Relationships Amongst Temporal Attentional Limitations

Do Temporal Information Processing Limitations Share Cognitive Causes? A Correlational
Study Across Attentional Forms and Modalities

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Abstract

Selective attention can be directed according to behavioral goals or grabbed by salient stimuli. Whether controlled in a goal-directed or stimulus-driven fashion, attention has a dark side: Unattended items are frequently missed. Such failures have been explored through numerous experimental paradigms across sensory modalities, but their relationships have been incompletely characterized. In two experiments, we adopted an individual differences approach to better understand the common and dissociable cognitive components in temporal attention paradigms. In Experiment 1, participants ($n=56$) were tested twice on the attentional blink (predominantly goal-directed attention), surprise-induced blindness (predominantly stimulus-driven attention), and their auditory analogues. Despite high effect reliability and significant within-modality correlations across effects, we found no significant correlations across modalities. In Experiment 2, participants ($n=52$) completed different versions of the visual tasks and a contingent capture task, whose deficit has been ascribed to both goal-directed and stimulus-driven components. Using exploratory factor analyses and partial correlations, we found that capture-related deficits accounted for the modest relationship between blink and surprise effects. Furthermore, surprise effects quickly habituated, blink effects persisted unchanged, and capture-related deficits showed an intermediate pattern. We conclude that each attentional paradigm involves multiple cognitive components, some shared and others distinctly related to different forms of attentional control.

Key phrases: capacity limitations, visual attention, auditory attention, selective attention, individual differences

General importance

In daily life, we fail to notice many events that are clearly visible or audible, often to our detriment. For example, we may miss an important traffic signal or become distracted by a nearby conversation. Some people are more prone to missing such events than others. By leveraging these individual differences, here we show that the underlying cognitive causes of failing to see and failing to hear are different. Furthermore, these failures can occur either because we are voluntarily paying attention to something else or had our attention grabbed by an unexpected sight or sound. These different scenarios involve both shared and distinct cognitive causes. Our findings inform our theoretical and practical understanding of the trade-off between staying on task and attending to what is new.

Introduction

Selective attention allows us to enhance certain stimuli while ignoring or suppressing others. Attending to an item, feature, location, or time often yields improved detection and discrimination. But attention has a dark side: Unattended items are frequently missed (Chun & Marois, 2002). For example, when individuals attempt to discriminate a target and then detect a probe in a rapid stream of distractors, they often miss the probe when it closely follows the target (200-500 ms). This effect is the attentional blink, so named because it appears only when the target stimulus is attended and relevant to the task (Chun & Potter, 1995; Dux & Marois, 2009; Raymond, Shapiro, & Arnell, 1992). Conversely, a task-irrelevant stimulus that is rare and unexpected can also cause a detection impairment. This effect, termed surprise-induced blindness, has a timecourse similar to the attentional blink within each trial, though the effect rapidly habituates as the inducing stimulus becomes familiar (Asplund, Todd, Snyder, Gilbert, et al., 2010; Asplund, Todd, Snyder, & Marois, 2010). Corresponding effects have been found in the auditory domain, both an auditory attentional blink (Mondor, 1998; Obana et al., 2020; Tremblay et al., 2005) and surprise-induced deafness (Obana et al., 2020). Each of these four paradigms reveals a cost of temporal selective attention, though the similar detection failures are caused by rather different inducing stimuli and contexts. It is therefore unclear whether common or distinct cognitive mechanisms underlie the deficits.

The relationship amongst different attentional paradigms has been the object of both empirical and theoretical work, with researchers aiming to characterize attention's taxonomy and to understand the function of its components (Alais et al., 2006; Awh et al., 2012; Chun et al., 2011; Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Posner & Cohen, 1984; Skogsberg et al., 2015). A primary distinction is between different attentional forms or sources of control. Attention can be directed according to behavioral goals, or it can be

involuntarily grabbed by salient stimuli (Corbetta & Shulman, 2002; Egeth & Yantis, 1997). Both behavioral and neural evidence supports this dissociation between goal-directed and stimulus-driven attention (Awh et al., 2012; Corbetta & Shulman, 2002; Egeth & Yantis, 1997). Coherent behavior, however, requires coordination across these attentional forms, so the dissociation may be partial or managed through a hierarchy of control (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Folk, Remington, & Johnston, 1992; Serences et al., 2005).

Although most theories of attention center on vision, similar functional distinctions are thought to apply in the auditory domain. The partial dissociation of goal-directed and stimulus-driven auditory attention, for example, is supported by multiple neural and behavioral studies (Alho et al., 2015; Corbetta & Shulman, 2002; Hughes et al., 2013; Salmi et al., 2009; Vachon et al., 2017). The similarity of the attentional taxonomies in vision and audition raises an interesting question: Are there modality-specific systems with similar properties, or is attentional control supramodal? On the one hand, auditory and visual cueing appear to operate across modalities, especially for spatial redirection (McDonald et al., 2012). More complex or “higher-order” attention also involves interactions across modalities, perhaps owing to central task coordination or task-switching (Pashler et al., 2001; Tombu et al., 2011). On the other hand, attention within each modality can be independent. For example, contrast and pitch discrimination thresholds are not affected by cross-modal secondary tasks (Alais et al., 2006). Stimulus-driven attention also appears to have modality-specific components. The electrophysiological markers of novelty or surprise (e.g. the P3a) have different distributions in audition and vision (Berti & Schröger, 2001), and fMRI-based measures show only partial overlaps across modalities (Crottaz-Herbette et al., 2005; Downar et al., 2000).

Many studies have used the attentional blink (hereafter abbreviated AB) to test the independence of auditory and visual attentional resources. Several lines of reasoning and evidence are relevant, including the similarity of paradigm design and observed effects within each modality, the degree of interference across modalities, and the relationships of individual differences in effect magnitude. We now consider each of these ideas in turn.

Although the theoretical accounts of the AB are varied (Dux and Marois, 2009), most researchers agree that the deficits result from competition for goal-directed attentional resources. Such explanations are common to visual and auditory ABs, and the paradigms are also procedurally similar in stimulus presentation rates and masking (Arnell & Jolicoeur, 1999; Potter et al., 1998; Tremblay et al., 2005). Accordingly, the deficits follow comparable timecourses, although auditory ABs typically have smaller magnitudes.

When participants perform auditory and visual AB tasks concurrently, interference across the modalities is taken as evidence for a common supramodal attentional resource. Indeed, cross-modal ABs are often reported under these conditions, although such deficits are smaller than their unimodal counterparts (Arnell & Jenkins, 2004; Arnell & Jolicoeur, 1999; Jolicoeur, 1999). Other researchers, however, have found that cross-modal ABs occur only in the presence of a task-switch (e.g. from target discrimination to probe detection) or a spatial shift of attention (Martens et al., 2010; Potter et al., 1998; Soto-Faraco & Spence, 2002). Overall, the evidence from cross-modal interference experiments is consistent with modality-specific attentional resources underlying each AB type, although shared resources may exist as well.

Another approach to assessing the shared or distinct cognitive components across tasks is to leverage individual differences in performance. Researchers reason that the extent to which two measures reflect the same underlying process is reflected in the correlation of these measures across participants (Dale & Arnell, 2013; Lui & Wong, 2019; Skogsberg et

al., 2015). For example, auditory and visual AB magnitudes have been found to be weakly correlated, if at all (Martens et al., 2010, 2015; Willems & Martens, 2016; Wu et al., 2020). Similarly, individuals who have no measurable visual AB still show an auditory one (Martens et al., 2009). Such results are consistent with the findings from cross-modal interference studies, again suggesting largely dissociable attentional resources by modality.

The logic of individual differences has also been used with the AB to better understand the phenomenon itself and attentional function more generally. Correlative approaches have confirmed putative component processes of the AB, including distractor suppression (Dux & Marois, 2008; Martens & Valchev, 2009), working memory filtering (Arnell & Stubitz, 2010), and item selection (Arnell et al., 2006; Willems et al., 2013). Comparisons across different types of visual AB paradigms have found common attentional processes overall, though paradigms with a task-switch involve different cognitive components as well (Dale et al., 2013; Kelly & Dux, 2011). Specifically, paradigms that involve only target discrimination group together in factor analyses, with partially separate groupings for paradigms in which target discrimination is followed by probe detection.

Although the AB has aided our understanding of modality-specific attentional resources, it and related paradigms have been employed far less to study the relationship between goal-directed and stimulus-driven attentional control. Indeed, the extent to which these components are contingent on the same attentional resources remains unresolved. Several lines of reasoning and evidence, many analogous to the comparisons across modalities discussed above, are relevant to attentional taxonomy. Foremost, AB and surprise paradigms (surprise-induced blindness and surprise-induced deafness) share features of design and outcome within each modality: An attention-demanding stimulus causes a transient impairment in probe detection or target discrimination. The timecourse of this deficit is also comparable across paradigms. Particularly in visual paradigms, performance is

relatively intact when the probe immediately follows the inducing stimulus, an effect termed Lag-1 sparing (Asplund, Todd, Snyder, Gilbert, et al., 2010; Chun & Potter, 1995; Dux & Marois, 2009; Raymond et al., 1992). Conversely, backward masking of the deficit-inducing stimulus appears to have more importance to the attentional blink than to surprise-induced blindness, though the evidence for this difference is weak at best (Asplund, Todd, Snyder, Gilbert, et al., 2010). A far more striking difference between the goal-directed and stimulus-driven paradigms is the rate of effect attenuation. Whereas the AB can last for hundreds or thousands of trials (Chun & Potter, 1995; Dux & Marois, 2009; Raymond et al., 1992), the longevity of surprise effects is approximately two orders of magnitude less. These latter effects habituate, often completely, after only a handful to tens of trials (Asplund, Todd, Snyder, Gilbert, et al., 2010; Obana et al., 2020).

Measuring interference between forms of attentional control, however, is not analogous to running a cross-modal AB investigation. Whereas cross-modal AB effects can be compared to within-modality AB effects, such separation is not possible with attentional control. Indeed, stimulus-driven attention is typically assessed by examining its effects, whether facilitatory or deleterious, on goal-directed processes (Asplund et al., 2020; Horstmann, 2005, 2015). A potential solution is to vary the degree or type of interactions. For example, in a contingent capture paradigm, an otherwise irrelevant distractor captures attention only when it contains a target-defining feature (Folk et al., 1992, 2002, 2008; Maki & Mebane, 2006; Visser et al., 2004). On its face, the contingent capture paradigm shares features with both surprise-induced blindness and the AB, with similar perceptual effects and timecourses within each trial. Some researchers have even argued that contingent capture effects represent a form of AB because the goal-directed attentional component is critical to the effect (Folk et al., 2002, 2008; Maki & Mebane, 2006). The potential relationship

between contingent capture and surprise-induced blindness is less clear, as neither habituation rates nor individual differences in effect magnitudes have been compared.

In the present study, we sought to understand the shared and distinct cognitive components across temporal attention paradigms. We adopted an individual differences approach and also examined the features of each paradigm, particularly the rate of effect habituation. In a first experiment, we compared attentional blink and surprise paradigms, in both the visual and auditory modalities. In a second experiment, we focused on the visual paradigms, and added a contingent capture paradigm, to better understand the deficit relationships found in the first experiment.

Experiment 1: Relationships Across Attentional Forms and Modalities

Our primary aim was to assess the relationship of attentional forms within each modality. Participants were thus tested twice on tasks involving the attentional blink, surprise-induced blindness, and their auditory analogues. The magnitude of the correlations relative to effect reliability would indicate the degree of shared resources across goal-directed and stimulus-driven attention. We expected small but significant correlations given the partial dissociation between attentional forms (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002). We also expected little to no correlation in deficits across modalities (Martens et al., 2010, 2015; Willems et al., 2013), although this prediction was less clear for stimulus-driven effects (Horstmann, 2015).

Materials and Methods

Participants

Eighty-three participants with self-reported normal or corrected-to-normal vision and normal hearing were recruited from the National University of Singapore (NUS) community. These individuals began a six-session study that included numerous behavioral and neuroimaging components. The present experiment was a planned subcomponent of this

overall study, and only the relevant tasks are reported and analyzed here (see Supplemental Table 1 for the complete protocol). Sixteen participants did not complete all of the sessions relevant to the present experiment, reducing the sample to 67 participants. Furthermore, 11 participants failed to meet criterion performance for at least one of three measures ($>75\%$ visual target discrimination, $>60\%$ auditory target discrimination, $d' > 0.5$ for probe detection) during at least one session; data for these individuals was also removed from the sample (Dale et al., 2013; Obana et al., 2020). Thus, the final sample contained 56 participants (38 females, 18 males) between the ages of 19-30 ($M=22.4$ years, $SD=2.0$). The recruited sample size was determined from relevant neuroimaging studies (Wu et al., 2020) as well as previous individual differences studies (Dale et al., 2013; Kelly & Dux, 2011; MacLean & Arnell, 2012; Obana et al., 2020). We also achieved, even after drop-outs and data removals, a subject-to-variable ratio of at least 10:1 to support exploratory factor analyses (Howard, 2016; Lui & Wong, 2019). For this experiment and the subsequent one, participants provided written informed consent and were paid for their participation in accordance with a protocol approved by the NUS Institutional Review Board.

