Distraction and the auditory attentional blink

János Horváth · Annamária Burgyán

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Abstract When two target stimuli (T1 and T2) are presented in close succession within a stimulus sequence, detection or discrimination performance for T2 is often impaired; this phenomenon is called the *attentional blink* (AB). Growing evidence suggests that the AB is present not only for visual, but also for auditory stimuli. Because sounds have a strong potential to attract attention when they are presented after longer silent intervals or in a sequence from which they stand out because of their rare or novel physical features, it seems possible that the involuntary and excessive allocation of attention to T1 (distraction) may contribute to the AB. By varying the saliency of T1, we showed that distraction does contribute to the auditory AB effect, but the contribution is short-lived: Only stimuli immediately following T1 are affected.

Keywords Attention · Attentional blink · Orienting · Distraction · Audition · Stimulus-driven · Saliency

Introduction

When two target stimuli (the first target [T1] and the second target [T2]) are presented in close succession within a stimulus sequence providing masking, detection or discrimination performance for T2 is often impaired; this phenomenon is called the *attentional blink* (AB). Whereas

numerous studies have investigated the AB in the visual domain (for a recent review, see Dux & Marois, 2009), relatively few studies have addressed whether the AB is also present in other modalities. In the auditory domain, results resembling those obtained in visual paradigms have been reported by a number of studies (e.g., Duncan, Martens, & Ward, 1997; Mondor, 1998; Shen & Mondor, 2008; Vachon & Tremblay, 2008; Van der Burg, Olivers, Bronkhorst, Koelewijn, & Theeuwes, 2007). Whereas the AB is probably the sum of different effects (Dux & Marois, 2009), most explanations of the AB have been based on the assumption that AB is caused by interference from the voluntary, task-relevant processing of T1. In the present study, we investigated, in an auditory paradigm, whether (auditory) AB was caused (at least in part) by the exogenous, saliency-dependent allocation of attentional resources to T1.

It is well known that auditory stimuli attract attention depending on their context. Notably, sounds presented after longer silent periods or those that stand out from a series of sounds because of their rare or novel physical features or because they violate a temporal regularity of the sequence have a strong potential to draw attention to themselves (see, e.g., Cherry, 1953; Näätänen, 1990; Schröger, 1997). The processes leading to exogenous auditory attention capture have been extensively studied with the event-related potential (ERP) technique. Briefly summarized, this line of research provides evidence that incoming sounds are processed by a sensory filter, which “absorbs” predictable stimuli; that is, the sensory filter processes sounds fitting the given auditory context without involving attentional, capacity-limited resources. Infrequent, temporally unpredictable sensory events, on the other hand, lead to the allocation of attentional resources to the processing of the event (for a summary, see, e.g., Escera & Corral, 2007; Rinne, Särkkä, Degerman, Schröger, & Alho, 2006). This

J. Horváth (✉)
Institute for Psychology, Hungarian Academy of Sciences,
Szondi u. 83/85, P.O.B. 398, Budapest 1394, Hungary
e-mail: horvath@cogpsyphy.hu

A. Burgyán
Faculty of Education and Psychology, Eötvös Loránd University,
Budapest, Hungary

stimulus-driven attention capture mechanism is also active in situations in which the stimuli are attended: Task-irrelevant sounds or task-relevant sounds with rare task-irrelevant feature variations also initiate a change in the attentional state that is detrimental to the task-relevant processing; that is, we get *distracted* (see, e.g., Horváth, Winkler, & Bendixen, 2008; Roeber, Widmann, & Schröger, 2003; Schröger & Wolff, 1998). It has been shown that the distracted state persists for at least 150 ms after the triggering event: When a task-relevant auditory event is closely (by 150 ms) preceded by a rare, salient, but task-irrelevant sound event, the N1 ERP (for a review, see Näätänen & Picton, 1987) elicited by the task-relevant event is reduced, suggesting that after the salient event, the allocation of input attention becomes temporarily suboptimal for the processing of the task-relevant event (Horváth & Winkler, 2010). Although the attentional changes can be suppressed if rare sounds are cued just before their delivery, only processes upstream from the sensory filter are affected by *direct* preparatory activities (Sussman, Winkler, & Schröger, 2003). It has to be noted that top-down influences can affect the sensory filter in *indirect* ways: Sussman, Winkler, Huotilainen, Ritter, and Näätänen (2002) showed that if the auditory input has a temporal structure that is difficult to find at first hearing, supplying information on the “hidden” structure leads to the reorganization of the auditory input into a predictable pattern, in which previously outstanding tones become a natural part of a longer repeating pattern and, therefore, no longer stand out. In summary, the auditory system automatically provides a signal that “highlights” auditory events that stand out from the established stimulus context. It seems plausible that tasks involving the detection of outstanding sounds rely on this signal and the mechanisms triggering the allocation of attention to such sounds.

