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Does working memory capacity predict cross-modally induced failures of awareness?

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ABSTRACT

People often fail to notice unexpected stimuli when they are focusing attention on another task. Most studies of this phenomenon address visual failures induced by visual attention tasks (inattentional blindness). Yet, such failures also occur within audition (inattentional deafness), and people can even miss unexpected events in one sensory modality when focusing attention on tasks in another modality. Such cross-modal failures are revealing because they suggest the existence of a common, central resource limitation. And, such central limits might be predicted from individual differences in cognitive capacity. We replicated earlier evidence, establishing substantial rates of inattentional deafness during a visual task and inattentional blindness during an auditory task. However, neither individual working memory capacity nor the ability to perform the primary task predicted noticing in either modality. Thus, individual differences in cognitive capacity did not predict failures of awareness even though the failures presumably resulted from central resource limitations.

1. Introduction

The striking limits on the capacity of attention are perhaps best illustrated by inattentional blindness, the failure to notice highly visible unexpected objects when attention is engaged in another task (Mack & Rock, 1998; Simons & Chabris, 1999). These failures occur both in the laboratory and in real-world situations (Chabris, Weinberger, Fontaine, & Simons, 2011; Drew, Vo, & Wolfe, 2013; Haines, 1991; Memmert & Furley, 2007). Moreover, they are not limited to vision, but also occur in audition (inattentional deafness; Dalton & Fraenkel, 2012; Koreimann, Gula, & Vitouch, 2014; Mack & Rock, 1998). For example, people fail to notice the repeated and salient presentation of the words “I am a gorilla.” when they are focused on another conversation (Dalton & Fraenkel, 2012). Inattentional deafness is perhaps even more surprising than inattentional blindness given how audition is thought of as an “alarm sense,” alerting us to unexpected events (Koreimann et al., 2014).

Given the multi-modal nature of perceptual experience, perhaps cross-modal stimuli would be more likely to capture attention. That is, the limits on awareness might be modality specific; visual attention decreases the chances of noticing

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visual unexpected events and auditory attention reduces the likelihood of detecting unexpected auditory events. If so, each modality could help overcome strict limits on attention in other modalities. Alternatively, if attention limits are more central, it should be possible to induce failures of awareness across modalities. Attention to an auditory task should yield failures of visual awareness, and vice versa.

To date, only a few studies have explored whether people fail to notice unexpected events in one modality while focusing attention on a task in a different modality. For example, in a variant of a task in which participants watched a video and counted how many times one set of players passed a ball (Wayand, Levin, & Varakin, 2005, modeled after Neisser, 1979; Simons & Chabris, 1999), 59% of participants neither saw nor heard when a women walked into the scene and scratched her nails on a chalkboard. Similarly, participants engaged in a visual line-length judgment task failed to hear a pure tone played over headphones (Macdonald & Lavie, 2011). Noticing rates for the tone were strongly modulated by the perceptual load of the visual task, a pattern that generalizes to failures to notice an auditory cockpit alarm with increased visual workload (Dehais et al., 2013). Similarly, auditory tasks can induce failures of visual awareness (Fougnie & Marois, 2007; Pizzighello & Bressan, 2008), a finding consistent with failures of visual awareness resulting from auditory distractions like talking on a mobile phone (Hyman, Boss, Wise, McKenzie, & Caggiano, 2010; Strayer & Drews, 2007). These cross-modal awareness failures suggest central limits on attention rather than just modality specific ones. If so, individual differences in cognitive capacity or executive functioning might predict such failures of awareness.

A growing literature has sought individual-difference predictors of inattentional blindness, largely without success. Some evidence finds a weak correlation between inattentional blindness and the basic personality trait openness to experience (Kreitz, Schnuerch, Gibbons, & Memmert, 2015), but individual differences in other personality measures that are thought to be related to attention (emotional distress, anxiety, worry, depression, schizotypy, achievement motivation) do not appear to predict noticing (Bredemeier, Hur, Berenbaum, Heller, & Simons, 2014; Kreitz, Schnuerch, et al., 2015). A potential link between inattentional blindness and absorption (the trait tendency to become absorbed in a momentary experience; Tellegen & Atkinson, 1974) appears to be dependent on task characteristics (Kreitz, Furley, Memmert, & Simons, 2015; Richards, Hellgren, & French, 2014).

The evidence for cognitive predictors of inattentional blindness is murky at best. Individual differences in the ability to focus attention, as measured by performance on the primary task, appear unrelated to noticing (Bredemeier & Simons, 2012; Simons & Jensen, 2009). Although some studies link noticing to working memory capacity (Hannon & Richards, 2010; Richards, Hannon, & Derakshan, 2010), others find that the association depends on the difficulty of the primary task (Calvillo & Jackson, 2014) or find small effects only for one of several inattentional blindness tasks (Kreitz, Furley, et al., 2015). Finally, some studies find an association only for a selected subset of participants (Seegmiller, Watson, & Strayer, 2011), and one large study found no link at all (Bredemeier & Simons, 2012).

The inconsistency in this pattern of results might reflect the existence of a small effect measured imprecisely due to relatively small sample sizes. Or, it could reflect the existence of different forms of inattentional blindness. The term inattentional blindness encompasses at least two different mechanisms for inducing failures of awareness, one tapping the limits of spatial attention and one drawing upon more central limits on attention (Most, 2010). Spatial limits might cause inattentional blindness when the unexpected object appears away from the attended region (Most, Simons, Scholl, & Chabris, 2000; Newby & Rock, 1998), whereas more central limits might cause inattentional blindness when people fail to notice objects near or within the spatial focus of attention (Most et al., 2001; Neisser & Becklen, 1975; Simons & Chabris, 1999). If so, individual differences in working memory capacity should contribute more when inattentional blindness results from central limits than from spatial limits.