Laboratory Protocol

For the larger study from which the present experiment's data were drawn, each participant completed 6 sessions over a span of 3 weeks. The study included multiple tasks designed to test selective and sustained attention in the visual and auditory domains. Two such tasks were of interest for the present experiment, a visual temporal attention task and an auditory one (Figure 1). Each task was repeated with minor variations across multiple sessions (Table 1). Throughout the study, participants were encouraged to take breaks between the tasks to prevent fatigue.

Table 1. Schedule of visual and auditory task variants during the overall study. The “Day (relative)” column specifies the number of days relative to the previous session. (Two participants completed Sessions 0 and 1 on the same day due to scheduling constraints.)

Session	Day (relative)	Task	Description
0		Visual practice (no surprises)	152 trials total. All participants achieved >75% target accuracy during this practice/screening session.
1	+3 to +14	Visual	Six blocks, with 168 trials total. Task performed in a magnetic resonance (MR) scanner.
2	+1	Auditory	Three blocks, with 168 trials total.
3	+1	Visual	Identical to Session 1, save with different surprise stimuli and the task was performed in the laboratory.
4	+1	Auditory	Identical to session 2, save with different surprise stimuli.
5	+1 to +10	Visual	Identical to Session 1.

Apparatus and Stimuli

For the visual task, targets and distractors were upper-case letters presented in Courier New Font on a dark gray background. Each target was a red D or F, whereas the probe was a white X. Distractor letters excluded D, F, X, I, L, O, and Q. “Surprise stimuli” differed greatly from both targets and distractors and were used to test involuntary attentional capture. Surprise stimuli alternated between grayscale male faces (set of 24 from Asplund, Fougner, Zughni, Martin, & Marois, 2014) and colorful objects (set of 24) by surprise trial. The 24 surprise stimuli used for Session 1 were used again for Session 5; conversely, none of these surprise stimuli appeared in Session 3. Inside the MR scanner, stimuli were presented by a MacBook Air with OS 10.12.1 connected to a 32-inch LCD monitor (NordicNeuroLab, Bergen, Norway) running at 60 Hz. In the laboratory, stimuli were presented by a PC with Windows 7 and an NVIDIA Quadro FX 3450/4000 SD graphics card. The attached 22-inch LCD monitor (Samsung SyncMaster 2233) ran at 60 Hz. All stimuli were scaled so that they subtended 1.0° x 1.0° of visual angle regardless of session location, as participants’ eye

distance from the monitor was 191 cm in the MR scanner and 57 cm in the laboratory. The auditory and visual tasks were both presented using PsychoPy (Peirce, 2007). In the MR scanner, participants made responses using an MR-compatible button box. In the laboratory, participants made responses on a standard computer keyboard.

For the auditory task, targets were low-pitched or high-pitched complex tones comprised of five log-related frequencies (794 to 1260 Hz, or 1349 to 2142 Hz), whereas the probe was a 4000 Hz pure tone. Distractors were 19 pure tones of log-related frequencies ranging from 697 to 2911 Hz. Surprise stimuli alternated between task-irrelevant sounds (a set of 24, including an alarm, a cough, a cat meowing, and car honking) sampled from freesound.org (Font et al, 2013) and spoken letters (set of 24, with H and W excluded). None of the 24 surprise stimuli presented in Session 2 were presented in Session 4. A female native English speaker spoke the letters, which were recorded using an Olympus IC recorder and Bose microphone. All surprise sounds were compressed to 110 ms in duration without changing the pitch using Audacity (The Audacity Team). Sound stimuli were then adjusted to have equal mean absolute amplitudes, after which the probe (45%), distractor (30%), and surprise (30%) intensities were further adjusted to be a percentage of the target intensity. These values were based on previous experiments in our lab (Obana et al., 2020) and additional pilot tests. Auditory stimuli were presented binaurally through Creative headphones at a maximum volume of 70 dB.

Task Procedures

The visual and auditory tasks were designed to be generally similar, each built around a typical attentional blink (AB) task with target discrimination amongst two alternatives followed by probe detection (Figure 1). Targets and probes were embedded within a rapid serial presentation, with no items repeated during each stream. The stimulus onset asynchrony (SOA) between successive items in each 16-stimulus stream was 117 ms. A

target appeared during every trial at serial position 3, 4, or 5, whereas the probe appeared during 75% of trials. When present, the probe appeared at lags 1, 2, 3, 5, 7, or 9 relative to the target, with the same number of trials per lag condition in each block, where they were presented in a pseudorandom order. The shortest three lags were expected to be within the AB window, whereas the longest three were expected to be outside it. Note that lag 1 was expected to be within the AB window, as lag-1 sparing effects are typically modest when the paradigm includes a task switch (e.g. target discrimination followed by probe detection) (Dux & Marois, 2009). Nevertheless, different mechanisms may be involved at lag 1, a concern we addressed in Experiment 2 in this study and in other work in the auditory domain (Obana et al., 2020).

Figure 1. Trial design for Experiment 1. Participants identified a target and then detected a probe within a stream of distractors. Participants reported the target and whether the probe

was present when prompted at the end of each trial. In a subset of trials, a surprise stimulus would appear 3 or 7 items before the probe, corresponding to 6 or 2 items after the target. (A). For the visual task, the target was a red letter (D or F), the probe was a white letter X, and distractors were other white letters. Surprises alternated by trial between greyscale faces and colorful objects. (B). For the auditory task, targets were complex tones (low or high), the probe was a high-pitched pure tone, and distractors were other pure tones. Surprises consisted of various task-irrelevant sounds.

In addition to these typical AB-related trials, a small percentage of trials (14%) contained an unexpected stimulus. In these “surprise” trials, the task-irrelevant surprise stimulus appeared at lags 2 or 6 relative to the target. More importantly, when the probe was present, such conditions corresponded to surprise-probe lags of 7 and 3. We reasoned that the surprise-probe lag 3 would be within the window for surprise-induced blindness or surprise-induced deafness. The lag 7 trials, by contrast, would likely be outside this window. Across the 24 surprise trials in each session, 12 (50%) were surprise-probe lag 3, 6 (25%) were surprise-probe lag 7, and 6 (25%) contained a surprise stimulus but no probe. These trial types were evenly distributed across blocks. To reduce inter-subject variability not due to inherent attentional differences, the order of surprise stimulus presentation, the order of surprise trial types, and the trial number when they occurred was the same for all participants for a given session. (They were also the same for Sessions 1 and 5, and 2 and 4; see Table 1.) Surprise trials could not occur in the first three trials or the last trial of each block, and such trials were separated by at least two non-surprise trials to prevent carryover effects.

For the visual task, each 6.25-second trial began with the presentation of a white fixation cross ($0.8^\circ \times 0.8^\circ$) for 500 ms, which became larger ($1.0^\circ \times 1.0^\circ$) and turned yellow to signify that the rapid serial visual presentation (RSVP) stream would begin in 750 ms

(Figure 1A). Participants searched the subsequent RSVP stream (1867 ms) for the target and probe. Following a blank gap (233 ms), they were prompted to identify the target and indicate whether the probe was present. A maximum of 2.9 s after the blank gap was given for participants to respond to both response prompts. After this period, no further responses were recorded and the white fixation cross returned until the start of the next trial. Failure to respond was rare: No session had more than 0.16% of trials without a target response or 0.64% of trials without a probe response (percentages are averages across participants), and no participant had more than 3.57% (target) or 4.17% (probe) no response trials in any given session. The timing between each trial was optimized for functional Magnetic Resonance Imaging (fMRI) (Wu et al., 2020). As such, it followed an exponential distribution with a range of 1.25-10 s and mean of 3.75 s. Each session contained six blocks of 28 trials each; the 168 trials took approximately 40 minutes to complete, including breaks.

For the auditory task, each 6.25-second trial began with a reminder of the target and probe sounds, which were played for 110 ms each with a gap of 85 ms. After 750 ms, the rapid auditory stream (RAP) began, which consisted of 110 ms stimuli separated by a gap of 7 ms (Figure 1B). Participants searched for the target and probe through this RAP. The identity of the target and the presence of the probe were indicated by keypress when prompted following a blank gap (233 ms). The maximum time allowed for both responses was 2.9 s. The timing between each trial was fixed at 0.75 s. Except for the blank gap and the response prompts, a white fixation cross ($0.8^\circ \times 0.8^\circ$) was shown on the screen throughout the block. Each session contained three blocks of 56 trials each; the 168 trials took approximately 25 minutes to complete, including breaks.

Before the main experimental blocks in each session, each participant completed 3 practice blocks of 8 trials each. The first block contained targets but no probes; the second block contained probes but no targets; and the third block contained both. Before beginning

each practice and task block of the auditory task, participants could play the target and probe sounds as many times as desired.

Transparency and Openness

For both Experiments 1 and 2, we provide explanations for sample size determination, data exclusions, experimental manipulations, and dependent measures. The study's analysis and design were not preregistered; we instead rely on internal and external replications to determine effect reliability and size. All visualizations and statistical analyses were performed using RStudio version 1.0.136 (R Foundation for Statistical Computing) running R version 3.2.4. Data, materials, and analysis from Experiment 1 are not available by the funder's request. Anonymized data from Experiment 2 have been made publicly available on Figshare and can be accessed at <https://doi.org/10.6084/m9.figshare.19410905>.

Statistical Approach

Analysis of variance (ANOVA) tests were conducted using the ez package (version 4.4-0). Greenhouse-Geisser corrections were applied to the reported p -values whenever Mauchley's sphericity test indicated a significant violation. For effect sizes, we report η_G^2 for ANOVA results and Cohen's d for t-tests, with the latter calculated using the effectsize package (version 0.3.3) (Ben-Shachar et al., 2020). Correlations across effects were characterized using Bayes Factors and exploratory factor analyses. Each of these specialized approaches is motivated and described in detail before the presentation of the relevant results.

Results

Before testing for relationships across the attentional limitations, we first characterized each deficit and its degree of habituation across and within sessions. Next, we calculated reliability scores for each metric, with the stability of each deficit within and across sessions providing a theoretical upper limit to relationships across the deficits. Finally,

we used Pearson correlations to explore these relationships across attentional limitation type and modality.

Target Discrimination Accuracy

For each participant and session, average target discrimination accuracy across lags was calculated separately for probe-present and probe-absent trials (Table 2). The high accuracy indicated that participants had little difficulty in discriminating between the red target letters or complex target tones. Target performance did not vary as a function of target-probe lag in any session or modality (repeated measures ANOVAs, all $F(5, 275)s < 1.82$, $ps > .13$, $\eta_G^2s < .024$), and probe presence did not affect target performance either (paired t-tests, all $|t(55)| < 1.86$, $ps > .067$, $ds < .25$). Auditory target discrimination improved slightly but significantly across sessions ($F(1, 55) = 39.26$, $p < .001$, $\eta_G^2 = .057$; Table 2), whereas visual target discrimination remained close to ceiling and unchanged ($F(2, 110) < 0.01$, $p = .99$, $\eta_G^2 < .001$).

Table 2. Proportion of correct target discrimination responses for the visual and auditory tasks by session (see Table 1 for session descriptions). Accuracy is the mean proportion correct across participants, with the standard deviation in parentheses.

	Test		Retest (lab)		Retest (scanner)	
	Session 1 (visual) Session 2 (auditory)		Session 3 (visual) Session 4 (auditory)		Session 5 (visual)	
Probe	Present	Absent	Present	Absent	Present	Absent
Visual target accuracy	.98 (.02)	.98 (.04)	.98 (.03)	.98 (.03)	.98 (.03)	.98 (.04)
Auditory target accuracy	.90 (.11)	.91 (.10)	.94 (.08)	.95 (.09)		

Probe Detection Performance

Probe detection was considered separately for each type of attentional limitation (attentional blink or surprise effects), with separate averages by modality, session, and lag (Figure 2). For the attentional blink, mean probe detection was calculated for trials that contained a probe but not a surprise stimulus, contingent on correct target identification (probe|target). For statistical purposes, these trials were then aggregated into short (lags 1, 2, and 3) and long (lags 5, 7, and 9) lag conditions. We reasoned that the former would fall within the attentional blink window (including lag 1; see Materials and Methods: Task Procedures), whereas the latter would be largely outside it. This conjecture was borne out by the behavioral results. To test for the presence and consistency of blinks within each modality, separate repeated-measures ANOVAs with lag and session as within-subjects variables (2x3 for visual, 2x2 for auditory) were conducted on probe detection scores. For the visual modality, significant main effects of lag ($F(1, 55) = 84.04, p < .001, \eta_G^2 = .31$) and session ($F(2, 110) = 26.37, p < .001, \eta_G^2 = .038$) were accompanied by a significant interaction ($F(2, 110) = 12.68, p < .001, \eta_G^2 = .010$). The significant interaction and main effect of session were likely due to the change in testing environment. Blink magnitudes (long lag – short lag) were similar for Sessions 1 ($M \pm SD: .33 \pm .25$) and 5 ($.29 \pm .25$), but reduced for Session 3 ($.23 \pm .25$). For the auditory modality, significant main effects of lag ($F(1, 55) = 55.93, p < .001, \eta_G^2 = .11$) and session ($F(1, 55) = 35.91, p < .001, \eta_G^2 = .054$) were accompanied by a significant interaction ($F(1, 55) = 15.22, p < .001, \eta_G^2 = .013$). These effects were caused by substantial blink habituation from Session 2 ($.14 \pm .14$) to Session 4 ($.07 \pm .12$), akin to the improvement in auditory target discrimination across sessions. Nevertheless, follow-up paired t-tests showed the presence of a blink for every session regardless of modality (all $t(55)s > 4.64, ps < .001, ds > .63$).