The situations in which auditory distraction occurs cover most setups in which a robust auditory AB can be observed (see the references above). Setups in which stimuli do not allow for the establishment of a more-or-less regular or homogeneous auditory context, in which target status cannot be determined on the basis of primary physical feature differences (e.g., detecting various spoken digits in a mixture of various spoken letters), generally do not produce a robust auditory AB (Arnell & Jenkins, 2004; Koelewijn, Van der Burg, Bronkhorst, & Theeuwes, 2008; Potter, Chun, Banks, & Muckenhoupt, 1998; but see Tremblay, Vachon, & Jones, 2005, Experiment 3; Martens, Johnson, Bolle, & Borst, 2009, Experiment 2). In the design most commonly used to elicit a robust AB, the two targets are presented among many nontarget stimuli in the context of short stimulus sequences. Because the sequence of nontargets preceding the targets establishes a stimulus context from which targets stand out, the sensory filter

described above automatically “highlights” these sounds, which leads to an excessive allocation of attention to these targets. Therefore, it seems possible that AB effects found in similar setups are, at least in part, due to this bottom-up mechanism triggered by T1. Because distraction effects generally increase with the saliency of the rare sound (see, e.g., Berti, Roeber, & Schröger, 2004; Escera, Yago, & Alho, 2001; Yago, Corral, & Escera, 2001), we assessed the effect of distraction by manipulating the magnitude of T1 saliency in relation to nontarget tones. We hypothesized that AB effects should be larger for higher T1 saliency. Closely following the design used by Vachon and Tremblay (2005), we used detection tasks: T1 was a tone separated by its tonal frequency from nontargets, whereas T2 was a complex tone comprising components in the frequency range of the nontarget tones.

Experiment 1

Method

Eighteen paid volunteers (ten of them female; age 19–25 years) reporting normal hearing status participated in Experiment 1. All the participants gave written informed consent after the experimental procedures were explained to them. The participants were seated in a comfortable chair in a sound-attenuated room during the experiment. Sounds were presented through a headphone (HD-600, Sennheiser, Germany). The intensity level of the stimuli was individually adjusted to a 40-dB sensation level (above hearing threshold level).

Three types of tones were presented. *Nontarget* sounds were sinusoid tones with random frequencies in the 440–1760 Hz range in 1-semitone (ST) steps. *T1s* were sinusoid tones with frequencies of 3951 and 2960 Hz (14 and 9 ST higher than the highest nontarget tone); these are referred to as *14ST-T1* and *9ST-T1*, respectively, in the following. *T2* was a complex tone with three sinusoid components, separated by +7 and +12 ST, as compared with the lowest component (with relative intensities of –12 and –24 dB, respectively). The frequency of the lowest T2 component was random in the range of 440–880 Hz, with 1-ST steps. The signal energy of T2 was the same as that of the nontarget tones. The duration of the tones was 30 ms (including 2.5-/2.5-ms linear rise/fall times).

On each trial, a sequence of tones was presented. The sequences (see Fig. 1) started with 7–15 nontarget tones (randomly, with uniform distribution). T1 could be delivered in the position following this initial sequence. T2 could be delivered in the next (lag 1), the third (lag 3), or the 7th (lag 7) position after T1. The positions between T1 and T2 positions were filled with nontarget tones. When no

Fig. 1 The schematic temporal structure of the tone sequences presented on each trial in both experiments. Target stimuli (T1 and T2) are presented in gray. T1s were pure tone stimuli separated by 9 or 14 semitones (9ST-T1 and 14ST-T1) from the frequency range of the standard tones (S), whereas T2s were complex tones with components fully within the frequency range of the standard tones

T1 or T2 was delivered in a given position, a nontarget tone was presented instead. The sequence was concluded by 5–7 nontarget tones (randomly, with uniform distribution). The onset-to-onset interstimulus interval was 90 ms.

The participants' task was to report specifically whether they had heard a T1 ("high") or T2 ("complex") in the sequence; they were informed that it was possible to hear both T1 and T2, only T1, only T2, or neither of them. The discrimination of the two types of T1s was not part of the task. Participants were also asked to report what they had heard and to refrain from guessing. The experimenter started the next trial after the report. No feedback about the accuracy of the reports was provided.

