous component processes (Experiment 1) and reflected either their additive or a superadditive combination. That is, we found that automated and endogenous attention always combined and never interfered. Second, we found that combining attention affected processing of response targets in a predictable manner. Specifically, both the speed of target processing and the underlying sensory processing of target features, as revealed by RT and accuracy data, were facilitated correspondingly during combined orienting. Third, we found that combined attention involved flexible allocation of attentional resources. When the task was easy requiring only a simple perceptual discrimination, automated and endogenous attention combined in a superadditive manner (Experiment 1). When the task was difficult requiring a more complex perceptual discrimination and thus more endogenous resources, automated and endogenous attention combined in an additive manner (Experiments 1 and 2). This shows that when resources available to endogenous attention are not fully exhausted they are flexibly allocated toward the combined effect and consequently result in a superadditive combination of the two component processes. When resources available to endogenous attention are near exhaustion, however, the combined effect approximates an additive combination of the two component processes. Finally, our data indicated that combined attention emerged in a similar fashion both when the two component processes converged onto the same spatial location (Experiment 1) and when they diverged across two different spatial locations (Experiment 2). Again, in this comparison, automated and endogenous systems were found to combine rather than interfere. Taken as a whole then, these results strongly suggest that combined attention reflects a general mechanism by which attentional systems evaluate and integrate incoming sensory information with the present goal states, compound and dynamically allocate available resources to individual components, and act correspondingly to facilitate stimulus processing at a sensory level and manual responses at a behavioral level. At least three broad implications follow from this conclusion.

The first highlights a fundamentally novel way of conceptualizing attentional processes in which multiple attention control systems may be engaged jointly by the same sensory cue. This extends the prevailing attentional theories (e.g., Corbetta & Shulman 2002), in which isolated effects of exogenous and endogenous attention on behavior and sensory processing are emphasized. These data also support and extend the recent proposal (Awh et al. 2012) that attention is independently biased by current goals (i.e. endogenous attention), physical salience (i.e. exogenous attention), and stimulus selection history, whereby selection history may be conceptualized as reflecting overlearned behavioral relevance, as we have tested it here (Ristic & Kingstone 2012), stimulus’ motivational value (e.g., Anderson et al. 2011a, 2011b; Hickey et al. 2010) or prior selection (Awh et al. 2012). Expanding this recent notion, our results not only show that independent attentional control mechanisms may be engaged jointly but also that they may be accessed by a single cue, which by the virtue of its properties affords processing in multiple attention control systems.
The second implication concerns the flexible nature of resource allocation during combined attention, pointing to the adaptability of attentional responses as a function of environmental demands. We found that, under low task demands when perceptual discrimination of the target was easy, automated and endogenous systems combined in a superadditive manner. This replicates past results in which a similar superadditive relationship emerged between exogenous and endogenous attention under low task demands in which participants were simply asked to detect an onset of a salient target (Olk et al. 2008; Ristic & Kingstone 2006). However, when we increased the demands on the endogenous component by asking participants to discriminate between complex target images in Experiment 1, automated and endogenous systems combined in an additive manner. Moreover, when attentional demands on the endogenous component were further increased to include both the difficult target discrimination and the maintenance of the complex cue-target contingencies in Experiment 2, all available resources were directed towards the endogenous system, at the expense of other component processes (i.e., automated orienting). Importantly, however, the combined effect remained unchanged relative to Experiment 1.

Hence, when a single cue accesses multiple attentional systems resources available to component processes may be pooled dynamically. It appears though that the resource demands placed on the endogenous component play a large role in such active resource distribution. When resources available to the endogenous system are not fully exhausted, like in Experiment 1 easy task, they are flexibly allocated toward the combined effect and result in a superadditive combination of attentional systems; however, when endogenous resources are fully taxed by the task, like in Experiment 2 difficult task, automated and endogenous attention combine in an additive manner. Moreover, when the task requires resources from both automated and endogenous systems, both may be pooled towards one component. However the magnitude of that component continues to approximate the combined effect. Thus, the endogenous system’s resource requirements appear to be a key determinant of the nature of combined attention. This notion fits well with developmental investigations, which show that the ability to combine attentional resources depends on the development of an adult-like endogenous system resource capacity (Ristic & Kingstone 2009).