The habituation of the auditory attentional blink was not expected, and it was remarkable in comparison to the relative consistency of its visual counterpart. Auditory ABs

were considerably smaller than visual ABs, but their decrease across sessions ($.07 \pm .13$) was numerically larger than the visual AB's decrease ($.04 \pm .16$). More strikingly, the auditory AB decreased by just over 50% across sessions, whereas the visual AB decreased by just 12%.

Figure 2. Results for Experiment 1 by modality, type of attentional limitation, and session. Mean probe detection accuracy in the visual (A and B) and auditory (C and D) modalities is plotted as a function of the lag between the critical stimulus (target or surprise) and the probe. For the attentional blink (A and C), probe detection was calculated contingent on correct target report. Error bars represent the standard error of mean (SEM) at each lag. Solid lines

represent test session performance, whereas dashed lines represent retest session performance. SiB = surprise-induced blindness. SiD = surprise-induced deafness.

For surprise effects, the probe detection rate was calculated for trials that contained a probe at Lag 9 relative to the target (surprise-probe Lag 3, surprise-probe Lag 7, and probe only; Figure 2) and for the corresponding probe-absent trials. As there were both relatively few probe-absent trials and low false alarm rates, we used hit rates to calculate surprise effects (Supplementary Table 2). For each modality, we tested for surprise effects and their changes across sessions using two-way repeated measures ANOVAs, with within-subject variables of surprise (surprise-probe Lag 3 or probe only) and session. For the visual task, there were significant effects of surprise ($F(1, 55) = 14.87, p < .001, \eta_G^2 = .028$), session ($F(2, 110) = 45.24, p < .001, \eta_G^2 = .19$), and their interaction ($F(2, 110) = 24.68, p < .001, \eta_G^2 = .077$). Significant surprise effects were observed during Session 1, but during neither Session 3 nor Session 5 (Table 3). Notably, there were no significant surprise effects during Session 3 despite the presentation of a new set of surprise stimuli. For the auditory task, there were also significant effects of surprise ($F(1, 55) = 35.20, p < .001, \eta_G^2 = .15$), session ($F(1, 55) = 25.92, p < .001, \eta_G^2 = .037$), and their interaction ($F(1, 55) = 27.14, p < .001, \eta_G^2 = .031$). Although auditory surprise effects attenuated across the test and retest sessions, they were nevertheless significant during each session (Table 3).

Table 3. Descriptive and inferential statistics for surprise deficit magnitude in each session and modality. Surprise deficits were assessed with paired t-tests, with surprise-absent Lag 9 trial performance compared to either all surprise-probe Lag 3 trials or the first four of these trials (where the deficits were larger). Results in **bold** were significant at $p < .05$.

		All surprise trials	First 4 surprise trials
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Modality	Session	<i>M</i> (<i>SD</i>)	<i>t</i> (55)	<i>d</i>	<i>M</i> (<i>SD</i>)	<i>t</i> (55)	<i>d</i>
Visual	1	.11 (.15)	5.46	.74	.32 (.30)	7.97	1.07
	3	.01 (.06)	0.72	.10	.02 (.13)	1.42	.19
	5	-0.02 (.08)	-1.63	.22	-0.02 (.11)	-1.19	.16
Auditory	2	.26 (.28)	6.87	.93	.39 (.36)	7.96	1.07
	4	.11 (.23)	3.53	.48	.15 (.27)	4.29	.58

We used varying surprise stimuli to reduce habituation (Asplund, Todd, Snyder, Gilbert, et al., 2010; Obana et al., 2020), but surprise effects still greatly reduced within sessions (Figure 3). As such, we decided to calculate our surprise effects in two ways, 1) based on all Lag 3 surprise trials and 2) based on the first four Lag 3 surprise trials, corresponding to the first block of the auditory task or the first two blocks of the visual task. These two ways were used for characterizing the deficits (Table 3) and for correlation analyses.

Figure 3. Surprise effects and their habituation in the visual (A) and auditory (B) modalities. Note that “surprise number” refers to Lag 3 surprise trials, which were half of all trials with a surprise stimulus. Mean probe detection accuracy is plotted as a function of surprise stimulus presentation number. Black bars represent test session performance, whereas grey or white bars represent retest session performance. The dotted line indicates the probe detection rate for Lag 9 non-surprise trials, averaged across both test and retest sessions. (These averages differed by only .008 for auditory and .025 for visual.) SiB = surprise-induced blindness. SiD = surprise-induced deafness.

Correlation Analyses

We next subjected the four attentional deficits to a series of correlational analyses across participants. First, we assessed the consistency of each effect across time, provided that it did not completely habituate. Second, we examined the relationship amongst the different attentional limitations. For these analyses, the magnitude of each attentional blink and surprise effect was represented as a single value for each participant. To obtain this value, the attentional deficit was calculated from the period of expected maximum effect, and then differences in baseline performance across participants were statistically controlled for using regression (MacLean & Arnell, 2012). For attentional blinks, the mean probe detection accuracy for the long lag condition (average of performance at lags 5, 7, and 9) was regressed out from short lag condition performance (average across lags 1, 2, and 3). For surprise effects, the mean probe detection accuracy for surprise-absent Lag 9 trials was regressed out from the mean accuracy of the surprise-probe Lag 3 trials. Only trials with correct target identification were included in the attentional blink analyses, whereas no such contingency was required for the surprise effects. Given the rapid habituation of the surprise effects, particularly in the visual modality, we calculated and examined surprise effects in two ways, based on either all surprise trials or only the first four (see above).

Internal-Consistency and Test-Retest Reliability

Before testing the degree of association across attentional deficits, we characterized each effect using two measures of reliability based on Pearson correlations. Internal-consistency reliability reflected within-session stability of the effect, whereas test-retest reliability reflected effect stability across sessions. Internal-consistency reliability was assessed using a split-half approach. Each deficit (residuals; see above) was calculated from either odd-numbered or even-numbered trials, and a correlation coefficient was calculated from each resulting paired set of residuals (Dale et al., 2013). Test-retest reliability was assessed by correlating each deficit's residuals across sessions. As only half as many trials

were used for calculating within-session reliability as between-session reliability, we used the Spearman-Brown method to correct for correlation attenuation for the internal-consistency reliability r -values. All 12 surprise-probe Lag 3 trials were included for internal-consistency reliability calculations, whereas test-retest reliability was calculated with all of these trials included and then again with only the first four, when the surprise effects were strongest (see above). Reliability scores were high across sessions and modalities, given that the effects in question were present (Tables 4A and 4B). The measures were lower for effects that showed partial habituation (e.g. auditory AB; Table 4A) or complete habituation (e.g. visual surprise effects; Table 4B).

Table 4A. Internal-consistency and test-retest reliability for attentional blink (AB) magnitude by modality and session. Internal-consistency reliability is reported uncorrected (“split-half”) and corrected using the Spearman-Brown method. All r -values were significant at $p < .05$.

	Test session		Retest session		Test-retest r
	Split-half r	Corrected r	Split-half r	Corrected r	
Visual AB (Sessions 1 & 3)	.84	.91	.81	.89	.62
Visual AB (Sessions 1 & 5)	.84	.91	.72	.84	.70
Auditory AB (Sessions 2 & 4)	.59	.74	.34	.51	.41

Table 4B. Internal-consistency and test-retest reliability for surprise effect magnitude by modality and session. Internal-consistency reliability is reported both uncorrected (“split-half”) and corrected using the Spearman-Brown method. Correlations were calculated from all surprise trials. The SiD (surprise-induced deafness) test-retest r -value was .46 when only the first four surprise trials were used. No SiB (surprise-induced blindness) was evidenced in Sessions 3 and 5 (see Table 3). All r -values were significant at $p < .05$.

	Test session		Retest session		Test-retest r
	Split-half r	Corrected r	Split-half r	Corrected r	
Visual surprise (SiB) (Sessions 1 & 3)	.36	.53	-	-	-
Visual surprise (SiB) (Sessions 1 & 5)	.36	.53	-	-	-
Auditory surprise (SiD) (Sessions 2 & 4)	.81	.89	.74	.85	.54

Relationships Amongst Attentional Deficits

To determine the relationships across the four attentional limitations, we calculated Pearson correlations from deficit residuals. Each r -value reflects the square root of the shared variance for a pair of tasks, from which one can infer the degree of shared cognitive processes (with proper controls and caveats). The correlation coefficient can also be used for hypothesis testing. Given our questions, for each correlation we calculated both a p -value for null hypothesis testing and a Bayes Factor (Baguley & Kaye, 2010). A Bayes Factor (B) represents the degree of support for the alternative hypothesis (H1) relative to the null hypothesis (H0). For example, $B = 10$ indicates that the data support H1 ten times more than they support H0, given certain test assumptions. Two such assumptions are the expected effect size and the distribution of the alternative hypothesis (H1). For the expected effect size, we selected $r = 0.4$, which is typical for correlations across attentional blink paradigm types (Dale et al., 2013; Kelly & Dux, 2011; MacLean & Arnell, 2012). For the distribution, we used a half-normal, signifying that we expected effects smaller than $r = 0.4$, but correlation values up to twice this value were still plausible (Dienes & McLatchie, 2018). All Bayes Factor analyses were performed on Fisher transformed z -values, using calculators implemented in R (Dienes, 2008).

We focused our analyses on the test session for each task, when the deficits themselves were strongest. Within each modality, the attentional blink and surprise effects (first four surprise trials) were significantly correlated across participants (Figure 4; Visual: $r(54) = .35, p = .009, B = 11.96$; Auditory: $r(54) = .42, p = .001, B = 47.74$). These effects held when all surprise trials were used for calculating SiB and SiD magnitudes (Visual: $r(54) = .40, p = .002, B = 32.40$; Auditory: $r(54) = .28, p = .038, B = 4.05$). In contrast, neither the attentional blink ($r(54) = -.07, p = .60, B = 0.22$) nor the surprise deficits ($r(54) = .18, p = .18, B = 1.26$) were significantly correlated across modalities. These null effects were not equivalent, however: The Bayes Factor for the former indicates moderate evidence in favour of the null hypothesis of no relationship across blinks, whereas the evidence for the surprise effects is more equivocal. Indeed, when each effect's residuals were calculated from all surprise trials the Bayes Factor was again just over 1 ($r(54) = .21, p = .12, B = 1.74$).

Figure 4. Correlations of deficit residuals across type of attentional limitation and modality for Experiment 1. The first four surprise-probe Lag 3 trials were used for the plots above, but similar patterns were observed when all trials were used. (A) Correlation between visual attentional blink (AB) and surprise-induced blindness (SiB) residuals. (B) Correlation between auditory AB and surprise-induced deafness (SiD) residuals. (C) Correlation between visual and auditory AB residuals. (D) Correlation between the visual and auditory surprise effect residuals. The line of best fit for each comparison is shown; dashed lines indicate non-significant relationships.

A concern with our results is that significant correlations were obtained from within-session comparisons, whereas cross-modality comparisons were between-sessions and

weaker. Comparing deficit types across sessions, however, was hindered by significant and substantial habituation of the surprise and auditory blink effects. Accordingly, correlations across both deficit type and session provided little conclusive evidence about the relationships, with Bayes Factors ranging from 0.38 to 7.19 (Supplementary Table 3A). Nevertheless, Other evidence suggests that within-session correlations were unlikely to have been due to overall fluctuations in performance. Target detection performance for probe-present trials was not correlated with residual attentional blink magnitude in either the visual ($r(54) = .22, p = .11, B = 1.87$) or auditory ($r(54) = -.19, p = .17, B = 0.14$) modality. Furthermore, neither target discrimination (all $|r|s < .10, ps > .47, Bs < 0.59$) nor probe hit rates at Lag 9 (all $|r|s < .06, ps > .68, Bs < 0.44$) were correlated across modalities (Supplementary Table 3A).