A recent series of studies tested this hypothesis using both dynamic and static inattentional blindness tasks in which the unexpected object appeared at or away from the focus of attention (Kreitz, Furley, et al., 2015). Yet, individual differences in working memory largely were unrelated to failures of awareness, regardless of the way in which inattentional blindness was induced. Only in a static task was working memory capacity weakly associated with noticing of an unexpected object that appeared within the spatial focus of attention (Kreitz, Furley, et al., 2015).

Although this study suggests that centrally-induced inattentional blindness is largely unrelated to individual differences in working memory capacity, both the inducing task and the unexpected object were visual. Cross-modal failures of awareness might represent a better test case for individual differences because they rely only on central processing limits rather than on modality-specific or spatial limits on attention. The possibility that individual differences in cognitive capacity might predict cross-modal failures of awareness gains support from the link between visual task demands and the probability of noticing an unexpected auditory stimulus (Macdonald & Lavie, 2011).

We hypothesized that participants with a greater working memory capacity should be more likely to notice an additional pure tone while performing a visual task (Study 1) and that they should have a higher probability of noticing an additional visual object while performing an auditory task (Study 2). In testing these hypotheses, we designed our studies to conceptually replicate two findings of cross-modal awareness failures (Macdonald & Lavie, 2011; Pizzighello & Bressan, 2008).

In both studies, we calibrated the difficulty of the primary task for each participant, but presented the unexpected stimulus with the same task parameters for all participants. Consequently, the primary task on the critical trial should be less demanding for someone who is better able to perform the task, leaving more central resources available to detect an unexpected stimulus. Prior studies found no link between the ability to perform a visual primary task and the probability of detecting an unexpected visual event (Bredemeier & Simons, 2012; Simons & Jensen, 2009). We examined this association for our cross-modal tasks as well.

2. Study 1

Study 1 tested whether individual differences in working memory predict noticing of an unexpected auditory pure tone when participants are performing a visual line-judgment task (Macdonald & Lavie, 2011). We expected to replicate the finding that a substantial number of participants would miss the unexpected tone, and we predicted a relationship between individual differences in working memory capacity and the likelihood of noticing the tone.

2.1. Method

The study design, testing procedures, and analysis plan of Study 1 and Study 2 were pre-registered on the Open Science Framework. The pre-registered plan and all code and data are available at https://osf.io/hw8er and https://osf.io/cf4ed/.

2.1.1. Participants

A total of 100 undergraduate students completed the tasks in a single session lasting approximately one hour in exchange for 10 Euro. Of the 99 participants who reported normal or corrected-to-normal vision, data from 13 participants were excluded from the analyses for the following reasons: lost data for the inattentional blindness task due to a technical failure (1 participant) or a failure to notice or correctly describe the tone under full-attention conditions ($N = 13$; this exclusion rule is standard in the inattentional blindness literature; Mack & Rock, 1998). The analysis included the remaining 86 participants ($M = 22.2$ years; $SD = 2.8$ years; 36 female).

2.1.2. Materials and procedure

Participants were tested alone or in pairs. When tested in pairs, they were separated by dividers and were instructed to work quietly. Detailed instructions appeared on the screen prior to each task. Participants first completed a cross-modal inattentional deafness task, followed by three working memory tasks in a randomized order (when two participants took part simultaneously, they received the same random order of working memory tasks). The tasks and materials are described below.

2.1.2.1. Cross-modal inattentional deafness task. The cross-modal inattentional deafness task was adapted from the high-load condition of Macdonald and Lavie (2011). On each trial, following a 1000-ms fixation screen, a cross appeared for 200 ms centered on the screen (the extent of the longer arm was always 6° of visual angle), followed immediately by a black-and-white pattern mask for 500 ms. Participants were asked to press "A" or "L" on the keyboard to indicate whether the horizontal or the vertical arm of the cross was longer (key assignment was counterbalanced across participants). While participants viewed the fixation screen, the cross, and the pattern mask, they listened to white noise through headphones. Participants were told that the white noise was intended to cancel out other external, potentially distracting noise and to help them to concentrate on their task.

After ten easy practice trials, participants completed a set of trials in which the length difference between the two arms, and thus the difficulty of the task, was adaptively adjusted: an incorrect answer on one trial led to a greater length difference (easier to judge) on the next trial, whereas three accurate answers in a row led to smaller length differences (more difficult to judge). This adaptive thresholding procedure (3-1 method; Levitt, 1971) determined the task difficulty at which the participant could respond accurately 79% of the time.

Once the threshold was determined, the critical trial occurred next, without any interruption or forewarning. On the critical trial, the lengths of the arms were identical for all participants (6° vs. 5.6°, the mean threshold from two earlier studies with more than 300 participants in total; see Kreitz, Furley, et al., 2015). The unexpected stimulus was a low-pitch pure tone (180 Hz) presented for 200 ms together with the cross and the white noise.[3] After responding to the cross task, participants were asked if they had noticed anything on the preceding trial that had not been present on earlier trials. Independent of their answer, they then were asked whether the additional stimulus had been something visual or something auditory and to specify what the additional auditory event had been (the noise was overall higher, the noise was overall lower, an additional short high tone, an additional short low tone). The questions were forced-choice and participants were instructed to guess if they had not noticed anything. After completing three more trials without an additional stimulus, the same critical sound appeared again (divided-attention trial). Finally, after answering an identical set of questions, participants completed one more trial in which they were instructed to ignore the cross, with the same auditory stimulus occurring again (full-attention trial).

