SURPRISE-INDUCED DEAFNESS – TEMPORAL CHARACTERISTICS OF A STIMULUS-DRIVEN LIMITATION IN AUDITORY SELECTIVE ATTENTION

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A THESIS SUBMITTED
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PSYCHOLOGY FACULTY OF ARTS AND SOCIAL SCIENCES

NATIONAL UNIVERSITY OF SINGAPORE

2016

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DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in this thesis.

This thesis has also not been submitted for any degree in any university previously.

Takashi Obana

15 August 2016

Acknowledgements

I have been through many challenges in my life but the PhD journey was the most intense and longest one for me. I would never have gotten this far if it were not for many truly sincere kind souls I had fortunate encounter with. First, I would like to thank three persons who were directly involved in this project – Stephen, Chris, and Yushi.

I would like to thank Stephen – my supervisor – for making everything possible. He took a great risk to embark with me on the insane journey aiming to finish the whole PhD in 2 years which eventually turned out to be 1.5 years! On a personal level, Stephen changed how I perceive myself. I learned that I work so much better under supportive, encouraging, and trusting boss rather than the other way around. Above all, I deeply thank him for being a great friend since the day my PhD started!

I would never have acquired the strongest force to paddle the boat forward if it were not for Chris – my co-supervisor! I cannot thank him enough for the very close, sincere, encouraging, highly intellectual, and precise supervision. It was an honor and great privilege to have had – and will have – literally hundreds of e-mail correspondences. The countless skills and knowledge he taught me will definitely be treasures of my life. Furthermore, above all, I had a fortunate occasion to witness a person whom Abraham Maslow will call “self-actualized”.

I thank Yushi and Sze Chi – my research cum personal assistants – for always giving me generous help whenever I needed to do labor-intensive jobs! Yushi always checked on me whether I am still alive and her warmth was tremendously therapeutic for me. Sze Chi’s knowledge about programming helped me solve some of the persistent problems.

I thank Dr. Chua and Dr. Penney for their extremely thorough and rigorous supports to improve my thesis. They have taught me a lifelong lesson to think logically and convey the idea clearly. I am sure that I will treasure this lesson for the rest of my life.

On top of sincere supports on the content of my research, I was extremely fortunate to get substantial help from the Department of Psychology and Faculty of Arts and Social Sciences. I truly thank Dr. Sim Tick Ngee, Dr. Melvin Yap, Dr. Ryan Hong, Dr. Bruce Lockhart, Dr. Shirlena Huang, and Ms. Pearly Ang. Their empathy was, without any doubt, the foundation of me continuing to do rigorous research.

I thank everyone in the Cognition and Education lab for sparing precious time reviewing the nature of my research.

I also thank everyone in SINAPSE for their empathetic supports and encouragements. Gwen, thank you so much for your continuous warm care and matcha milk candies! Vedanta, your English lesson will forever stay with me. Tiffany, your rigorous Python code will forever stay with us! Esther, I'm glad that we both survived PhD and Multivariate!

I thank my friend Egor to have enlightened me in so many ways. I am grateful for the continuous encouragement from Tetsuyasu, Tomonori, Jimmy, and Patrick.

I also thank gangs from Vintage Dog, Gombo Rhythm, The B.B. Boogie, Subway 35, and Skunk Jive. We will keep rocking and rolling.

I must be one of the most fortunate guy to have been brought up by an extremely loving family. I am grateful to my father, mother, and sister for instilling me both samurai bushido and zen spirit.

To my small bird Mimo. I thank you for your faith in me and for every positive change that I went through.

To Hayashi-san, who taught me the importance of self-reliance. The way you lived will continue to nurture our souls. We are all still grateful to have been your apprentices.

To Megumi, who taught me how to live. I will never forget our correspondences. Thank you for sharing your life with me.

To Takaki, who always spiritually supported me no matter what, I remember you every day. You taught me how to burn my life and fight with our enemies. I always miss you.

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SUMMARY

Organisms are inherently sensitive to unusual sound in the environment since hearing serves as an “early warning system”. Although this is an adaptive function for survival, the evaluation of such sound depletes the capacity limited cognitive resource and makes one susceptible to miss processing the task-relevant sound. This thesis focused on the temporal characteristics of such phenomenon and established a new paradigm named surprise-induced deafness (SiD). Four main experiments have revealed that participants indeed showed tendency to miss the task-relevant sound presented in rapid auditory stream (RAP) when they were distracted by task-irrelevant, unexpected sound. On the other hand, participants showed habituation to the surprise stimulus (SS) and such deficit disappeared quickly. The deficit as well as the habituation were most clearly observable when the SS was presented 360 ms before the designated target. The experiments also revealed that the habituation rate and magnitude of deficit were modulated by varying the content of SS and frequency of its presentation. To verify that SiD is tapping onto the stimulus-driven limitation of auditory selective attention, I have directly compared SiD with the paradigm which taps onto goal-directed limitation – i.e., auditory attentional blink or AAB. The result suggested that SiD indeed taps onto limitation that is partially dissociable from the one AAB taps onto. Taken together, I claim that the series of current experiments successfully established and validated

the new paradigm called SiD which enables exploring the temporal characteristics of stimulus-driven limitation in auditory selective attention.