Factor Analysis

To better understand the relationships amongst the attentional paradigms and the limitations contained therein, we conducted an exploratory factor analysis (EFA). This approach allowed us to discover and characterize any common latent factors, which in turn may relate to shared cognitive processes. The analysis was conducted on the blink and surprise deficit residuals. The surprise deficit was again calculated from the first four surprise trials, and only test session residuals were used. We used the `fa()` function in the `psych` package (version 1.5.8; Revelle, 2015) to extract factors, using oblimin rotation and Kaiser normalization (Dale et al., 2013). Parallel analysis (Skogsberg et al., 2015; Humphreys & Montanelli, 1975) suggested a two-factor solution, accounting for 44% of the cumulative variance (Table 5). The auditory blink and surprise deficits loaded onto the first factor, whereas the visual blink and surprise deficits loaded onto the second factor. These results held regardless of whether all surprise trials or only the first four were included in the analysis (Supplementary Table 4A). Consistent with the weak correlations of deficits across

modalities (Figure 4), the two factors were virtually uncorrelated ($r = .06$). As such, an alternative factorization with varimax rotation (forcing uncorrelated factors) produced highly similar results (Supplementary Table 4B).

For comparison purposes, we also conducted a two-factor principal components analysis (PCA) using varimax rotation and Kaiser normalization (Supplementary Table 5). The factors and their loadings were similar to the exploratory factor analysis results, with a first component (35% explained variance) related to the auditory deficits and a second component (35% explained variance) related to the visual ones. In contrast, all five AB paradigms in Dale et al. (2013) loaded onto their first component, which accounted for 52% of the variance.

Table 5. Exploratory factor analysis results. The factor loadings and proportion of explained variance are shown for a two-factor solution with oblimin rotation. Factor loadings above the cutoff of 0.4 are indicated in bold (Howard, 2016). (AB = Attentional Blink; SiB = surprise-induced blindness; SiD = surprise-induced deafness.

	Factor 1	Factor 2
Loadings		
- Visual AB	.00	.46
- Auditory AB	.67	-.19
- Visual surprise (SiB)	.00	.74
- Auditory surprise (SiD)	.67	.20
Proportion of variance	.23	.21

Interim Discussion

In this experiment, we explored the relationships amongst attentional blink and surprise paradigms, for both their visual and auditory forms. We found substantial perceptual deficits with each paradigm. Furthermore, the deficits shared a similar temporal structure, with a strong effect at short lags and a significantly weaker or absent effect with longer lags.

In contrast, the deficits differed markedly in their magnitude across trials and sessions. Whereas visual surprise effects lasted for only a few trials, visual blinks were virtually unchanged across sessions. The auditory effects had intermediate habituation profiles, and each persisted through the entire experiment.

Each deficit also varied in magnitude across participants, thereby allowing us to test whether the individual differences in performance were related across paradigms. Within each modality, blink and surprise deficits were moderately, yet significantly, correlated. No such significant relationships were found across modalities, though the null result was convincing only for the blink effects. In this Interim Discussion, we explore our findings' implications on how attentional control and the paradigms themselves are related across modalities. As Experiment 2 further examines the relationship across attentional forms, the relevant comparisons for Experiment 1 are considered in the General Discussion.

Relationship of Effects Across Modalities

Our finding no relationship between blink magnitudes across modalities is consistent with other studies that have used an individual differences approach (Martens et al., 2009, 2010, 2015; Willems & Martens, 2016). Unlike in these previous experiments, however, we used a tone-based auditory task and a more typical letter-based visual task. Such tasks may seem dissimilar on their face, but spoken letters have complex temporal profiles and masking properties. Each tone is consistent across time, similar to the sequentially static letters of visual attentional blink tasks. As such, tones have frequently been used in auditory AB studies (Arnell & Jolicoeur, 1999; Mondor, 1998; Tremblay et al., 2005).

Cross-modal attentional blinks have been reported when participants perform visual and auditory task components in sequence or concurrently (Arnell & Jenkins, 2004; Arnell & Jolicoeur, 1999; Jolicoeur, 1999). Although the presence of cross-modal blinks may indicate that each unimodal blink draws on a common supramodal attentional resource, other

researchers have argued that cross-modal blinks are due to a spatial shift of attention, a task-switch, or other coordination required for processing two concurrent streams (Martens et al., 2010; Potter et al., 1998; Soto-Faraco & Spence, 2002). Our results are relevant to this debate in three respects. First, when a combination of tone and visual letter tasks was used to test for cross-modal attentional blinks, these blinks were considerably smaller than those found with spoken letters in similar experiments (Arnell & Jolicoeur, 1999). Removing the common linguistic component may have further dissociated the cognitive resources on which each task drew. Second, the individual differences approach circumvents task-switches across modalities. The correlative approach, however, is vulnerable to finding associations due to situational differences in arousal or mood, which we addressed by having participants complete each task modality on a different day. Third, because we used target-probe paradigms, each modality contained a task switch. With these features taken together, our results are most consistent with modality-specific attentional resources underlying each blink type, including any component of the observed deficits that were due to a task switch.

The correlation of blink deficits across modalities was convincingly null, but the surprise deficit correlation was inconclusive. The literature is likewise equivocal. On the one hand, there are common neural correlates for processing rare, unexpected stimuli across modalities (Corbetta & Shulman, 2002; Crottaz-Herbette et al., 2005; Downar et al., 2000). On the other hand, each of these overlaps are partial at best, and other studies have found more complete dissociations for novelty-related processing across modalities (Berti & Schröger, 2001).

Habituation of Deficits

The correlation results were sometimes rendered challenging to interpret due to effect habituation. Such habituation, however, also provided useful insights into the deficits and their relationships. For example, the visual attentional blink decreased by only 12% across

sessions, consistent with previous reports of its persisting over hundreds of trials (Chun & Potter, 1995). By contrast, the auditory attentional blink decreased by over 50%. To the best of our knowledge, this dramatic habituation has not been reported for any auditory attentional blink paradigm (Arnell & Jolicoeur, 1999; Mondor, 1998; Potter et al., 1998; Soto-Faraco & Spence, 2002; Tremblay et al., 2005; Vachon et al., 2010). Habituation may have occurred but gone unnoticed in each of these studies, or it may become prevalent only across numerous trials or multiple sessions. Regardless, the difference in habituation rates further supports the presence of dissociable mechanisms—including chiefly goal-directed attentional ones—that underlie each modality’s attentional blink.

Considering habituation rates was also informative for surprise deficits. Relative to the blink deficits, the pattern of habituation was reversed with respect to modality. In the visual task, the probe detection deficit habituated rapidly, whereas habituation was slower and incomplete for the auditory task. These results are consistent with previous reports of surprise-induced blindness (Asplund, Todd, Snyder, Gilbert, et al., 2010; Asplund, Todd, Snyder, & Marois, 2010) and surprise-induced deafness (Obana et al., 2020); vibrotactile distraction effects appear to habituate slowly as well (Asplund et al., 2020). One possibility is that these habituation differences are due to stimulus features. For example, the auditory surprise stimuli may have been experienced as more heterogeneous and therefore remained relatively novel and deviant. Against this account, Obana et al. (2020) found that using the same surprise stimulus for each surprise trial still led to relatively slow habituation. A second possibility is that the differences in habituation rates are due to an overall difference in task difficulty. Although probe detection performance was lower in the auditory task overall, however, it was virtually equivalent across modalities during the first few surprise trials. Indeed, surprise-induced blindness generally has larger initial effects compared to surprise-induced deafness (Asplund, Todd, Snyder, Gilbert, et al., 2010; Asplund, Todd, Snyder, &

Marois, 2010; Obana et al., 2020). Based on the habituation rate differences, we conclude that rare, unexpected events are processed across the modalities via at least partially dissociable mechanisms.

Electrophysiological evidence supports such a partial dissociation as well. On the one hand, task-irrelevant and rare auditory or visual stimuli evoke a similar positive event-related potential (ERP) roughly 250-400 ms after their presentation (Berti & Schröger, 2001; Courchesne et al., 1975; Friedman & Simpson, 1994). This timing matches the behavioral timecourse of auditory and visual surprise deficits within a given trial (Asplund, Todd, Snyder, Gilbert, et al., 2010; Obana et al., 2020). The ERP also attenuates following repeated stimulus presentations, leading it to be termed a P3a or novelty P3 component (Friedman et al., 2001). The rate of such reductions is commensurate with what has been observed in BOLD studies of novel visual stimuli (Asplund, Todd, Snyder, & Marois, 2010; Yamaguchi et al., 2004). On the other hand, surprise-induced deafness appears to habituate far more slowly than what has been reported for the novelty P3. Additional mechanisms may be either specific to, or more prominent in, auditory processing. Indeed, two related ERP signatures are associated with auditory deviance detection beyond the novelty P3 (Alho et al., 2015; Escera et al., 1998; Horváth et al., 2008; Näätänen et al., 2007). The N1 and mismatch negativity (MMN) components index transient changes and stimuli that are deviant relative to more frequent standards. The N1/MMN and P3 are only loosely coupled to each other in auditory distraction paradigms, and each may influence subsequent attentional priorities (Horváth et al., 2008). Although analogous ERP components have been found in the visual modality, it is unclear whether they are as central to stimulus-driven attention in these other modalities, or indeed to the surprise deficits reported here (Näätänen et al., 2007).

Experiment 2: Alignment Between Tasks and Attentional Forms

Although each paradigm in Experiment 1 was intended to align with either goal-directed or stimulus-driven attention, a given paradigm did not exclusively draw on a single form. For example, surprise deficits are indicative of stimulus-driven disruption of a goal-directed attentional process. Empirical work has partially dissociated surprise deficits from the attentional blink, a deficit that is due primarily to goal-directed processes (Asplund, Todd, Snyder, & Marois, 2010; Obana et al., 2020). A partial dissociation is consistent with our correlation results in Experiment 1, though the shared variance across paradigms may reflect shared cognitive components.

In Experiment 2, we sought to better understand the relationship between attentional forms by understanding their alignment with our paradigms of interest. We focused our efforts on the visual domain because the visual attentional blink and surprise-induced blindness paradigms appeared to engage distinct attentional forms, as evidenced by the starkly different habituation rates of each effect. A visual focus also allowed us to employ a conceptually intermediate task, a non-spatial version of the contingent capture paradigm (Folk et al., 2002, 2008; Maki & Mebane, 2006). In contingent capture, a distractor captures attention, typically to the detriment of subsequent target discrimination. Crucially, that distractor captures attention only if it contains a feature that matches top-down attentional settings. For example, if one is searching for a red letter, a peripheral red distractor would impair detection of a red letter, whereas a green distractor would not. Although contingent capture has been studied primarily in the context of involuntary spatial shifts of attention, it is also observed in non-spatial paradigms, making it suitable for our purposes (Folk et al., 2008; Ghorashi et al., 2003; Maki & Mebane, 2006).

The contingent capture (CC) paradigm sits between the attentional blink (AB) and surprise-induced blindness (SiB) in terms of design and theoretical conceptualization. We therefore used the paradigm to better understand the shared components across our three

temporal attention paradigms. If CC shares cognitive components with the AB, it should correlate more strongly with the AB task. Conversely, if the processes most relevant to the deficit are akin to surprise capture (Horstmann, 2005), it would more closely align with SiB. A third possibility, which we found most likely, is that CC is truly intermediate. As such, it would share attentional components with the AB and SiB, with its effects correlating more strongly with each of the two deficits than they would correlate with each other. In addition, although CC effects are evidently not transient across trials, they may nonetheless habituate. The degree of habituation would offer another clue as to the relationship of the paradigms and the attentional forms underlying their effects.

Experiment 2 allowed us to generalize the findings from Experiment 1 while addressing a number of its limitations. The key modifications to the tasks were threefold. First, we separated the AB and SiB effects into different tasks, thereby providing greater independence of task demands and estimated effects. Second, we used target discrimination for all tasks instead of a mix of target discrimination and probe detection. As SiB had thus far been tested only with probe detection tasks, this change provided a helpful test of effect generalizability (Asplund, Todd, Snyder, Gilbert, et al., 2010; Asplund, Todd, Snyder, & Marois, 2010). The AB produces similar results with two-target and target-probe versions, though the two paradigm types do involve partially separable components, likely due to the task-switch in the latter (Dale et al., 2013; Kelly & Dux, 2011). We eliminated the task-switch in Experiment 2. Third, we made the target discrimination task more challenging by including additional stimulus options. We therefore expected larger deficits and a broader range of target performance. With greater target variability, we could also test whether overall target discrimination ability was correlated with deficits across participants (Arnell et al., 2006; Dale et al., 2013; Dux & Marois, 2008).

One additional aspect of Experiment 2 is noteworthy: It is an internal replication attempt for a somewhat weak effect (the AB-SiB correlation). Such replications are important for establishing the reliability and effect sizes for relationships of interest. Accordingly, we include a cross-experiment Bayes factor analysis (internal meta-analysis) at the end of the Results section.

Materials and Methods

Participants

Eighty-two participants with self-reported normal or corrected-to-normal vision participated for either course credit or monetary compensation. Thirty of these participants were excluded from the sample either for failing to complete all study components (20), for experimenter error (2), or due to poor task performance (8). Specifically, participants were excluded if either their second target discrimination during Lag 8 trials in the AB task was less than 30% in any session or their target discrimination during non-surprise trials in the SiB task was less than 30% in any session. The final sample thus contained 52 participants (27 males, 25 females) between the ages of 19-27 ($M = 21.7$ years, $SD = 1.93$).