2.1.2.2. 2-back-identity. A sequence of letters (C, F, K, M, P, S, W, X; each 1.7° of visual angle) appeared at the center of the display for 500 ms each, with a blank-screen gap of 2000 ms between letters. Participants were instructed to press the Enter key as quickly and accurately as possible whenever a letter matched the one presented two items earlier in the sequence (adapted from Owen, McMillan, Laird, & Bullmore, 2005). After a 20-item practice sequence, participants completed a

[3] Before conducting the main study, we conducted a piloted study with 17 participants to determine a stimulus strength (i.e., loudness) that we hoped would avoid floor or ceiling effects in noticing rates. Given our goal of exploring individual differences, we needed noticing rates to be as close to 50% as possible.

100-item experimental sequence. Twenty-five of the letters in the experimental sequence were matches. The measure of working memory in this task was Pr (i.e., hits minus false alarms; Snodgrass & Corwin, 1988).

2.1.2.3. 2-back-spatial. The procedure was the same as for the 2-back-identity task except that instead of the eight different centrally-presented letters, circles (2° diameter) appeared sequentially at eight different spatial locations (arranged equally-spaced on an imaginary circle with a diameter of 15°). Participants were instructed to press the Enter key whenever the current circle location matched the location two items earlier (adapted from Boot, Kramer, Simons, Fabiani, & Gratton, 2008).

2.1.2.4. Automated operation span (Aospan). Participants memorized lists of letters while simultaneously solving simple mathematical problems (Unsworth, Heitz, Schrock, & Engle, 2005). The task included 15 trials (3 trials each with 3, 4, 5, 6, and 7 letters to memorize), and as a measure of working memory, we used the number of correctly recalled letters across all trials in which the participant recalled all of the letters correctly (the Ospan score; Unsworth et al., 2005).

2.1.2.5. Materials and setup. The cross-modal inattentional deafness task, the 2-back-identity task, and the 2-back-spatial task were programmed and run in Presentation (Neurobehavioral Systems, Berkeley, CA). The Aospan was programmed and run in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Participants responded via a standard keyboard, or in case of the Aospan, a standard mouse. For the inattentional deafness task, participants wore on-ear headphones (Logitech UE 4000) and placed their head in a chin rest (NovaVision, Magdeburg, Germany) which ensured an exact viewing distance of 50 cm from the 24-inch display (resolution: 1920 × 1080 pixels, controlled by an Esprimo 710 3.3 GHz Core i3–3220 computer). For the three working memory tasks, participants sat at an approximate distance of 50 cm from the display.

2.2. Results and discussion

Rather than conducting null-hypothesis significance tests, we followed recent recommendations to focus on estimation (Cumming, 2012, 2014); we report effect-sizes with 95% confidence intervals.

Participants were considered to have missed the unexpected stimulus if they did not report noticing it or if they claimed to have noticed something but either failed to report that it was auditory or could not identify which type of auditory event it was. All participants whose data were included in the analyses noticed and correctly identified the unexpected stimulus in the full-attention trial. Thus, a failure to report the unexpected sound on the critical trial can be attributed to the absence of attention rather than to the limits of hearing (Mack & Rock, 1998).

A recent meta-analysis (Redick & Lindsey, 2013; see also Kane, Conway, Miura, & Colflesh, 2007) suggests that complex span tasks like the Aospan and n-back measures do not share sufficient variance to be used interchangeably as measures of working memory. Thus, we explored the relationship between each working memory measure and inattentional blindness separately rather than creating a composite working memory measure.

Replicating earlier evidence that participants can miss an unexpected auditory event when performing an attention-demanding visual task (Macdonald & Lavie, 2011), 64% of the participants missed the tone on the critical trial, and 7% missed it on the divided-attention trial (see Fig. 1). Thus, engagement in a visual task not only induces visual awareness failures (e.g., Mack & Rock, 1998; Simons & Chabris, 1999), but also auditory awareness failures.

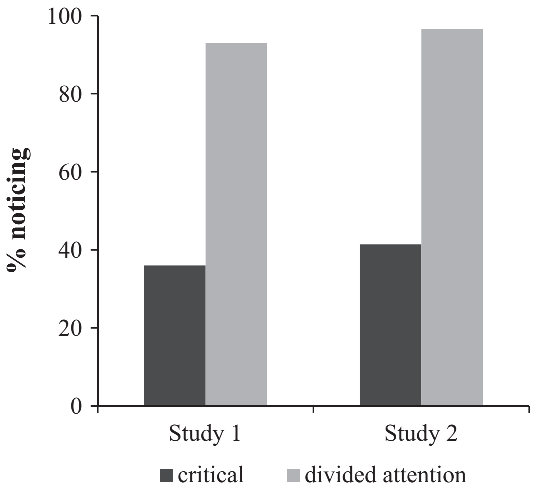

Fig. 1. Percentage of participants in Study 1 (visual primary task, auditory unexpected stimulus) and in Study 2 (auditory primary task, visual unexpected event) who noticed the unexpected object. Results are illustrated separately for the critical trial and the divided-attention trial.

Table 1
Correlations between measures of working memory and noticing; Study 1.

	1	2	3	4	5
(1) Noticing critical	–	.21	.14	.07	−.11
(2) Noticing divided attention	[.00, .40]	–	.01	.04	.07
(3) 2-back-identity	[−.07, .34]	[−.20, .22]	–	.54	.24
(4) 2-back-spatial	[−.14, .28]	[−.17, .25]	[.37, .68]	–	.15
(5) Aospan	[−.32, .10]	[−.14, 28]	[.03, .43]	[−.06, .35]	–

Note. The lower and upper bounds of the 95% confidence interval are shown in square brackets below the diagonal. Correlations between noticing and working memory measures are point biserial. Correlations among the working memory measures are Pearson's *r*.