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Chapter I

Introduction

Audition provides an important interface with the world, allowing us to communicate with others and alerting us to important events. Its role in socializing supports psychological wellbeing (Hallberg et al., 1993; Hallberg et al., 2008; Helvik et al., 2006), and it is frequently important to survival itself, such as when a car's horn or a fire alarm warns us of impending danger. In order to respond appropriately to auditory information, we need to enhance relevant sounds while ignoring noise. This function is served by auditory selective attention (Fritz, Elhilali, David, & Shamma, 2007; Parmentier, 2014). Attention is particularly crucial in audition because, unlike vision, auditory processing is not spatially restricted to a small region of foveation (Broadbent, 1958; Scharf, 1998).

Numerous empirical studies have investigated selective attention's enhancing effects, the so-called "bright side" of attention. These effects frequently do not extend to every stimulus presented, however, because our available cognitive resources are limited

(Kahneman, 1973; Styles, 2005, 2006). As a result, attending to some stimuli can cause us to fail to perceive others, the so-called "dark side" of attention (Chun & Marois, 2002). Such perceptual failures can represent significant costs, as missed events can be behaviorally relevant.

Selective attention can be controlled voluntarily or by salient events in our environment (Egeth & Yantis, 1997; Matthews, 2000; Theeuwes, 2010; Yantis, 2000). We voluntarily try to attend to someone's voice in a noisy party, whereas a loud and unusual noise (such as the aforementioned fire alarm) can grab our attention reflexively. These forms of attentional control have been termed goal-directed and stimulus-driven respectively. As the names suggest, attention is directed to a stimulus that is relevant to our current goals in the former, whereas certain properties of the stimulus are crucial in the latter (Connor, Egeth, & Yantis, 2004; Pashler, Johnston, & Ruthruff, 2001). The overall operation of selective attention depends on a delicate balance between these two forms of attention (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Johnston & Strayer, 2001) because "[h]uman behavior emerges from the interaction of the goals that people have and the stimuli that impinge on them" (Pashler et al., 2001, p. 630).

To better understand the function of these different forms of attention, researchers have taken advantage of the "dark side" of attention. That is, numerous studies have focused on the behavioral *costs* of attending to salient or goal-relevant stimulus (i.e., goal-directed or stimulus-driven limitations), using such indirect measures to understand attentional processes and their control (Matthews, 2000; Styles, 2006).

This approach has been used extensively in the visual domain. For example, the "attentional blink" (AB; Raymond, Shapiro, & Arnell, 1992) demonstrates the temporal characteristics of a goal-directed limitation in visual selective attention. In AB experiments, a rapid serial visual presentation (RSVP) of stimuli (e.g. 100 ms per item) is presented at fixation (Eriksen & Spencer, 1969). When participants are asked to identify or detect two designated targets among distractors in this RSVP stream, the accuracy of the second target detection or identification significantly drops when it is presented around 200 – 500 ms after the first target (see Dux & Kelly, 2012; Kelly & Dux, 2011). However, participants do not show this "blink" (i.e. lower second target performance) when they are instructed to ignore the first target (see Dux & Marois, 2009; K. L. Shapiro, Arnell, & Raymond, 1997 for a review). Although many different theoretical accounts of these findings have been developed (see Dux & Marois, 2009 for a review) most agree that the goal-directed deployment of attentional resources for processing the first target causes temporary deficit in processing the subsequent target. The AB is therefore not due to bottom-up sensory processing triggered by physical saliency, but instead due to active attentional processes involved in identification of the target.

In addition to the goal-directed attentional blink, a similar processing deficit can be induced through involuntary attentional capture. When novel, unexpected, and task-irrelevant stimuli are inserted into an RSVP stream before the presentation of the designated target, target detection is profoundly impaired (Asplund, Todd, Snyder, Gilbert, & Marois, 2010). The deficit has a timecourse similar to the AB's, with detection of subsequent stimuli suffering most around 200-400 ms and recovering by around 800 ms. As unexpected stimuli induce the deficit, Asplund et al. (2010) termed it "surprised-induced blindness" (SiB). As opposed to the AB, SiB represents a stimulus-driven limitation of visual selective attention because participants are not instructed to deploy their attentional resources for processing the surprising stimulus; instead, the stimulus grabs attention, rendering a subsequent target invisible.