Laboratory Protocol

Each participant completed two one-hour sessions over 6-10 days. Each session included four separate tasks, whose order was counterbalanced across participants and sessions. Participants were encouraged to take breaks between these components, which included an AB task, a SiB task, and a CC task (Figure 5). A fourth RSVP task was meant to examine distractor inhibition and will be part of a separate report.

Apparatus and Stimuli

Targets and distractors were upper-case letters, excluding A, E, I, O, Q, and U. Each stimulus subtended 1.5° and was presented in Courier New Font on a grey background. Targets were presented in red (RGB value: [255,0,0]), whereas distractors were presented in

one of six colors at random, blue ([0,0,255]), yellow ([200,200,0]), magenta ([200,0,200]), cyan ([0,200,200]), light grey ([200,200,200]), or dark grey ([50,50,50]). (See Serences et al., 2005.) All stimuli were presented on an Apple iMac running the Psychophysics ToolBox (Version 3.0.11; Brainard, 1997; Pelli, 1997) for MATLAB 2012a. Participants viewed the screen from a distance of approximately 57 cm.

Figure 5. Trial design for the tasks in Experiment 2. (A) Attentional blink (AB). Participants searched for two red target letters (T1, T2) within an rapid serial visual presentation (RSVP) stream of colored distractor letters. The T1-T2 lag was either 3 or 8 (300 or 800 ms SOA). (B) Contingent capture (CC). Participants searched for one red target letter within an RSVP stream of distractors. During each trial, the white box around the letters changed either green or red for 100 ms; this change occurred either 3 or 8 items (300 or 800 ms SOA) before the target. (C) Surprise-induced blindness (SiB). Participants searched for one red target letter

within an RSVP stream of distractors. In a subset of trials, a grayscale surprise face stimulus would appear 3 items (300 ms SOA) before the target. SOA = stimulus onset asynchrony.

Task Procedures

For all three tasks, participants searched for one or two red letter targets embedded within an rapid serial visual presentation (RSVP) stream of 16 items at fixation (Figure 5). Except for “surprise” stimuli (see below), these items were all letters that appeared for 50 ms with a 50 ms trailing blank gap, yielding a stimulus onset asynchrony (SOA) of 100 ms. Each trial began with a white square outline (2.5° across) in the center of the screen. After 400 ms, it was joined by the RSVP stream of letters, which the square surrounded. At the conclusion of the trial, participants were prompted to report the identities of the target(s). The next trial began automatically after a 600 ms blank screen. Each task began with instructions and eight practice trials.

The AB task consisted of one block with 96 trials. During each trial, two red target letters appeared. The first was presented at positions 5, 6, or 7, whereas the second appeared, with equal probability, at either Lag 3 (300 ms SOA) or 8 (800 ms SOA) relative to the first target. Participants were asked about the two targets’ identities on successive response screens. Reversed responses were scored as correct.

The CC task consisted of two blocks of 96 trials (192 trials total). Each trial included one red letter target that was preceded by a change in the outline square’s color to either red (target color) or green (non-target color) for 100 ms. This distracting change began with RSVP item 5, 6, or 7, whereas the target appeared at either Lag 3 (300 ms SOA) or Lag 8 (800 ms SOA) relative to the color distractor. Target lags and distractor colors were crossed, yielding four equiprobable conditions.

The SiB task consisted of two blocks of 96 trials each. Every trial included one red letter target, which could appear in any serial position from 7 to 14. Within each block, 6 trials (6.25%) also contained a “surprise” stimulus, an unexpected and task-irrelevant grayscale morphed face (Asplund et al., 2014). Surprise stimuli were presented for 100 ms with a 300 ms SOA relative to the target, thereby putting the target at Lag 3. Surprise trials were separated by at least one standard trial, and they could not be the first or last trial in a block. Surprise stimuli appeared in only the first 60 trials and final 60 trials, a manipulation that appeared to have a negligible effect on performance.

Results

We first examined each attentional limitation task by session, characterizing any observed habituation effects. We next calculated internal-consistency and test-retest reliability based on the deficit residuals. Finally, we tested the relationships amongst the attentional limitations using pairwise and partial correlations on the deficit residuals, with both *p*-values and Bayes Factors (*B*) reported for interpreting the coefficients.

Task Performance

For the attentional blink (AB) task, first target (T1) discrimination performance was high within each lag and session condition, with strong test-retest reliability across sessions (Table 6). A 2x2 ANOVA with variables of lag (3 or 8) and session (test or retest) revealed a numerically small (.02) yet significant main effect of lag ($F(1, 51) = 6.26, p = .016, \eta_G^2 = .005$). Second target (T2) accuracy rates were calculated as a function of lag, contingent on T1 accuracy (T2|T1). A large AB was evidenced in each session (Figure 6A): Performance was significantly better at Lag 8 compared to Lag 3 (2x2 ANOVA, main effect of lag: $F(1, 51) = 403.78, p < .001, \eta_G^2 = .61$). In addition, the AB habituated slightly across sessions (Lag x Session interaction: $F(1, 51) = 9.43, p = .003, \eta_G^2 = .007$; main effect of session: $F(1, 51) = 13.65, p < .001, \eta_G^2 = .012$). Nevertheless, the AB (here defined as Lag 8 – Lag 3) was

significant in both the test ($M \pm SD$: $.49 \pm .18$; $t(51) = 19.36$, $p < .001$, $d = 2.71$) and retest ($.43 \pm .18$; $t(51) = 17.46$, $p < .001$, $d = 2.44$) sessions.

Table 6. First target (T1) discrimination accuracy by lag and session in the attentional blink (AB) task. Means are across participants, with standard deviations in parentheses. Note that T1 performance was similar to second target (T2) performance at Lag 8 in the AB task, target performance in non-surprise trials in the surprise-induced blindness (SiB) task, and target performance at Lag 8 in the contingent capture (CC) task (Figure 6).

	Test session	Retest session	Test-retest r
Lag 3	.83 (.13)	.82 (.16)	.71
Lag 8	.81 (.15)	.80 (.14)	.73

Figure 6. Results for Experiment 2 by task and session. Error bars represent the standard error of mean (SEM) for each condition combination. (A) Attentional blink (AB). Mean T2 discrimination accuracy contingent on correct T1 discrimination ($T2|T1$) as a function of T1-T2 lag. (B) Contingent capture (CC). Mean target detection accuracy as a function of colored distractor-target lag and distractor color. (C) Surprise-induced blindness (SiB). Mean target detection accuracy as a function of surprise (Lag 3 versus No surprise).

The contingent capture (CC) task data were subjected to a 2x2x2 repeated-measures ANOVA, with within-subject variables of distractor color (red or green), lag (3 or 8), and session (test or retest). There were significant main effects of color ($F(1, 51) = 38.62, p < .001, \eta_G^2 = .029$) and lag ($F(1, 51) = 51.42, p < .001, \eta_G^2 = .042$), but not session ($F(1, 51) = .63, p = .43, \eta_G^2 = .002$). All interactions were significant, including the two-way interactions of Color x Lag ($F(1, 51) = 34.16, p < .001, \eta_G^2 = .021$), Color x Session ($F(1, 51) = 12.10, p = .001, \eta_G^2 = .005$), and Lag x Session ($F(1, 51) = 4.07, p = .049, \eta_G^2 = .002$), as well as the three-way interaction of Color x Lag x Session ($F(1, 51) = 5.83, p = .019, \eta_G^2 = .002$). These interactions with session indicate a reduced contingent capture effect (Figure 6B), though each main effect and two-way interaction was also present within each session. Separate 2x2 ANOVAs for each session revealed significant main effects of color (test session: $F(1, 51) = 37.20, p < .001, \eta_G^2 = .061$; retest session: $F(1, 51) = 14.45, p < .001, \eta_G^2 = .010$) and lag (test session: $F(1, 51) = 48.96, p < .001, \eta_G^2 = .065$; retest session: $F(1, 51) = 24.09, p < .001, \eta_G^2 = .026$), as well as significant Color x Lag interactions (test session: $F(1, 51) = 34.52, p < .001, \eta_G^2 = .039$; retest session: $F(1, 51) = 11.62, p = .001, \eta_G^2 = .009$). The difference in performance across lags, specifically when the distractors matched the red target, is indicative of the CC effect (Figure 6B). This difference was large (Figure 6B) and statistically significant during both test ($M \pm SD: .14 \pm .14; t(51) = 7.23, p < .001, d = 1.01$) and retest ($.08 \pm .12; t(51) = 5.01, p < .001, d = .70$) sessions. In contrast, performance was only slightly lower at Lag 3 than Lag 8 when the critical distractor was green (Figure 6B), differences that were not significant in either session (test: $t(51) = 1.94, p = .057, d = .27$; retest: $t(51) = 1.99, p = .052, d = .28$). Similarly, performance was lower following Lag 3 red distractors than green ones (test session: $t(51) = 7.27, p < .001, d = 1.0$; retest session: $t(51) =$

4.12, $p < .001$, $d = .58$), an effect that was not present at Lag 8 (test session: $t(51) = 1.25$, $p = .22$, $d = .18$; retest session: $t(51) = 0.14$, $p = .89$, $d = .02$).

In the surprise-induced blindness (SiB) task, target discrimination performance was consistently high for trials without a surprise stimulus during the test ($M \pm SD$: $.83 \pm .10$) and retest ($.83 \pm .12$) sessions (test-retest reliability: $r(50) = .76$, $p < .001$). A 2x2 repeated-measures ANOVA with variables of surprise (all surprise trials versus all non-surprise trials) and session revealed significant main effects of surprise ($F(1, 51) = 118.55$, $p < .001$, $\eta^2 = .32$) and session ($F(1, 51) = 13.74$, $p < .001$, $\eta^2 = .042$), as well as a significant Surprise x Session interaction ($F(1, 51) = 18.45$, $p < .001$, $\eta^2 = .042$). Surprise stimuli significantly impaired target discrimination performance in both the test ($M \pm SD$: $.32 \pm .22$; $t(51) = 10.30$, $p < .001$, $d = 1.44$) and retest ($.17 \pm .18$; $t(51) = 6.67$, $p < .001$, $d = .93$) sessions, but the SiB effect was also significantly larger in the test session ($t(51) = 4.16$, $p < .001$, $d = .58$; Figure 6C).

Figure 7. Surprise-induced blindness (SiB) habituation. Mean target discrimination accuracy as a function of surprise stimulus presentation number. The dashed line corresponds to the average detection rate for non-surprise trials across both test and retest sessions.

As expected, the SiB deficit decreased during the course of each session (Figure 7). Unlike in Experiment 1, however, SiB habituation remained incomplete. Performance during the last four surprise trials of each session was still significantly lower than non-surprise trials during both the test ($M \pm SD$: $.15 \pm .29$; $t(51) = 3.83$, $p < .001$, $d = .54$) and retest ($.13 \pm .25$; $t(51) = 3.79$, $p < .001$, $d = .53$) sessions. Accordingly, we used metrics derived from all surprise trials as the default for subsequent correlation analyses.

Although each deficit's magnitude significantly reduced across the two sessions, the reductions also differed. We first tested for differences in absolute deficit reductions, calculating each effect magnitude through subtraction from baseline, e.g. Lag 8 – Lag 3. (Note that we did not use regression here because we were interested in percentage point changes and were not performing correlation analyses.) The resulting deficit difference scores were subjected to a repeated-measures ANOVA with task (AB, CC, and SiB) and session as the within-subject variables. There were significant main effects of task ($F(2, 102) = 113.07$, $p < .001$, $\eta_G^2 = .41$) and session ($F(1, 51) = 32.49$, $p < .001$, $\eta_G^2 = .060$). More importantly, there was a significant interaction ($F(2, 102) = 4.54$, $p = .019$, $\eta_G^2 = .016$). The SiB effect decreased more across sessions ($M \pm SD$: $.15 \pm .25$) than did either the AB ($.06 \pm .14$; paired t-test: $t(51) = 2.12$, $p = .039$, $d = .30$) or CC ($.05 \pm .14$; $t(51) = 2.62$, $p = .012$, $d = .37$), whereas the declines in effect magnitude were not significantly different across the latter two deficits ($t(51) = 0.36$, $p = .72$, $d = .050$).

The absolute magnitude of the AB and CC deficit habituation was similar, but only the former was small relative to the effect itself. Accordingly, we tested for difference in relative deficit reductions, calculating the change in each participant's performance across sessions divided by the test session performance. The results of this percent change transformation were then assessed with non-parametric statistics because the normality

assumption was saliently violated. Wilcoxon signed-ranks tests showed that SiB decreased significantly more than the AB (SiB median change: -61.0%; AB median change: -11.6%; $Z = 2.12$, $p = .034$, moderate effect size of $r = .29$) and CC decreased more than the AB, albeit not significantly (CC median change: -41.4%; $Z = 1.87$, $p = .061$, moderate effect size of $r = .26$). The difference between the SiB and CC decreases was not significant ($Z = 0.12$, $p = .91$, small effect size of $r = .016$). In summary, the SiB effect habituated the most across sessions and the AB habituated the least, with CC effect habituation in between.