There were ten different types of trials/sequences. Unknown to the participants, nine of these contained a T2 and resulted from the permutations of the T1 stimulus (14ST-T1 present, 9ST-T1 present, or no T1 present) and lag (1, 3, or 7) factors. The tenth type of sequence—the catch trial—contained neither T1 nor T2. (That is, overall, six of the ten sequence types contained a T1.) The presentation of catch trials was necessary because, in this arrangement, some participants might discover that T2 was present on most trials (90%), which might lead to reports that reflect this knowledge, and not the participants' percept regarding T2. If a participant reported the presence of T2 on a high proportion of catch trials, it would indicate that responses were based not on the actual percept, but on guessing or response bias. Each experimental block contained two of each type of trial, which were presented in random order, for a total of 20 trials per block. Overall, 20 blocks were presented, separated by short breaks as needed, for 40 instances of each trial/sequence type during the experiment.

Before the experiment, participants were familiarized with the stimulus material and target events. First, 20 sequences containing a single 9ST-T1 with 50% probability were presented. If the participant had difficulty in discriminating sequences with T1 presence and absence, sequences containing a single 14ST-T1 with 50% probability were

presented. This was sufficient in all cases to demonstrate the difference between the T1 and the standards, and it was followed by training with sequences containing a single 9ST-T1 with 50% probability (one to three blocks of 20 sequences). To demonstrate the difference between pure and complex tones, a six-element alternating sequence of single pure and complex tones was presented, which was followed by a random sequence of pure and complex tones (50%–50%), for which participants had to report whether they heard a pure or a complex tone. Then one to three blocks of 20 sequences containing a single T2 with 50% probability were presented.

Hit rates for T2 on those trials on which the presence or absence of a T1 was correctly detected were submitted to a stimulus (14ST-T1, 9ST-T1, no T1) $\times$ lag (1, 3, 7) repeated measures analysis of variance (ANOVA). Similarly, hit rates for T1 on those trials on which the presence of T2 was correctly detected were submitted to a stimulus (14ST-T1 and 9ST-T1) $\times$ lag (1, 3, 7) repeated measures ANOVA. Greenhouse–Geisser correction was applied as appropriate. Partial eta-squared values are reported. All significant effects are reported.

Results and discussion

The mean correct response rate (or correct rejection rate) combined for T1 and T2 for catch trials (on which neither T1 nor T2 was present) was $97\% \pm 1\%$ (range: 85%–100%). False alarms on catch trials resulted from the report of either T1 ($2\% \pm 3\%$; range: 0.0%–7.5%) or T2 ($1\% \pm 2\%$; range: 0%–7.5%), but not both. This suggests that participants generally refrained from guessing the presence of targets; therefore, no participant's data were rejected from the analyses.

The ANOVA of the hit rates for T2 on the trials on which the presence or absence of T1 was correctly reported (see Fig. 2), showed a stimulus main effect, $F(2, 34) = 74.57$, $\varepsilon = .67$, $\eta_p = .81$, $p < .001$, a lag main effect, $F(2, 34) = 51.87$, $\varepsilon = .95$, $\eta_p = .75$, $p < .001$, and a

Fig. 2 Mean T2 detection hit rates, with standard errors, for those trials on which the presence or absence of T1 was correctly reported in Experiment 1

stimulus $\times$ lag interaction, $F(4, 68) = 26.03$, $\varepsilon = .59$, $\eta_p = .62$, $p < .001$. A Tukey HSD test showed that hit rates increased significantly with increasing lag for the 14ST-T1 and 9ST-T1 trials ($p < .001$), but no significant difference was found for the no-T1 trials. At lag 1, all three hit rates differed significantly ($p < .001$). At lag 3, hit rate was higher on no-T1 trials, as compared with the other two trial types ($p < .001$). At lag 7, hit rate was higher on no-T1 than on 9ST-T1 trials ($p < .05$).

The ANOVA of the hit rates for the detection of T1 on trials on which T2 was present and its presence was correctly reported (see Fig. 3) showed a stimulus main effect, $F(1, 17) = 20.55$, $\eta_p = .55$, $p < .001$, showing that the detection of 9ST-T1 was more difficult than that of the 14ST-T1. There was also a lag main effect, $F(2, 34) = 12.66$, $\varepsilon = .56$, $\eta_p = .43$, $p < .001$. A Tukey HSD test showed that hit rate was significantly lower for lag 1, than for lag 3 or 7 ($p < .001$).