Table 2
Results of the binary logistic regression with simultaneous entry (SE in parentheses); Study 1.

Variables	*B* (SE)	Wald	Exp(*B*)	Exp(*B*) lower	Exp(*B*) upper
Constant	−1.45 (1.04)	1.92	0.24		
2-back-identity	0.09 (0.07)	1.77	1.09	0.96	1.25
2-back-spatial	0.00 (0.04)	0.00	1.00	0.92	1.09
Aospan	−0.02 (0.01)	1.82	0.98	0.95	1.01
$R^2 = .04$ *(Cox & Snell), Model:* $\chi^2\ (3) = 3.58$, $p = .31$					

Note. The upper and the lower bounds of the 95% confidence interval of Exp(*B*) are depicted as well. No variable had a $p < .05$.

Table 3
Results of the binary logistic regression with simultaneous entry in two blocks (SE in parentheses); Study 1.

Variables	*B* (SE)	Wald	Exp(*B*)	Exp(*B*) lower	Exp(*B*) upper
Constant*	23.05 (11.20)	4.24	1.02e10		
Ability primary task*	−0.13 (0.06)	4.46	0.88	0.78	0.99
$R^2 = .06$ *(Cox & Snell), Model:* $\chi^2\ (1) = 5.50$, $p = .02$					
Constant*	23.87 (11.55)	4.27	2.32e10		
Ability primary task*	−0.14 (0.07)	4.89	0.87	0.76	0.98
2-back-identity	0.10 (0.07)	1.95	1.10	0.96	1.26
2-back-spatial	0.02 (0.05)	0.13	1.02	0.93	1.11
Aospan	−0.02 (0.02)	1.07	0.99	0.96	1.01
$R^2 = .11$ *(Cox & Snell), Model:* $\chi^2(4) = 9.63$, $p = .05$					

Note. The regression analyses were performed in two separate blocks. The variables of the first block are depicted first and the variables of the whole model, including the second block, are depicted below it. The upper and the lower bounds of the 95% confidence interval of Exp(*B*) are depicted as well.
* $p < .05$.

The lack of ceiling or floor effects permits an analysis of whether or not individual differences in working memory predict noticing. None of the working memory measures correlated with noticing on the critical trial or on the divided-attention trial (Table 1), although noticing rates in the divided-attention trial were sufficiently high to render the correlations effectively meaningless. In a regression model, none of the working memory measures successfully predicted noticing on the critical trial (Table 2). Failures of awareness apparently are not related to individual working memory capacity, even when those failures are induced by modality-general attention limits.

We next assessed whether individual differences in the ability to perform the cross task predicted noticing on the critical trial. Surprisingly, participants who were better able to perform the cross task (could distinguish smaller length differences at threshold) were *more* likely to miss the unexpected sound on the critical trial (Table 3). Most previous studies report no link between primary task ability and noticing (e.g., Bredemeier & Simons, 2012; Simons & Jensen, 2009), and this pattern is in the opposite direction to what would be expected. The unexpected pattern found in this study might reflect motivational differences. Participants who perform better on the cross task might be motivated to devote more attention to the task regardless of the task difficulty, leaving less resources for the detection of an unexpected stimulus on the critical trial. However, this explanation is post-hoc and the finding might well be spurious: primary task ability accounted for only 6% of the variance in noticing.

3. Study 2

Study 2 was designed as a conceptual replication of Study 1, but with an auditory primary task and an unexpected visual stimulus. The design of Study 2 was matched to that of Study 1 as closely as possible. Few studies to date have explored whether focusing attention on auditory information can induce inattentional blindness (Fougnie & Marois, 2007;

Pizzighello & Bressan, 2008). One study used an auditory primary task to induce inattentional blindness, demonstrating a cross-modal failure of awareness (Pizzighello & Bressan, 2008). Another induced failures of visual awareness by asking participants to perform a verbal working memory task; unexpected visual stimuli presented during the retention interval often went unnoticed (Fougnie & Marois, 2007). The latter finding provides a clear demonstration of inattentional blindness induced by taxing central resources. In both cases, inattentional blindness does not depend on visual distraction. To date, no study has explored associations between such centrally-induced failures of awareness and individual differences in central capacity.

In Study 2, we presented an unexpected visual object during auditory stimulation, used a visual display without other stimuli, and we monitored eye movements to ensure fixation. As in Study 1, we examined the relationships among working memory, primary-task performance, and noticing.

3.1. Method

3.1.1. Participants

A total of 100 undergraduate students completed the tasks in a single session that lasted approximately one hour in exchange for 10 Euro. Of the 97 participants who reported normal or corrected-to-normal vision and hearing, data from ten participants were excluded from the analyses for the following reasons: they indicated in the follow-up questionnaire that they had anticipated the unexpected object (2 participants), their data for the inattentional blindness task were lost due to a technical failure (1 participant), they failed to maintain fixation on the fixation cross during the critical trial or the divided-attention trial (2 participants), or they did not notice the critical stimulus on the full-attention trial (6 participants). The analyses included the remaining 87 participants (M = 21.6 years; SD = 3.5 years; 38 female).

3.1.2. Materials and procedure

Except as noted, the experimental procedure was identical to Study 1. We installed a webcam on top of the computer display so that the experimenter could monitor eye movements as participants completed the task. To allow for on-line monitoring, participants were tested individually in Study 2. We used the same working memory measures as in Study 1, but replaced the inattentional deafness task with a cross-modal inattentional blindness task that was as similar as possible to the cross-modal task of Study 1.