Effect Reliability

We next assessed the reliability of each effect. As in Experiment 1, these correlational analyses were performed on residuals from regressions that controlled for baseline performance differences across participants. AB magnitude was determined by regressing out second target (T2) discrimination performance at T1-T2 Lag 8 from performance at Lag 3. Only trials for which the first target was reported correctly (T2|T1) were included in this analysis. The magnitude of SiB was determined by regressing out the mean target discrimination accuracy for surprise-present trials from surprise-absent trials. The magnitude of the contingent capture effect was obtained by regressing out target discrimination performance at colored distractor-target Lag 8 from performance at Lag 3. Only trials with target-colored (red) distractors were included in this analysis, though similar results were obtained when performance was instead controlled for using green distractors at distractor-target Lag 3. The residuals from these regressions were then used for calculating internal-consistency and test-retest reliability (Table 7). Reliability was generally high across measures and effects.

Table 7. Internal-consistency and test-retest reliability for each task's associated attentional limitation magnitude by session. Internal-consistency reliability is reported both uncorrected

(“split-half”) and corrected using the Spearman-Brown method. All r -values were significant at $p < .05$ except SiB test-retest at $p = .072$. If the first four surprise trials were used instead (as in Experiment 1), the test-retest result was $r(50) = .05, p = .72$. For contingent capture effects, the test-retest result when regressions controlled for green distractors at distractor-target Lag 3 was $r(50) = .50, p < .001$.

Task	Test session		Retest session		Test-retest r
	Split-half r	Corrected r	Split-half r	Corrected r	
Attentional blink (AB)	.70	.82	.65	.79	.70
Contingent capture (CC)	.40	.57	.61	.76	.43
Surprise-induced blindness (SiB)	.57	.72	.46	.63	.26

Relationships Across Attentional Limitations

To assess the relationships across the three attentional limitations, we calculated the Pearson correlation for each pair of tasks from the deficit residuals (Figure 8). We report both the p -value and Bayes Factor (B) for each correlation coefficient. During the test session, the CC effect was significantly correlated with both the AB ($r(50) = .52, p < .001, B = 393.1$) and SiB ($r(50) = .44, p = .001, B = 53.46$) deficits, which were themselves non-significantly correlated with each other ($r(50) = .25, p = .072, B = 2.56$). The three deficits were not significantly correlated with one another during the retest session, though the associated Bayes Factors revealed support for neither a relationship nor the lack of one (B -values near 1, Supplementary Table 3B). The lack of correlation is likely due to effect habituation. Retest session AB magnitude was significantly correlated with both test session CC magnitude ($r(50) = .55, p < .001, B = 766.4$) and SiB magnitude ($r(50) = .31, p = .024, B = 5.85$). Such results demonstrate that the associations across attentional limitations were not driven by session-specific variations in attentional performance. Furthermore, they were not due to overall facility with target discrimination in RSVP streams, as first target (T1) performance

was below ceiling and was not correlated with the AB deficit magnitude in either the test ($r(50) = -.09, p = .52, B = 0.21$) or retest ($r(50) = .09, p = .53, B = 0.55$) sessions.

Figure 8. Correlations of deficit residuals across type of attentional limitation for each session of Experiment 2. Lower panels (with black points) show results for the test session, whereas upper panels (with grey points) results for the retest session. The line of best fit for each comparison is shown, with dashed lines for non-significant relationships. Results were similar when surprise-induced blindness (SiB) magnitude was calculated from only the first

four surprise trials (test session, SiB and AB: $r(50) = .18, p = .20, B = 1.19$; SiB and CC: $r(50) = .48, p < .001, B = 149.0$).

Partial Correlations and Factor Analysis

To better understand the pattern of correlations, we considered whether the shared variance between any two attentional limitations could be explained by variability in the third. That is, to what degree were the associations between two deficits unique? And which attentional limitations are more closely related to each other? To address these questions, we used partial correlations amongst the three sets of deficit residuals in the test session.

Relationships between CC and either the AB or SiB remained significant when controlling for the third task (CC and SiB, controlling for AB: $r(50) = .37, p = .007, B = 14.87$; CC and AB, controlling for SiB: $r(50) = .47, p < .001, B = 119.7$). In contrast, the relationship between the AB and SiB was no longer significant when controlling for CC ($r(50) = .03, p = .84, B = 0.38$). These same results held when only the first four surprise trials were used for calculating SiB magnitude (AB and SiB, controlling for CC: $r(50) = -.10, p = .51, B = 0.21$; CC and SiB, controlling for AB: $r(50) = .46, p < .001, B = 94.09$; CC and AB, controlling for SiB: $r(50) = .50, p < .001, B = 252.1$).

An Exploratory Factor Analysis (EFA) of test session performance confirmed and conceptually extended these findings. Parallel analysis suggested a one-factor solution (oblimin rotation) that accounted for 47% of the variance. CC had the highest factor loading (.95), whereas AB (.55) and SiB (.46) loadings were lower. These results indicate that the tasks share variance and may share an underlying process (or processes) that is most strongly associated with CC. Similar results were obtained from a Principal Components Analysis (PCA), with the first component explaining 61% of the variance (Supplementary Table 6).

Replication and Bayes Factor Analysis

Our study included an internal replication of the correlation between AB and SiB effects. In addition, we tested for the correlation between auditory attentional blink (AAB) and surprise-induced deafness (SiD) effects in both the present study and a separate study conducted in our laboratory (Obana et al., 2020). These replications allow us to assess the overall likelihood of real relationships between our measures of interest. Testing for effect consistency is important in our specific case because the observed relationships were often small or modest for each task pair. More generally, there has been an increasing emphasis on conducting replications and drawing inferences across multiple experiments, practices that provide higher confidence in the results and better estimates of effect magnitudes.

To assess the replicability of our correlations across attentional forms, we calculated Bayes Factors for each individual experiment as described in Experiment 1. We then calculated cumulative Bayes Factors for pairs of experiments using the `MetaB()` function implemented in R (Dienes, 2008). Briefly, each cumulative B -value represents the degree of support for H1 when the B -value from one study is used as a prior (expected effect) for another. When considering the experiments and sessions with statistically significant deficits, the cumulative Bayes Factors indicated strong evidence in favor of a moderate but consistent correlation between the blink and surprise effects within each modality, accounting for about 10% of the total variance (Table 8).

Table 8. Replicated surprise-blink relationships across Experiment 7 from Obana et al. (2020) and Experiments 1 and 2 from the present study. Bayes Factors ($B_{H(0,0.424)}$) were calculated using a half-normal distribution for the model of the alternative hypothesis (H1) (Dienes & McLatchie, 2018). Each Bayes Factor (B) represents the degree of support for H1 over the null hypothesis (H0). For example, $B=10$ indicates that H1 is 10 times more likely than H0 given the evidence. Cumulative B represents the meta-analytic Bayes Factor across different

data sets from which the same relationship is examined. Posterior means, standard deviations, and 95% credible intervals for these meta-analyses are effect size estimates and their uncertainty as r -values. For a complete table of Bayes Factors, including cumulative B values within Experiment 2, see Supplementary Tables 3A and 3B.

Relationship	Data	N	r -value	p -value	Individual Experiment $B_{H(0,r=0.40)}$	Cumulative $B_{H(0,r=0.40)}$	Posterior Mean (SD)	Meta 95% Credible Interval
Auditory AB-SiD	Obana et al., Expt. 7	84	.270	.012	8.8			
	Expt. 1, Test	56	.416	.001	48	329	0.33 (0.086)	0.17, 0.47
	Expt. 1, Retest	56	.244	.069	2.6	871	0.30 (0.073)	0.17, 0.43
Visual AB-SiB	Expt. 1, Test	56	.345	.009	12			
	Expt. 2, Test	52	.251	.072	2.6	34	0.30 (0.10)	0.12, 0.47
	Expt. 2, Retest	52	.104	.462	0.62	21	0.24 (0.081)	0.084, 0.38

General Discussion

In two experiments, we employed an individual differences approach to characterize the relationships amongst attentional forms (goal-directed and stimulus-driven control) and modalities. In addition, we considered the behavioral features of each effect, particularly its habituation across trials and sessions. We then used these relationships and effect features to draw inferences about shared and dissociable cognitive components across paradigms (Arnell et al., 2006; Dale et al., 2013; Kelly & Dux, 2011; Martens et al., 2010; Willems & Martens, 2016). In Experiment 1, we found that attentional blinks (ABs) were correlated with surprise deficits within each modality. By contrast, auditory and visual blinks were not correlated with each other, while the relationship of surprise effects across modalities was inconclusive. Although the deficits all shared similar timecourses, with maximal effects in the 200-500 ms range typically reported for the AB, the effects differed markedly in their longevity across

trials and sessions. Visual surprise effects (surprise-induced blindness) evaporated after only a handful of critical trials, whereas their auditory counterparts (surprise-induced deafness) had only partially habituated by the end of the experiment. This pattern was reversed for blinks: Whereas the visual deficits were robust across multiple sessions, the auditory ones reduced by half. Considering all of the results together, we inferred that paradigms involving different attentional forms have some shared components—perhaps even partially overlapping mechanisms for goal-directed and stimulus-driven attention—within both the visual and auditory modalities, perhaps with a closer relationship in the latter. In contrast, attentional control in our contexts appears to be largely distinct across modalities.

In Experiment 2, we used variations of the two visual paradigms and a non-spatial contingent capture (CC) paradigm to better understand the relationship amongst paradigms and attentional components. The AB and surprise-induced blindness (SiB) results accorded with the earlier findings, both within each paradigm and for the correlation between them. CC effects were found to have a similar timecourse as both the AB and SiB, and the individual differences for each deficit pair were significantly correlated. Furthermore, partial correlation analyses revealed that the CC effect could explain the shared variance between the other two deficits. An exploratory factor analysis confirmed this relationship amongst the three paradigms. Finally, CC effects were found to habituate across sessions at a rate intermediate to the other two deficits. Based on this evidence, we conclude that CC shares cognitive components with both the AB and SiB, including goal-directed and stimulus-driven attentional processes. These cognitive components are likely not the only ones of relevance across the three paradigms, however, an idea we explore more thoroughly in the sections below.

Procedural adjustments for Experiment 2 allowed us to generalize, replicate, and extend the findings from Experiment 1. Foremost, we switched from probe detection to target

discrimination tasks. AB paradigms using these different task types have been shown to draw on partially dissociable components (Dale et al., 2013; Kelly & Dux, 2011), whereas the SiB had yet to be tested with a discrimination task. We found that the SiB effect was comparable for discrimination and detection task types, though the former appeared to have an elongated habituation profile that is worthy of future investigation (Asplund, Todd, Snyder, Gilbert, & Marois, 2010; Asplund, Todd, Snyder, & Marois, 2010). The relationships between the AB and SiB were also found to generalize across task type. The relationships between the auditory AB and surprise deficits were consistent across the present study and other work in our laboratory (Obana et al., 2020). As such, the reader can have increased confidence in the conclusion that there are moderate, yet reliable, relationships across the AB and surprise effects within both the visual and auditory modalities.

Effect Habituation

The magnitude of each deficit, save the visual attentional blink, decreased by at least 40% from the test to retest sessions in both Experiments 1 and 2. Different habituation rates and degrees provided insights amongst the deficits, as discussed in ensuing sections. Habituation, however, also presented difficulties for using correlational approaches. With reduced effects across sessions, one would expect measurement noise to become more prominent relative to the stable individual differences of interest. Furthermore, the degree of effect habituation is not necessarily related to the magnitude of the initial effects. We addressed these challenges in several ways. Foremost, we focused our analyses on periods when each deficit was strongest. Surprise deficit magnitudes were calculated from the first four surprise trials. Test session data were examined separately instead of being averaged with the retest session data (Dale et al., 2013; Kelly & Dux, 2011), and internal-consistency reliability measures provided estimates of correlation ceilings within each session. Finally, all

correlations were assessed using Bayes Factors; tests involving retest sessions were generally found to offer inconclusive evidence about the relationships in question.

The Attentional Blink and Surprise Effects

As predicted, blink and surprise deficits were moderately correlated within each modality. From these correlations, we infer that there are shared cognitive components responsible for each pair of deficits. This conclusion is consistent with the existence of partial overlaps between goal-directed and stimulus-driven forms of attention in both the visual (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Folk, Remington, & Johnston, 1992; Serences et al., 2005) and auditory domains (Alho et al., 2015; Corbetta & Shulman, 2002; Hughes et al., 2013; Salmi et al., 2009; Vachon et al., 2017). Neural evidence suggests that these forms of attention draw on shared resources within the inferior frontal junction (IFJ), at least in the visual domain (Asplund, Todd, Snyder, & Marois, 2010; Tombu et al., 2011). During normal ongoing behavior, the attentional forms also interact, which could be accomplished either within the IFJ or across more distributed networks supporting goal-directed or stimulus-driven attention (Corbetta & Shulman, 2002; Serences et al., 2005).

Although the interactions across attentional forms appear to have broad similarities for vision and audition, it is not known whether the mechanisms overlap or are even analogous. In the visual domain, cognitive and neural components supporting different attentional forms are grossly distinct (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002), but more substantial neural overlaps have been reported for auditory attention (Salmi et al., 2009). For example, Alho et al. (2015) report neural overlaps in the temporo-parietal junction, superior parietal cortex, and superior and middle frontal cortex. It is possible that this similarity in mechanism underlies the more similar habituation profiles across blink and surprise deficits within the auditory modality.