Understanding the flexible resource allocation in many ways also concerns the long-standing theoretical question of attentional resource allocation. One the one hand, classic studies have also reported brief interference, i.e., interactions between exogenous and endogenous systems, indicating shared resources, under increased task difficulty (e.g., Berger et al. 2005; Muller & Rabbitt 1989); however, similar interactions were not present when automated orienting was recently pitted directly against endogenous attention (Ristic & Kingstone 2012; Ristic et al. 2012). In contrast to these results, which were based on the experiments that engaged multiple attention systems by physically distinct cues (i.e., exogenous orienting is engaged using spatially nonpredictive peripheral cues while endogenous orienting is engaged using a spatially predictive central cue, e.g., Berger et al. 2005) here we engaged combined attention using a single behaviorally relevant cue, and observed that the characteristics of the combined attention changed dynamically with task demands.

As such, one possibility is that combined attention arises because automated and endogenous systems share a common pool of attentional resources (e.g., see Berger et al. 2005; or Ristic & Kingstone 2012 for more detailed discussions on attentional resource allocation). However, this account is not consistent with our data as it predicts an emergence of an underadditive relationship, i.e., interfering effects, especially under conditions when the two control systems are engaged in opposition like in Experiment 2. Another possibility is that combined attention emerges because resources from multiple, non-interacting, independent resource pools are combined. However, this account also does not fully agree with our data, as it neither allows for a flexible allocation of resources towards the combined effect nor, relatedly, for the emergence of a superadditive component combination. The final possibility is that combined attention depends on a coordinated effort of two independent but linked pools of attentional resources. This alternative fits best with the present data for three reasons. First, it is consistent with the notion that combined attention reflects the engagement of multiple attention systems by the same sensory cue, which has an ability to access resources available to each individual component. Second, it is consistent with our results showing that the nature of the combined effect (i.e., additive vs superadditive) varied with the resource demands placed on each component system, which were allocated jointly and flexibly in support of behavior and perceptual processing of targets. Finally, this alternative also dovetails with recent neuroimaging data indicating that the dorsolateral and the ventrolateral attention control networks work interdependently by communicating via a shared structure located in the frontal lobe’s middle frontal gyrus (Ristic & Giesbrecht 2011; Shulman et al. 2009). As such, rather than operating in a functionally and anatomically disconnected manner (Corbetta & Shulman 2002) attentional control networks appear to be engaged adaptably (e.g., see DiQuattro et al. 2013; Ristic & Giesbrecht 2011; Vossel et al. 2012) as a function of the incoming sensory information and
the task at hand rather than being driven solely by the mode of attentional control (i.e., exogenous vs. endogenous attention; Corbetta et al. 2008; Kincade et al. 2005). Taken together then, the present behavioral evidence and the existing neuro-imaging data support the notion that combined attention involves a cross talk between multiple independent attention networks that contribute their uniquely available resources to the combined effect dynamically as a function of the information present in the environment and current task demands.

Finally, our data also carry implications for understanding functional consequences of combined attention. It is well known that automated and endogenous orienting lead to increased sensory processing of attended targets, as indexed by the amplitude modulations of the early event-related components, like P1 (Eimer 1997; Tipper et al. 2008). Our data further suggest that combining multiple attention systems may also result in similar corresponding superadditive and/or additive increases in the amplitudes of the sensory components associated with the early cortical processing of attended events (e.g., Luck et al. 1994; Mangun & Hillyard 1991; Martinez et al. 1999). Dovetailing with this hypothesis, Hopfinger and West (2006) found that the sequential engagement of exogenous and endogenous attention by two different cues resulted in the overlapping amplitude enhancements of the early attention-related components. Future electrophysiological studies are needed to determine the nature, the time course, and functional consequences of combined attention on sensory processing. Along with investigations into the associated cortical control dynamics of combined attention, such studies have the potential to reveal fundamentally novel insights about the links between attentional systems, sensory processing, and complex behavior, and lead to important expansions in theoretical and methodological conceptualizations of human attention.

Acknowledgments This work was supported by grants from the Natural Sciences and Engineering Research Council (NSERC), Social Sciences and Humanities Research Council (SSHR), the Stairs Foundation, and William Dawson fund to J.R., and fellowships from NSERC, Fonds de Recherche Nature et Technologies Québec (FQRNT), and the Tomlinson foundation to M.L. We would also like to thank Brad Gibson and two anonymous reviewers for their helpful comments on an earlier version of this manuscript.

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