On each trial of that task, participants experienced a 1000-ms waiting interval, followed by a tone presented over headphones. The tone started at 400-Hz and either rose or fell in pitch continuously during its 200-ms presentation (frequency was increased or decreased, respectively). Participants pressed a button to indicate whether the tone rose or fell. Immediately after the end of the target tone, participants heard a white noise mask for 500 ms.

Participants were instructed to fixate a small black cross at the center the otherwise gray (RGB: 128, 128, 128) computer screen throughout each trial. They were told that doing so was important to equate conditions across participants and to avoid distraction. They were further told that an experimenter would monitor their eye-movements via the webcam. When participants failed to maintain fixation, the experimenter reminded them.

After ten easy practice trials, participants completed a set of trials in which the magnitude of the change in frequency, and thus the difficulty of the task, was adaptively adjusted (adaptive thresholding; see Experiment 1). The smaller the change in frequency, the more difficult was the primary task. Once the threshold was determined, the critical trial occurred next, without any interruption or forewarning.

The parameters for the critical trial were determined from testing of 30 pilot participants. The change magnitude was the same for all participants, and was set to 10 Hz, the average threshold from the pilot participants. The unexpected stimulus was a gray square (RGB: 108, 108, 108; 0.6° of visual angle) that appeared 2° below and slightly to right of the middle of the fixation cross. The brightness level of the unexpected object was set based on pilot testing to minimize the likelihood of floor or ceiling effects in noticing.

After responding to the pitch task, participants were asked if they had noticed anything on the preceding trial that had not been present on earlier trials. Independent of their answer, they then were asked whether the additional stimulus had been something visual or something auditory, where the additional object had appeared in relation to the fixation cross (upper right, lower right, lower left, upper left), and what shape the additional object had been (rectangle, square, triangle, diamond, cross, cross rotated 45°). The questions were forced-choice and participants were instructed to guess if they had not noticed anything. After completing three more trials without an additional stimulus, the same critical object appeared again (divided-attention trial). Finally, after answering an identical set of questions, participants completed one more trial in which they were instructed not to evaluate the change in pitch of the tone, with the same critical stimulus appearing again (full-attention trial).

3.2. Results and discussion

Due to computer error, data were missing from one participant for the 2-back-identity task and from one participant for the 2-back-spatial task. The correlational analyses reported below included all participants for whom we had data for both tasks.

Participants were considered to have missed the unexpected stimulus if they (a) did not report noticing it, (b) claimed to have noticed something but did not define it as an additional *visual* event, or (c) claimed to have noticed a visual event but incorrectly identified both its position and its shape. All participants whose data were included in the analyses noticed and correctly identified the unexpected stimulus in the full-attention trial. Thus, as in Study 1, a failure to report the unexpected object on the critical trial can be attributed to the absence of attention rather than to the limits of vision (Mack & Rock, 1998).

In Study 2, 59% of the participants missed the additional stimulus on the critical trial and 3% missed it on the divided-attention trial (see Fig. 1). Thus, we conceptually replicated evidence from Study 1 that failures of awareness can be induced by an attention-demanding task in a different modality; a majority of participants failed to notice an unexpected visual stimulus when they simultaneously performed an attention-demanding auditory task. As in Study 1, noticing levels were neither at floor or ceiling, making analysis of individual differences possible.

None of the working memory measures individually correlated with noticing on the critical trial (Table 4), and they collectively did not predict noticing in a regression model with simultaneous entry (Table 5). As in Study 1, noticing rates for the divided-attention trial were close to ceiling, rendering correlations with working memory performance effectively meaningless. Consistent with Study 1, even for failures of awareness that are driven by central rather than spatial limits, noticing is unrelated to individual differences in working memory capacity.

Unlike Study 1, and consistent with previous evidence (Bredemeier & Simons, 2012; Simons & Jensen, 2009), individual differences in the ability to perform the primary task were unrelated to noticing on the critical trial (Table 6). Our replication of this lack of association using a cross-modal task suggests that the unexpected negative association in Study 1 might be spurious. Neither the individual ability to perform the primary task nor individual working memory capacity explained variance in noticing.

Table 4
Correlations between measures of working memory and noticing; Study 2.

	1	2	3	4	5
(1) Noticing critical	–	.16	.14	.03	.11
(2) Noticing divided attention	[−.05, .36]	–	−.06	−.01	.13
(3) 2-back-identity	[−.07, .34]	[−.27, .15]	–	.17	.46
(4) 2-back-spatial	[−.18, .24]	[−.22, .20]	[−.04, .37]	–	.14
(5) Aospan	[−.10, .31]	[−.08, 33]	[.28, .61]	[−.07, .34]	–

Note. The lower and upper bounds of the 95% confidence interval are shown in square brackets below the diagonal. Correlations between noticing and working memory measures are point biserial. Correlations among the working memory measures are Pearson's *r*.

Table 5
Results of the binary logistic regression with simultaneous entry (SE in parentheses); Study 2.

Variables	*B* (SE)	Wald	Exp(*B*)	Exp(*B*) lower	Exp(*B*) upper
Constant	−1.59 (1.09)	2.15	0.20		
2-back-identity	0.06 (0.06)	0.89	1.06	0.94	1.20
2-back-spatial	0.00 (0.04)	0.00	1.00	0.93	1.07
Aospan	0.01 (0.02)	0.20	1.01	0.98	1.04
R^2 = .02 (Cox & Snell), Model: χ^2 (3) = 1.88, p = .60					

Note. The upper and the lower bounds of the 95% confidence interval of Exp(*B*) are depicted as well.
No variable had a $p < .05$.

Table 6
Results of the binary logistic regression with simultaneous entry in two blocks (SE in parentheses); Study 2.