Fig. 3 Mean T1 detection hit rates, with standard errors, for those trials on which T2 was present and successfully detected in Experiment 1

Experiment 1 successfully replicated the general AB findings from previous studies: Following T1, the T2 detection deficit was present at short lags, but it diminished with longer lags (Fig. 2). Importantly, the results indicate that there are at least two effects involved in the generation of AB in the present paradigm. The first is dependent on the saliency of the T1 stimulus in the context of the nontarget sequence and is relatively short-lived: The modulatory effect of saliency was present only for the immediately following T2, but not for T2s at lag 3 or lag 7. This saliency-dependent effect cannot be explained by forward masking: Because the effect of forward masking should be larger when the mask and the following tone are closer in their frequencies, forward masking should produce just the opposite of what was observed (i.e., the 9ST-T1 should mask T2 more effectively than should the 14ST-T1). Note that the results show an interference between the two types of targets in those trains where T2 was presented immediately after T1, as compared with the other two lags (see Fig. 3). This interference effect, however, did not significantly differ between the levels of T1 saliency.

Whereas T1 saliency modulated T2 detection performance at lag 1, this modulation was no longer observed at lag 3, which suggests that there was a second, non-saliency-dependent effect, which was present after both T1s for a longer period of time, that is commensurate to the duration of the auditory AB observed in previous studies.

Although the results of Experiment 1 are in line with the assumption that stimulus-driven bottom-up attention capture mechanisms (distraction) contribute to auditory AB, it could be still argued that the short-lived saliency-dependent effect is brought about by the *task relevancy* of the T1 stimuli, and not by their saliency per se. To investigate this possibility, we conducted Experiment 2, in which participants performed only the complex tone (“T2”) detection task and were not informed about the presence of the higher-frequency pure tones (“T1”).

Experiment 2

Method

Eighteen paid volunteers (11 of them female; age 18–26 years) reporting normal hearing status participated in Experiment 2. None of them had participated in Experiment 1. All the participants gave written informed consent after the experimental procedures were explained to them. The experimental procedures were identical to those in Experiment 1, except for the instructions, in which the high pure tones (T1s in Experiment 1) were not mentioned at all; also, only the familiarization procedure with the complex tones was carried out. Participants were instructed to report after

each sequence whether they had heard a complex tone in the sequence or not. Although only the complex tone was task relevant in [Experiment 2](#), for the sake of simplicity, we refer to the salient high-frequency tones as T1s and to the complex target tone as T2 in the following.

Results and discussion

One participant's data were excluded from the analyses because the correct rejection rate on the catch trials (on which neither T1 nor T2 was present) was only 60%, which suggests guessing or response bias. The remaining 17 participants' mean correct response rate on the catch trials was $96\% \pm 1\%$ (range: 85%–100%).

The ANOVA of the hit rates for T2 (see Fig. 4), showed a stimulus main effect, $F(2, 32) = 42.77$, $\varepsilon = .72$, $\eta_p = .73$, $p < .001$, a lag main effect, $F(2, 32) = 50.52$, $\varepsilon = .76$, $\eta_p = .75$, $p < .001$, and a stimulus $\times$ lag interaction, $F(4, 64) = 18.24$, $\varepsilon = .82$, $\eta_p = .53$, $p < .001$. A Tukey HSD test showed that hit rates increased significantly with increasing lag for the 14ST-T1 trials ($ps < .001$). For the 9ST-T1 trials, the hit rate was higher at lag 3 and lag 7 than at lag 1 ($ps < .001$), but no significant difference was found between lag 3 and lag 7 trials. There were no significant differences between no-T1 trials. At lag 1 and lag 3, all three hit rates differed significantly ($ps < .001$ at lag 1, and $ps < .05$ at lag 3). At lag 7, no significant differences were found.

These results show that the detectability of the complex target tones decreased when they were closely preceded by salient tones, even if the salient tones were task irrelevant; this effect was present at lags 1 and 3. Moreover, this effect was modulated by T1 saliency: T2s following more salient T1s were less easily detectable. Although this pattern is very similar to that obtained in [Experiment 1](#), there is also a difference: In [Experiment 1](#), T1 saliency modulated T2 detectability only at lag 1, but not at lag 3. A plausible

explanation for this difference is that in the dual detection task situation, explicit knowledge about salient T1s and their task relevancy may have enabled participants to temporally constrain the T1-saliency-related attentional effect, whereas in [Experiment 2](#), this was not possible.

General discussion

The present study investigated the role of stimulus-driven attention capture (distraction) in the prototypical paradigm used to elicit a robust auditory AB. The results show that salient tones embedded in a tone sequence draw attentional resources away from the processing of closely following stimuli, even if the salient tones are task irrelevant.