The relationship between the AB and surprise effects, however, is not equivalent to the relationship between goal-directed and stimulus-driven attentional control. Indeed, the paradigms are not “pure” in their reliance on one form of attention or another. Most saliently, the surprise deficits are indicative of disruption of a goal-directed attentional process, and are therefore best thought of as measuring an interaction of attentional control systems. Although such interaction effects can be distinguished from AB deficits (Asplund, Todd, Snyder, Gilbert, et al., 2010; Obana et al., 2020), some shared variance across paradigms may be due to other shared cognitive components, not an overlap of goal-directed and stimulus-driven attentional control per se.

The Attentional Blink and Contingent Capture

The significant correlation between the AB and CC effects in Experiment 2 is consistent with the latter’s conceptualization as a form of AB (Folk, Leber, & Egeth, 2002, 2008; Lien, Ruthruff, Goodin, & Remington, 2008). Beyond having similar procedures, the two paradigms have notable similarities in typical results and relevant theory. Foremost, they have comparable timecourses; each has a maximum effect approximately 200-500 ms after the inducing stimulus. Relatively spared performance at shorter lags (so-called Lag-1 sparing) has also been evidenced in each paradigm (Dux & Marois, 2009; Folk et al., 2008). Although there are multiple theoretical accounts for each deficit, most posit a limitation in deploying goal-directed attentional resources, resulting in disrupted target detection. In the AB, processing of the first target either leaves too few resources available to process the second target or disrupts its selection (Chun & Potter, 1995; Di Lollo, Kawahara, Ghorashi, & Enns, 2005; Dux, Asplund, & Marois, 2008; Dux & Marois, 2009). In CC, a critical distractor with target-defining features captures limited attentional resources to the same effect (Folk et al., 2008; Ghorashi, Zuvic, Visser, & Lollo, 2003).

Distractors with target-defining features are not unique to CC paradigms, and attentional effects resulting from distractor-target similarity can be found in many visual search paradigms (Egeth & Yantis, 1997). One such paradigm is the AB itself. The degree of stimulus similarity, either between the two targets or between the targets and distractors, affects blink magnitude (Chun & Potter, 1995; Folk et al., 2002; Maki & Mebane, 2006; Visser, Bischof, & Di Lollo, 2004). For example, Visser et al. (2004) showed that AB magnitude was substantially larger when distractors shared common characteristics with the targets. The researchers proposed that such distractors contingently captured attention, thereby hampering target processing. These effects held even when the distractors were spatially separated from the targets, thereby ruling out masking as the sole cause of the impairments. Individual differences approaches have yielded complementary results. Foremost, variation in AB magnitude was related to the ability to resist attentional capture by task-irrelevant distractors presented at a different spatial location (Martens & Valchev, 2009). Within a single RSVP stream, individuals whose second target performance was primed by a preceding distractor item had larger ABs; their susceptibility to distraction from target-defining features led to a more substantial blink (Dux & Marois, 2008).

A frequently-used AB control condition provides another example of procedural and conceptual overlap between CC and the AB. When participants are instructed to ignore the first target, the AB often entirely disappears. The deficit, however, may be partially attenuated if the targets share similar target-defining features. For example, an ignored female face may still affect the discrimination of a male face in a lag-dependent manner (Asplund, Fougine, Zughni, Martin, & Marois, 2014). Such effects have also been observed for letters, for which a first target is often defined based on its singleton color. When such a red-colored singleton was instead a distractor, it induced a blink-like deficit (Maki & Mebane, 2006). Critically, this effect was found only when the distractor matched the target

by being comprised of letters, as the distractor caused no reported disruption when it was made up of digits or a false font.

Taken together, the studies above suggest that the AB and CC deficits may share underlying causes. One possibility is that the AB effect is due to attentional capture, perhaps from distractors in the RSVP streams. An AB can be induced even without distractors presented between the first and second targets (Nieuwenstein et al., 2009), however, so the importance of capture effects may vary across AB paradigms. Regardless, the AB deficit may not be a “pure” effect, but rather an amalgam of capture effects and other temporal attention limitations. This characterization is consistent with other lines of evidence concerning AB deficits and paradigms (Dux & Marois, 2009).

A reasonable conclusion is that the AB and CC deficits draw on mechanisms that partially overlap, which are therefore also partially dissociable. Several additional lines of evidence support this intermediate position. First, each deficit affects the other. In addition to CC effects contributing to the AB, CC effects were found to be attenuated when the inducing stimulus was presented within an AB window (Du et al., 2013). Second, the neural correlates of each deficit partially overlap. Superior parietal and middle frontal (including the Inferior Frontal Junction, IFJ) regions have been associated with both paradigms and their deficits (Marois et al., 2000; Marois & Ivanoff, 2005), whereas more inferior regions—including the temporo-parietal junction, inferior frontal cortex, and anterior insula—appear to be more associated with CC (Serences et al., 2005). Finally, the correlation results in our second experiment indicated that shared components underpinned the AB and CC, while also showing that CC effect variance could be partially accounted for by other cognitive processes not related to observed AB variance.

Contingent Capture and Stimulus-Driven Effects

In Experiment 2, CC and SiB deficits were significantly correlated, a relationship that was largely unchanged when variability related to the AB was removed. Such results are consistent with the CC effect being partially due to stimulus-driven attentional effects. Although the dominant view of CC treats the effect as primarily goal-directed in nature, some researchers have emphasized the contribution of stimulus-driven influences as well (Theeuwes, Olivers, & Belopolsky, 2010). If task-irrelevant stimuli are not automatically or completely filtered out (Folk, Remington, & Johnston, 1992), the individual differences in responses to these stimuli may contribute to the observed CC effect variance.

The CC effect's habituation is a novel finding that supports the relevance of stimulus-driven attention to the deficit. Previous studies may have failed to identify CC habituation because the effect is typically quantified using averaged reaction times within a single experimental session (Belopolsky, Schreij, & Theeuwes, 2010; Folk et al., 2002, 2008; Liao & Yeh, 2011, 2013). Unlike the comparatively robust AB, both SiB and CC effects habituated substantially in Experiment 2, though the former's habituation was larger and more rapid. CC effect habituation may be akin to the slowly habituating deficit observed with a surprise-probe SOA of 100-130 ms (Asplund, Todd, Snyder, Gilbert, et al., 2010). A similar explanation has been given for both this deficit and CC effects: Salient stimuli capture attention in a stimulus-driven fashion, with goal-directed attention potentially becoming involved following stimulus evaluation (Belopolsky et al., 2010; Theeuwes et al., 2000). Accordingly, salient distractors have been reported to capture attention transiently, even when these stimuli do not match the target-defining color (Kawahara & Kihara, 2011).

The late engagement of goal-directed attention may also involve active inhibition of a spatial location or a specific stimulus. Indeed, locations where task-irrelevant cues had been presented were found to be suppressed (Belopolsky et al., 2010; Luck et al., 2020). Although the role of inhibition has not been explicitly examined for CC or SiB, distractor suppression

ability has been found to correlate with AB magnitude (Dux & Marois, 2008). Inhibition has been proposed to be a common mechanism across many forms of attentional capture (Gaspelin & Luck, 2019), and it is possible that individual differences in inhibition's deployment or effectiveness could be a common component across SiB, CC, and the AB.

The propensity for stimuli to capture attention is another possible link between the CC and SiB effects. On the one hand, the effects have seemingly different conditions that induce attentional capture: CC deficits are determined by critical distractor and target similarity in a target-defining feature, whereas surprise deficits are sensitive to violations of expectation (Asplund, Todd, Snyder, Gilbert, et al., 2010; Horstmann, 2005; Parmentier, Elsley, Andrés, & Barceló, 2011; Vachon, Hughes, & Jones, 2012). These latter violations often involve a highly dissimilar critical distractor (the “surprise” stimulus). On the other hand, the target-defining features in a CC experiment are often highly salient, such as the appearance of a color stimulus amongst monochrome distractors (Folk et al., 2008; Maki & Mebane, 2006), an abrupt onset at a peripheral spatial location (Folk et al., 2002; Liao & Yeh, 2013), or an ever-changing stream of task-irrelevant distractors at non-target locations (Martens & Valchev, 2009). As such, the salience of the critical distractor in both paradigms may cause an initial capture of stimulus-driven attention. The difference between contingent and surprise capture would then emerge in the degree of sustained attentional engagement. For example, Liao & Yeh (2013) found that abrupt onsets transiently captured attention regardless of attentional settings, whereas a distractor with a target-defined color captured attention for a more sustained duration. Such findings are consistent with the present work, in which CC was elicited from a target-defining color change. The capture effects habituated over time, however, suggesting either a larger stimulus-driven attentional role in our particular CC paradigm or a change in goal-directed attentional function across sessions. The relative importance of these different attentional contributions may change depending on

each paradigm's procedural details, akin to some differences in the mechanisms that contribute to the variety of AB paradigms (Dux & Marois, 2009).

Neural evidence is consistent with CC involving both stimulus-driven and goal-directed attentional components. Regions associated with stimulus-driven attention, particularly the temporo-parietal junction and inferior frontal cortex (Corbetta & Shulman, 2002), are integral to both CC and SiB paradigms (Asplund, Todd, Snyder, & Marois, 2010; Serences et al., 2005). These regions of overlap are distinct from the superior frontal and parietal areas associated with goal-directed attention, though the inferior frontal junction (IFJ) may be a critical region for all three deficits. Overall, the neural evidence echoes the behavioral evidence, with commonalities across all three paradigms and an intermediate position for CC.

Beyond Goal-Directed and Stimulus-Driven Attention

Although we focused on the contributions of goal-directed and stimulus-driven attentional control to each examined attentional limitation, other influences may also be present. For example, Folk et al.'s (1992, 2002, 2008) account for CC has been challenged by evidence from intertrial priming, which is not obviously either stimulus-driven or goal-directed in nature (Awh et al., 2012; Belopolsky et al., 2010). In a typical CC experiment, targets retain the same defining feature across an entire block of trials (Folk et al., 2002, 2008). Belopolsky et al. (2010) instead varied the relevant target feature—and thereby participants' goals—by trial. The CC hypothesis predicts that attentional capture would only occur during trials with a currently target-relevant feature, yet attentional capture was found when the target-relevant feature from the *preceding* trial was presented. Such stimulus history effects may better account for the deficits in many other CC experiments (Awh et al., 2012). There is disagreement about whether such influences are goal-directed, but they are at least distinct from voluntary attentional control (Luck et al., 2020).

A different attentional dichotomy, that between spatial and non-spatial paradigms, is perhaps even more important for understanding the connection between our work and the existing literature on attentional limitations. In the present study, we used versions of each paradigm that did not involve a spatial shift of attention, thereby removing a potentially shared attentional shifting mechanism. Attentional control, however, is more frequently studied with paradigms that include such spatial shifts. In the visual domain, relevant approaches include goal-directed search (Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Pinto et al., 2013), stimulus-driven surprise capture (Horstmann, 2005, 2015), and most variants of CC (Belopolsky et al., 2010; Folk et al., 1992; Kawahara & Kihara, 2011; Liao & Yeh, 2013). A similar, albeit reduced, emphasis on spatial attention is found in the auditory domain as well (Alho et al., 2015; Salmi et al., 2009). It is unclear whether the results from such spatial paradigms are commensurate with non-spatial paradigms and vice versa, but there is reason to be cautious. Foremost, visual search performance does not correlate with AB magnitude, so these measures appear to be assessing different goal-directed processes (Kawahara & Kihara, 2011; Klein et al., 2011). Second, AB magnitude does not correlate with CC effects when the critical distractor is presented away from fixation (Kawahara & Kihara, 2011). Despite the potential importance of the distinction between spatial and non-spatial paradigms, the difference may not be an absolute one. For example, our CC paradigm may still have involved a spatial component: The critical distractor square was peripheral to the centrally-presented letters. This unique spatial aspect of the paradigm may have reduced the correlative relationship with our AB and SiB paradigms, though it is important to note that it remained stronger than the AB-SiB correlation itself.

More broadly, other sources of influence and control on attention may be relevant to understanding the relationships across the attentional limitation paradigms. For example, SiB may involve similar affective components that are critical to emotion-induced blindness

(McHugo et al., 2013). Emotion-induced blindness has also been labelled as an “emotional AB”, and it has recently been found to share neural mechanisms with the AB (MacLeod et al., 2017). Other dispositional features, ranging from personality to the tendency to deploy attention in a more diffuse or focused manner, may also contribute to the observed relationships (MacLean & Arnell, 2012; Willems & Martens, 2016; Wu et al., 2020). Note that affective or dispositional features could be independent of cognitive features that underlie or influence the AB (Dux & Marois, 2009), although they could also interact with them. It will be the aim of future work in our laboratory and others to better characterize the relationships across different attentional paradigms, thereby allowing us to construct a more complete picture of the various components of, and influences upon, attention.