Variables	*B* (SE)	Wald	Exp(*B*)	Exp(*B*) lower	Exp(*B*) upper
Constant	−0.31 (0.33)	0.88	0.73		
Ability primary task	0.00 (0.02)	0.01	1.00	0.96	1.04
R^2 = .00 (Cox & Snell), Model: χ^2 (1) = 0.01, p = .94					
Constant	−1.87 (1.25)	2.27	0.15		
Ability primary task	0.01 (0.02)	0.22	1.01	0.97	1.05
2-back-identity	0.07 (0.06)	1.06	1.07	0.94	1.21
2-back-spatial	0.00 (0.04)	0.00	1.00	0.93	1.07
Aospan	0.01 (0.02)	0.27	1.01	0.98	1.04
R^2 = .02 (Cox & Snell), Model: χ^2(4) = 2.11, p = .72					

Note. The regression analyses were performed in two separate blocks. The variables of the first block are depicted first and the variables of the whole model, including the second block, are depicted below it. The upper and the lower bounds of the 95% confidence interval of Exp(*B*) are depicted as well.
No variable had a $p < .05$.

4. General discussion

We successfully induced failures of awareness by asking participants to focus attention on a task in one modality and presenting an unexpected stimulus in another modality (see also Macdonald & Lavie, 2011; Pizzighello & Bressan, 2008). Study 1 found inattentional deafness for a pure tone when participants simultaneously performed a demanding visual task and Study 2 found inattentional blindness for an unexpected gray square when participants performed a demanding auditory task. In both studies more than half of the participants did not notice the unexpected critical stimulus. Failures of awareness apparently can result, at least in part, from shared central resources rather than modality-specific ones (see also Fougnie & Marois, 2007; Giraudet, St-Louis, Scannella, & Causse, 2015; Raveh & Lavie, 2014; Sinnett, Costa, & Soto-Faraco, 2006).

By adaptively adjusting the difficulty of the primary tasks to the same threshold performance level in each study, we roughly equated the difficulty of the primary tasks, allowing for a more direct comparison of the results despite the differences in modality. Noticing rates were comparable in the two studies, a finding inconsistent with the proposal that auditory load may be ineffective in suppressing visual awareness and that shared capacity between modalities might be better shown with visual than with auditory load (Raveh & Lavie, 2014). Note, though, that noticing rates are easily influenced by stimulus salience (Koreimann et al., 2014; Mack & Rock, 1998), and cross-modal comparisons make equating salience difficult.

Although our study suggests a role for central resources in failures of awareness, another explanation appeals to the idea that attention sets (Folk, Remington, & Johnston, 1992) might be modality specific. Unexpected stimuli are missed more often when they differ from the attended stimuli in the visual (e.g., Most, Chun, Widders, & Zald, 2005; Most et al., 2001) and auditory modality (Dalton & Fraenkel, 2012). If the primary task establishes a modality-specific attention set (e.g., attend only to these particular visual items), then an unexpected auditory stimulus would not be part of that attention set (Pizzighello & Bressan, 2008). The same should be true for an unexpected visual stimulus if the task induced an attention set for auditory stimuli. If so, cross-modal failures of awareness might not result entirely from central capacity limits and instead might reflect a mismatch between attended features and features of the unexpected stimulus.

Nevertheless, as increased visual load also increases susceptibility to inattentional deafness (Macdonald & Lavie, 2011), central resource limits seem to play at least some part in cross-modal failures of awareness. If central capacity limits indeed drive cross-modal failures of awareness, we might expect working memory capacity to predict whether or not a person would notice an unexpected object. Yet, as in several previous studies (Bredemeier & Simons, 2012; Kreitz, Furley, et al., 2015), we found little evidence for such a relationship. This lack of a relationship under conditions that should be optimal for detecting one suggests that if such a relationship does exist, it likely is fragile or highly dependent on the specifics of the experiment or sample population (Bredemeier & Simons, 2012; Calvillo & Jackson, 2014; Seegmiller et al., 2011).

Finally, we twice replicated previous evidence (Bredemeier & Simons, 2012; Simons & Jensen, 2009) that a higher ability to perform the primary attention-demanding task does not increase the likelihood of noticing an unexpected object. In Study 1, better performance on the visual task surprisingly predicted slightly reduced likelihood of noticing the unexpected tone. That pattern might be consistent with greater motivation to perform the task rather than greater ability to do so, but given the weight of prior evidence and the lack of such an association in Study 2, it most likely was spurious. Consistent with earlier work, while task difficulty does influence the probability of failures of awareness (Cartwright-Finch & Lavie, 2007; Simons & Chabris, 1999), individual differences in the ability to meet those demands do not (Bredemeier & Simons, 2012; Simons & Jensen, 2009; see Raveh & Lavie, 2014 for different results with expected but unattended stimuli).

Cross-modal failures of awareness have potentially important consequences for alerting in daily life. If visual and auditory tasks draw on shared attention resources, then any demands on one modality may decrease noticing of unexpected events in another modality. For example, both drivers (Strayer & Drews, 2007) and pedestrians (Hyman et al., 2010) are more likely to miss unexpected visual events when talking on a phone. And, pilots in a flight simulator failed to detect a critical auditory alert during a demanding scenario (Dehais et al., 2013). Our results extend this earlier work by showing how cross-modal attention may limit the ability to detect unexpected events, even when participants are doing nothing in that other modality. Consequently, using cross-modal alerts may not be a panacea for the limits of awareness.

4.1. Limitations of the current study

In Study 1, participants listened to white noise through each trial. Although the white noise was task irrelevant, participants might have established an attention set to actively ignore all auditory information, making them less likely to notice the unexpected tone. Yet, previous research found little difference in noticing rates and effects of experimental manipulations for conditions with and without such noise (Macdonald & Lavie, 2011; Raveh & Lavie, 2014). And, in Study 2, many participants failed to notice an unexpected visual stimulus even in the absence of any visual information on screen other than a fixation cross.