Although input attention was drawn away by a salient tone, attention was essentially restored by about 270 ms from the onset of the distracting tone (lag 3) when salient tones were task relevant ([Experiment 1](#)). On the other hand, when salient tones were task irrelevant, T2 detection performance was still modulated by T1 saliency at lag 3 ([Experiment 2](#)). The lack of a similar modulation at lag 3 in [Experiment 1](#) suggests that explicit instructions regarding T1 may enable participants to form a more structured percept of the target sounds within the sequence. Nonetheless, this hypothetical structuring effort has its limits: T1 saliency still modulated T2 performance at lag 1 in [Experiment 1](#).

When the dual detection task was performed ([Experiment 1](#)), T2 detection rate was decreased by preceding T1s at lag 3, but no saliency modulation was observed. This suggests that a further, non-saliency-dependent effect was also present in this experiment. Because of its longer-lasting effect, commensurate with the duration of AB effects observed in previous studies, this effect is probably the AB effect brought about by having to perform two acts of target detection in a row in a short period of time. That is, the present study demonstrates that distraction triggered by salient stimuli may well overlap a “genuine” AB effect.

Whereas the distraction effect triggered by T1 is apparently not sufficient to fully explain AB in the auditory modality, it may explain why *lag 1 sparing*—that is, a lack of performance deficit in the position immediately following T1 (Potter et al., 1998)—might not be as easily observable in auditory AB studies as in visual paradigms (see, e.g., Arnell & Jenkins, 2004). In the visual modality, lag 1 sparing is generally explained by assuming that the detection of T1 leads to transient attentional enhancement, which improves performance for a closely following T2 (Nieuwenstein, Van der Burg, Theeuwes, Wyble, & Potter, 2009). This effect, however, seems to be constrained to visual paradigms in which exogenous attention capture by T1 does not occur. In setups with salient, task-irrelevant

Fig. 4 Mean T2 detection hit rates, with standard errors, in [Experiment 2](#)

T1s, a short-lived AB with no lag 1 sparing can also be observed (Spalek, Falcon, & Di Lollo, 2006, Experiment 4) that is similar to that measured in the present auditory paradigm. It seems that in the auditory modality, the transient attentional change triggered by a salient target impacts performance for closely following stimuli. Indeed, because T1 saliency affected the T2 detection deficit at lag 1 in the present experiments, it is possible that the deficit at this position was caused exclusively by the T1-saliency-dependent effect. This interpretation is in line with the results of a between-experiments comparison of T2 detection performance for lag 1 (one-way ANOVA with experiment as a between-subjects and lag as a within-subjects factor), which showed no significant effects including the experiment factor.

We started out with an observation about the auditory AB literature, suggesting that whereas a robust auditory AB can be found mostly in experiments utilizing a salient T1, studies using paradigms with nonsalient T1s generally do not produce a robust auditory AB. There are, however, some counterexamples: Tremblay et al. (2005, Experiment 3) and Martens et al. (2009, Experiment 2) presented target syllables within a mixture of different syllables and found marked AB effects. A speculative explanation accommodating these two findings is based on the fact that, in both experiments, T1 was presented at a *fixed* position within the stimulus sequences. Because of this, participants may have “focused” their attention on this temporal position (Nobre, Correa, & Coull, 2007). This hypothetical voluntary mobilization of attentional resources is similar to the saliency-related attentional change, in the sense that both “highlight” T1 or the T1 position relative to nontargets. Note that this selective mobilization is not related to the evaluation of T1 in task-related terms per se (i.e., whether it is a target or a nontarget); rather, it is related to the circumstances of its presentation (its saliency in one case and an attentional strategy, based on its temporal predictability, in the other case). Therefore, we suggest that the (voluntary or involuntary) mobilization of attentional resources enhancing T1, relative to the nontargets, may be a necessary condition for the elicitation of the auditory AB. Whereas this may be a *necessary* condition, it does not seem to be *sufficient*: A number of studies have shown that auditory AB does not occur (even when T1 is salient) when T2 is followed very closely (10 ms) or only after a relatively long delay (350 ms or more) by nontarget tones (Shen & Mondor, 2006; Vachon & Tremblay, 2005, 2006).

In summary, the present experiments showed that in the prototypical auditory paradigm used to elicit a robust AB, salient T1 stimuli bring about two overlapping effects, both of which impair T2 task performance: They trigger a T1-saliency-dependent, short-lived distraction effect and a

longer lasting “genuine” AB (caused by having to perform two tasks in close succession).

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