Conclusions

Our findings are consistent with partial overlaps and dissociations across both attentional paradigms and attentional forms. In both the visual and auditory domains, goal-directed and stimulus-driven attentional control have separable and common components (Alho et al., 2015; Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Serences et al., 2005). Additional processes likely contribute to the relationships across attentional paradigms, and these processes may include forms of attentional control that go beyond the traditional dichotomy of goal-directed and stimulus-driven sources (Awh et al., 2012). Equally important is the corollary: Each attentional limitation paradigm we investigated involves multiple sources of attentional control as well as other influences. This conclusion is consistent with empirical investigations of visual (Dale et al., 2013; Dux & Marois, 2009; Visser et al., 2004) and auditory (Vachon et al., 2010; Vachon & Tremblay, 2005, 2006) attentional blinks, though surprise deficits remain relatively underexplored in this regard. Overall, our study shows that tasks involving temporal attentional limitations only partially align with theorized cognitive components. It also demonstrates, however, that

these partial alignments can be used to understand more about the paradigms themselves and the cognitive architecture that underlies them (Skogsberg et al., 2015; Yeo et al., 2015).

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Supplementary materials

Although we believe that the information provided in the main paper answers our primary questions, additional procedural details and analyses provide useful context and generalizations. We have included them here for transparency and completeness.

Supplementary Table 1. Protocol for the study of which Experiment 1 was a part. Tasks primarily tested selective and sustained attention in the visual and auditory modalities. All questionnaires were administered using Qualtrics, with no imposed time limit. The “Day (rel.)” column gives the number of days relative to the previous session. Tasks in **bold** are of relevance to Experiment 1, and these tasks are described in its Methods section (Table 1). AB = attentional blink; SiB = surprise-induced blindness; MR = magnetic resonance; SART = sustained attention to response task; ANT = attentional network task; SiD = surprise-induced deafness; Grad-CPT = gradual-onset continuous performance task; ASRS = adult ADHD self-report scale; DCCS = dimensional change card sorting; PID-5 = personality inventory for DSM-5 for adults; WURS = Wender Utah rating scale.

Sess.	Day (rel.)	Task	Description	Session Duration
0		Visual AB practice (Behavioral; no surprises)	152 trials total. All participants achieved >75% target accuracy during this practice/screening session.	1 hour
1	+3 to +14	Visual AB and SiB (In MR scanner) Sleep quality and habits questionnaire Visual SART ANT	Six blocks, with 168 trials total. Adapted from the Karolinska sleepiness scale (Åkerstedt & Gillberg, 1990) and sleep quality index (Buysse et al, 1989). Adapted from Seli et al (2012). Adapted from Fan et al (2002).	2.5 hours; task order fixed across participants.
2	+1	Grad-CPT Auditory SART Auditory AB and SiD (Behavioral) Visual AB (Behavioral)	Adapted from Rosenberg et al (2013). Adapted from Seli et al (2012). Three blocks, with 168 trials total. With color-salient probe training; see Choi et al, 2012.	2 hours; task order for first 3 tasks counter-balanced across participants.
3	+1	Visual AB and SiB (Behavioral) Visual SART ANT ASRS questionnaire Online DCCS task Raven’s progressive matrices Decision-making tasks	Identical to Session 1, save with different surprise stimuli. Same as above. Same as above. Refer to Kessler et al (2004). Adapted from Zelazo (2006). Adapted from Form A; Bilker et al (2012). No time limit imposed.	2 hours; task order fixed across participants.
4	+1	Grad-CPT Auditory SART Auditory AB and SiD (Behavioral) Media-multitasking and video game experience questionnaire PID-5 questionnaire WURS questionnaire Musical background and experience questionnaire Decision-making tasks	Same as above. Same as above. Identical to session 2, save with different surprise stimuli. Refer to Ophir et al (2009). Refer to Markon et al (2013). Adapted from Ward et al (1993).	2 hours; task and questionnaire order counter-balanced across participants with the decision-making tasks last.
5	+1 to +10	Visual AB and SiB (In MR scanner) Sleep quality and habits questionnaire	Identical to Session 1.	1.5 hours

Supplementary Table 2. False alarm rates for the visual and auditory tasks by session and surprise-probe lag. Standard deviations are indicated in parentheses.

Surprise-Probe Lag	Test session			Retest session 1			Retest session 2		
	Session 1 (visual) Session 2 (auditory)			Session 3 (visual) Session 4 (auditory)			Session 5 (visual)		
	Lag 3	Lag 7	No Surprise	Lag 3	Lag 7	No Surprise	Lag 3	Lag 7	No Surprise
Visual	.03 (.10)	.08 (.17)	.04 (.04)	.03 (.12)	.04 (.10)	.02 (.03)	.02 (.08)	.03 (.12)	.02 (.03)
Auditory	.10 (.19)	.17 (.27)	.06 (.06)	.11 (.21)	.17 (.25)	.07 (.11)			

The reasonably low false alarm rates for surprise trials show both that surprise stimuli were not regularly mistaken for probes and that participants did not use the surprises to predict probes.

Supplementary Table 3A. Summary of all cross-session correlations within and across modalities for Experiment 1 (n=56) and Obana et al., 2020 (n=84). Surprise deficits were calculated from the first four trials unless otherwise specified. Bayes Factors ($B_{H(0,r=0.4)}$) were calculated using a half-normal distribution for the model of the alternative hypothesis (H1) (Dienes & McIatchie, 2018). Each Bayes Factor (B) represents the degree of support for H1 over the null hypothesis (H0). Results in **bold** are also included in the main text in either Table 9 or Results; they are reprinted here for comparison purposes. S1 = Session 1 (visual Test session); S2 = Session 2 (auditory Test session); S3 = Session 3 (visual Retest session 1); S4 = Session 4 (auditory Retest session); S5 = Session 5 (visual Retest session 2); AB = attentional blink; SiB = surprise-induced blindness; SiD = surprise-induced deafness. Acc. = accuracy.

Relationship	Data (Session)	<i>r</i> -value	<i>p</i> -value	Individual Expt. <i>B</i>
Auditory AB vs. SiD (Auditory)	Obana et al., Expt. 7	.270	.012	8.79
	Test	.416	.001	47.7
	Test (All surprises)	.278	.038	4.05
	Retest	.244	.069	2.58
Visual AB vs. SiB (Visual)	Test	.345	.009	12.0
	Test (All surprises)	.398	.002	32.4
	Retest (S3)	.258	.055	3.09
	Retest (S5)	.190	.160	1.37
Visual AB vs. Auditory AB	Test	-.071	.604	0.220
	Retest (S3 and S4)	.004	.977	0.317
	Retest (S5 and S4)	.095	.487	0.574
SiB (Visual) vs. SiD (Auditory)	Test	.183	.178	1.26
	Test (All surprises)	.212	.116	1.74
	Retest (S3 and S4)	.199	.141	1.51
	Retest (S5 and S4)	.142	.298	0.847
SiB (Visual) vs. Visual AB	Test (S1) vs. Retest (S3)	.210	.120	1.70
	Test (S1) vs. Retest (S5)	.315	.018	7.19
Visual AB vs. SiB (Visual)	Test (S1) vs. Retest (S3)	.250	.063	2.78
	Test (S1) vs. Retest (S5)	.036	.790	0.384
Auditory AB vs. SiD (Auditory)	Test (S2) vs. Retest (S4)	.211	.119	1.71
SiD (Auditory) vs. Auditory AB	Test (S2) vs. Retest (S4)	.154	.256	0.950
Visual AB vs. Target acc.	Test	.218	.106	1.87
Auditory AB vs. Target acc.	Test	-.187	.167	0.145
Visual Target acc. vs. Auditory Target acc.	Test	.099	.469	0.592
	Retest (S3 and S4)	.011	.937	0.330
	Retest (S5 and S4)	.093	.498	0.564
Visual Lag 9 probe acc. vs. Auditory Lag 9 probe acc.	Test	-.033	.808	0.262
	Retest (S3 and S4)	-.023	.868	0.276
	Retest (S5 and S4)	.057	.677	0.438

Supplementary Table 3B. Summary of all within and cross-session correlations for Experiment 2 (n=52). Surprise deficits calculated from all trials unless otherwise specified. Bayes Factors ($B_{H(0,r=0.4)}$) were calculated in the same way as reported for Supplementary Table 3A. Cumulative B represents the meta-analytic Bayes Factor across different data sets from which the same relationship is examined. For example, the first Cumulative B listed below combines information from the AB vs. SiB correlation with that same relationship in Experiment 1. Posterior means, standard deviations, and 95% credible intervals for these meta-analyses are r -value effect size estimates and their uncertainty. Results in **bold** are also included in the main text either in Table 9 or Results; they are reprinted here for comparison purposes. AB = attentional blink; SiB = surprise-induced blindness; CC = contingent capture. Acc. = accuracy.

Relationship	Data (Session)	r -value	p -value	Individual Expt. B	Cumulative B	Posterior Mean (SD)	Meta 95% Credible Interval
AB vs. SiB	Test	.251	.072	2.56	34.1	0.30 (0.10)	0.12, 0.47
	Test (First 4 surprises)	.181	.198	1.19			
	Retest	.104	.462	0.618	21.4	0.24 (0.081)	0.084, 0.38
AB vs. CC	Test	.522	<.001	393.12			
	Retest	.196	.163	1.38	234	0.37 (0.10)	0.19, 0.53
CC vs. SiB	Test	.437	.001	53.5			
	Test (First 4 surprises)	.482	<.001	148.99			
	Retest	.154	.274	0.930	30.7	0.30 (0.10)	0.11, 0.47
AB vs. CC	Retest vs. Test	.547	<.001	766.37			
AB vs. SiB	Retest vs. Test	.313	.024	5.85			
AB vs. Target acc.	Test	-.090	.524	0.214			
	Retest	.089	.532	0.553			

Note that the Retest sessions do not have large effects on the Cumulative B values in either direction. The Retest r -values do not provide strong evidence for or against a relationship between the variables in question. We argue, however, that these Retest values should be interpreted with caution because their underlying effects habituate to a substantial degree.

Supplementary Table 4A. Exploratory factor analysis results with the surprise deficits calculated from all surprise trials during the test session of Experiment 1. The factor loadings and proportion of explained variance are shown for a two-factor solution with oblimin rotation. Factor loadings above the cutoff of 0.4 are indicated in **bold** (Howard, 2016). Results for all Surprise trials are also included in the main text as Table 5; they are reprinted here for comparison purposes. AB = attentional blink; SiB = surprise-induced blindness; SiD = surprise-induced deafness.

Loadings	First 4 surprise trials		All surprise trials	
	Factor 1	Factor 2	Factor 1	Factor 2
- Visual AB	.00	.46	0.58	0.03
- Auditory AB	.67	-.19	-0.21	0.60
- Visual surprise (SiB)	.00	.74	0.68	-0.03
- Auditory surprise (SiD)	.67	.20	0.29	0.55
Proportion of variance	.23	.21	.23	.17

Supplementary Table 4B. Exploratory factor analysis results for test session residuals of Experiment 1. The factor loadings and proportion of explained variance are shown for a two-factor solution with varimax rotation. Factor loadings above the cutoff of 0.4 are indicated in **bold** (Howard, 2016). AB = attentional blink; SiB = surprise-induced blindness; SiD = surprise-induced deafness.

Loadings	First 4 surprise trials		All surprise trials	
	Factor 1	Factor 2	Factor 1	Factor 2
- Visual AB	0.01	0.46	0.59	0.04
- Auditory AB	0.67	-0.17	-0.16	0.60
- Visual surprise (SiB)	0.02	0.74	0.68	-0.03
- Auditory surprise (SiD)	0.68	0.23	0.33	0.55
Proportion of variance	.23	.21	.24	.17

Regardless of the rotation method used and the number of surprise trials included, the factor analysis revealed a similar trend: visual and auditory modalities load on different factors, suggesting weaker relations across modalities, consistent with the correlational results.

Supplementary Table 5. Principal Component Analysis results for test session residuals of Experiment 1. The component loadings are shown for a two-factor solution with varimax rotation. Component loadings above the cutoff of 0.4 are indicated in **bold** (Howard, 2016). AB = attentional blink; SiB = surprise-induced blindness; SiD = surprise-induced deafness.

Loadings	First 4 surprise trials		All surprise trials	
	Component 1	Component 2	Component 1	Component 2
- Visual AB	0.00	0.79	0.80	0.05
- Auditory AB	0.85	-0.21	-0.25	0.85
- Visual surprise (SiB)	0.03	0.82	0.82	-0.03
- Auditory surprise (SiD)	0.83	0.26	0.39	0.74
Proportion of variance	.35	.35	.38	.32

Supplementary Table 6. Principal Component Analysis results for test session residuals of Experiment 2. The component loadings are shown for a one-factor solution without rotation. Component loadings above the cutoff of 0.4 are indicated in **bold** (Howard, 2016). AB = attentional blink; SiB = surprise-induced blindness; CC = contingent capture.

Loadings	Component 1
- AB	0.77
- SiB	0.70
- CC	0.86
Proportion of variance	.61

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