Although we tested a sizable sample of college students, our individual-difference findings might not generalize to the broader population. To the extent that a relationship between noticing and cognitive abilities exists, it might be limited to a subset of the broader population that is not represented well in our sample (e.g., older participant: Graham & Burke, 2011; see Bredemeier & Simons, 2012 for discussion).

Finally, our studies measured failures of awareness for briefly presented unexpected stimuli (Macdonald & Lavie, 2011; Mack & Rock, 1998), and the pattern might not hold for sustained and dynamic unexpected objects or events if these effects are specific to the nature of the task (Kreitz, Furley, et al., 2015).

4.2. Conclusion

Failures of awareness occur not only when people allocate attention to another task in the same modality, but also when they devote attention to a task in a different modality. Although these failures presumably occur due to central resource limitations rather than modality-specific ones, noticing was largely unrelated to individual differences in working memory capacity or in the ability to meet the demands of the primary task.

Author contributions

Conceived and designed the experiment: CK PF DJS DM. Performed the experiment: CK. Analyzed the data: CK. Wrote the manuscript: CK PF DJS DM.

Ethical statement

All participants gave their informed consent prior to their inclusion in the study and were debriefed afterward. The work conforms to Standard 8 of the American Psychological Association's Ethical Principles of Psychologist and Code of Conduct.

Author note

The design and analysis plan for this study were pre-registered, and all plans and data are available at https://osf.io/hw8er and https://osf.io/cf4ed/.

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References

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control. *Acta Psychologica, 129*(3), 387–398. http://dx.doi.org/10.1016/j.actpsy.2008.09.005.

Bredemeier, K., Hur, J., Berenbaum, H., Heller, W., & Simons, D. J. (2014). Individual differences in emotional distress and susceptibility to inattentional blindness. *Psychology of Consciousness: Theory, Research, and Practice, 1*(4), 370–386. http://dx.doi.org/10.1037/cns0000032.

Bredemeier, K., & Simons, D. J. (2012). Working memory and inattentional blindness. *Psychonomic Bulletin & Review, 19*(2), 239–244. http://dx.doi.org/10.3758/s13423-011-0204-8.

Calvillo, D. P., & Jackson, R. E. (2014). Animacy, perceptual load, and inattentional blindness. *Psychonomic Bulletin & Review, 21*, 670–675. http://dx.doi.org/10.3758/s13423-013-0543-8.

Cartwright-Finch, U., & Lavie, N. (2007). The role of perceptual load in inattentional blindness. *Cognition, 102*(3), 321–340. http://dx.doi.org/10.1016/j.cognition.2006.01.002.

Chabris, C. F., Weinberger, A., Fontaine, M., & Simons, D. J. (2011). You do not talk about Fight Club if you do not notice Fight Club: Inattentional blindness for a simulated real-world assault. *I-Perception, 2*(2), 150–153. http://dx.doi.org/10.1068/i0436.

Cumming, G. (2012). *Understanding the new statistics. Effect sizes, confidence intervals, and meta-analysis*. New York: Routledge.

Cumming, G. (2014). The new statistics: Why and how. *Psychological Science, 25*(1), 7–29. http://dx.doi.org/10.1177/0956797613504966.

Dalton, P., & Fraenkel, N. (2012). Gorillas we have missed: Sustained inattentional deafness for dynamic events. *Cognition, 124*(3), 367–372. http://dx.doi.org/10.1016/j.cognition.2012.05.012.

Dehais, F., Causse, M., Vachon, F., Regis, N., Menant, E., & Tremblay, S. (2013). Failure to detect critical auditory alerts in the cockpit: Evidence for inattentional deafness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*. http://dx.doi.org/10.1177/0018720813510735.

Drew, T., Vo, M. L. H., & Wolfe, J. M. (2013). The invisible gorilla strikes again: Sustained inattentional blindness in expert observers. *Psychological Science, 24*(9), 1848–1853. http://dx.doi.org/10.1177/0956797613479386.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18*(4), 1030.

Fougnie, D., & Marois, R. (2007). Executive working memory load induces inattentional blindness. *Psychonomic Bulletin & Review, 14*(1), 142–147. http://dx.doi.org/10.3758/BF03194041.

Giraudet, L., St-Louis, M.-E., Scannella, S., & Causse, M. (2015). P300 event-related potential as an indicator of inattentional deafness? *PLoS One, 10*(2), e0118556. http://dx.doi.org/10.1371/journal.pone.0118556.g006.

Graham, E. R., & Burke, D. M. (2011). Aging increases inattentional blindness to the gorilla in our midst. *Psychology and Aging, 26*(1), 162–166.

Haines, R. F. (1991). A breakdown in simultaneous information processing. In G. Obrecht & L. W. Stark (Eds.), *Presbyopia research: From molecular biology to visual adaptation* (pp. 171–175). New York: Plenum.

Hannon, E. M., & Richards, A. (2010). Is inattentional blindness related to individual differences in visual working memory capacity or executive control functioning? *Perception, 39*(3), 309–319. http://dx.doi.org/10.1068/p6379.

Hyman, I. E., Jr, Boss, S. M., Wise, B. M., McKenzie, K. E., & Caggiano, J. M. (2010). Did you see the unicycling clown? Inattentional blindness while walking and talking on a cell phone. *Applied Cognitive Psychology, 24*(5), 597–607. http://dx.doi.org/10.1002/acp.1638.

Kane, M. J., Conway, A. R. A., Miura, T. K., & Colflesh, G. J. (2007). Working memory, attention control, and the n-back task: A question of construct validity. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 33*(3), 615–622. http://dx.doi.org/10.1037/0278-7393.33.3.615.

Koreimann, S., Gula, B., & Vitouch, O. (2014). Inattentional deafness in music. *Psychological Research Psychologische Forschung, 78*(3), 304–312. http://dx.doi.org/10.1007/s00426-014-0552-x.

Kreitz, C., Furley, P., Memmert, D., & Simons, D. J. (2015a). Inattentional blindness and individual differences in cognitive abilities. *PLoS One, 10*(8), e0134675. http://dx.doi.org/10.1371/journal.pone.0134675.

Kreitz, C., Schnuerch, R., Gibbons, H., & Memmert, D. (2015b). Some see it, some don't: Exploring the relation between inattentional blindness and personality factors. *PLoS One, 10*(5), e0128158. http://dx.doi.org/10.1371/journal.pone.0128158.
Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *The Journal of the Acoustical Society of America, 49*, 467.
Macdonald, J. S. P., & Lavie, N. (2011). Visual perceptual load induces inattentional deafness. *Attention, Perception, & Psychophysics, 73*(6), 1780–1789. http://dx.doi.org/10.3758/s13414-011-0144-4.
Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge: MIT Press.
Memmert, D., & Furley, P. (2007). "I spy with my little eye!": Breadth of attention, inattentional blindness, and tactical decision making in team sports. *Journal of Sport & Exercise Psychology, 29*. 365–347.
Most, S. B. (2010). What's "inattentional" about inattentional blindness? *Consciousness and Cognition, 19*(4), 1102–1104. http://dx.doi.org/10.1016/j.concog.2010.01.011.
Most, S. B., Chun, M. M., Widders, D. M., & Zald, D. H. (2005). Attentional rubbernecking: Cognitive control and personality in emotion-induced blindness. *Psychonomic Bulletin & Review, 12*(4), 654–661.
Most, S. B., Simons, D. J., Scholl, B. J., & Chabris, C. F. (2000). Sustained inattentional blindness: The role of location in the detection of unexpected dynamic events. *Psyche, 6*, 14.
Most, S. B., Simons, D. J., Scholl, B. J., Jimenez, R., Clifford, E., & Chabris, C. F. (2001). How not to be seen: The contribution of similarity and selective ignoring to sustained inattentional blindness. *Psychological Science, 12*(1), 9–17. http://dx.doi.org/10.1111/1467-9280.00303.
Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology, 7*, 480–494. http://dx.doi.org/10.1016/0010-0285(75)90019-5.
Neisser, U. (1979). The control of information pickup in selective looking. In A. D. Pick (Ed.), *Perception and its development: A tribute to Eleanore J Gibson* (pp. 201–219). New York: Hillsdale.
Newby, E. A., & Rock, I. (1998). Inattentional blindness as a function of proximity to the focus of attention. *Perception, 27*, 1025–1040.
Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping, 25*(1), 46–59. http://dx.doi.org/10.1002/hbm.20131.
Pizzighello, S., & Bressan, P. (2008). Auditory attention causes visual inattentional blindness. *Perception, 37*(6), 859.
Raveh, D., & Lavie, N. (2014). Load-induced inattentional deafness. *Attention, Perception, & Psychophysics.*. http://dx.doi.org/10.3758/s13414-014-0776-2.
Redick, T. S., & Lindsey, D. R. B. (2013). Complex span and n-back measures of working memory: A meta-analysis. *Psychonomic Bulletin & Review, 20*(6), 1102–1113. http://dx.doi.org/10.3758/s13423-013-0453-9.
Richards, A., Hannon, E. M., & Derakshan, N. (2010). Predicting and manipulating the incidence of inattentional blindness. *Psychological Research Psychologische Forschung, 74*(6), 513–523. http://dx.doi.org/10.1007/s00426-009-0273-8.
Richards, A., Hellgren, M. G., & French, C. C. (2014). Inattentional blindness, absorption, working memory capacity and paranormal belief. *Psychology of Consciousness: Theory, Research, and Practice, 1*(1), 60–69. http://dx.doi.org/10.1037/css0000003.
Seegmiller, J. K., Watson, J. M., & Strayer, D. L. (2011). Individual differences in susceptibility to inattentional blindness. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 37*(3), 785–791. http://dx.doi.org/10.1037/a0022474.
Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28*(9), 1059–1074.
Simons, D. J., & Jensen, M. S. (2009). The effects of individual differences and task difficulty on inattentional blindness. *Psychonomic Bulletin & Review, 16*(2), 398–403. http://dx.doi.org/10.3758/PBR.16.2.398.
Sinnett, S., Costa, A., & Soto-Faraco, S. (2006). Manipulating inattentional blindness within and across sensory modalities. *The Quarterly Journal of Experimental Psychology, 59*(8), 1425–1442. http://dx.doi.org/10.1080/17470210500298948.
Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General, 117*(1), 34.
Strayer, D. L., & Drews, F. A. (2007). Cell-phone induced driver distraction. *Current Directions in Psychological Science, 16*(3), 128–131. http://dx.doi.org/10.1111/j.1467-8721.2007.00489.x.
Tellegen, A., & Atkinson, G. (1974). Openness to absorbing and self-altering experiences (absorption), a trait related to hypnotic susceptibility. *Journal of Abnormal Psychology, 83*(3), 268–277.
Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods, 37*(3), 498–505.
Wayand, J. F., Levin, D. T., & Varakin, A. (2005). Inattentional blindness for a noxious multimodal stimulus. *The American Journal of Psychology, 118*(3), 339–352.