Importantly, whereas the attentional blink lingers for hundreds of trials (Maki & Padmanabhan, 1994 but see Choi, Chang, Shibata, Sasaki, & Watanabe, 2012), SiB rapidly habituates. With repeated presentations, an initially surprising stimulus captures attention less, thereby inducing virtually no deficit at all after only a few (2-6) presentations. Such habituation demonstrates that attention – instead of perception – best accounts for SiB. First, perceptual phenomenon such as visual forward masking tend not to habituate, even across hundreds or thousands of trials (Breitmeyer, Hoar, Randall, & Conte, 1984; Breitmeyer & Öğmen, 2006). Second, similar habituation is the hallmark of the orienting response (OR) (Kahneman, 1973; Pavlov, 1927; Sokolov, 2002). In both SiB and the OR, the participant orients attention to a task-irrelevant, unexpected stimulus and invests their limited cognitive resources to evaluate the stimulus. Both phenomena habituate once participants no longer need to evaluate the stimulus.

While the attentional blink and surprise-induced blindness have helped us understand temporal characteristics of goal-directed and stimulus-driven attention in the visual domain, less is known from analogous paradigms in the auditory domain, which also limits our understanding of auditory attentional function. After initial difficulties in finding an auditory attentional blink (Potter, Chun, Banks, & Muckenhoupt, 1998), subsequent studies have found and investigated the AAB (e.g. Arnell & Jolicœur, 1999; Mondor, 1998; Soto-Faraco & Spence, 2002). Similar to its visual counterpart, when a participant is given a task to detect the presence/absence of two targets in a rapid auditory presentation (RAP) stream, the performance of the second target suffers when it is brought closer to the first one. The deficit is also alleviated by the instruction to ignore the first target.

While the AB has been studied across different modalities, there is no study that directly replicated the surprise-induced blindness paradigm into the auditory domain. As a matter of fact, there are numerous neural and behavioral findings investigating the stimulus-driven process of auditory selective attention such as auditory distraction (e.g., Escera, Alho, Winkler, & Näätänen, 1998; Friedman, Cycowicz, & Gaeta, 2001; Niepel, Rudolph, Schützwohl, & Meyer, 1994; Parmentier, 2014; Schröger, 1996). However, studies tapping onto the temporal characteristics of such process using paradigm like RAP are still limited (e.g., Dalton & Lavie, 2004; Horváth & Burgyán, 2011). This represents an important gap in the literature because having a stimulus-driven auditory paradigm that is similar to SiB would allow for both the comparison of goal-directed and stimulus-driven auditory attention, as well as comparisons of auditory and visual stimulus-driven attentional control. As such, I hope to further elucidate how auditory selective attention functions, thereby better understanding how we successfully navigate the world, whether paying attention to important unexpected sounds or ignoring unimportant distracting ones.

In the current work, I ventured into the relatively unexplored subdomain of auditory attention's stimulus-driven limitations. To do so, I developed and investigated a new paradigm called surprise-induced deafness (SiD), which extended SiB into the auditory modality.

Specific Aims

In this thesis, I describe a series of experiments that investigate the temporal characteristics of stimulus-driven limitations in auditory selective attention. The thesis contains two empirical chapters, each of which has a specific aim. Chapter II establishes Surprise-induced Deafness (SiD) and explores its characteristics, such as the timecourse within a trial and habituation across them. After the initial experiment, Chapter II further explores the timecourse of habituation, testing whether changing the surprises or making them more frequent affects SiD. Chapter III reports an individual differences approach, in which I compared the goal-directed Auditory Attentional Blink with SiD. I conclude by discussing the theoretical and practical implications of Surprise-induced Deafness in Chapter IV.

Chapter II

Establishing and exploring SiD

Introduction

An organism's survival depends on its successful interaction with its environment. Therefore, it is crucial for them to effectively monitor for and respond to unexpected, sudden changes in the surroundings. Hearing is especially important for this function because it can serve as an "early warning system" (Scharf, 1998), sensitive to changes regardless of their location relative to gaze and body position. A subtle but unusual sound, such as hissing of a snake, could potentially indicate an imminent threat. Thus, detection of novel or deviant sounds among other stimuli is indeed an adaptive function of audition (Fritz et al., 2007).

The findings of numerous studies using electrophysiological measures show that hearing does monitor for potentially important stimuli by augmenting neural and behavioral reactions to novel (see Friedman et al., 2001 for a review) or deviant (see Parmentier, 2014 for a review) sounds. Multiple event-related potential (ERP) components have been found to correlate with auditory distraction induced by unusual sound. For example, when a participant is presented with a novel or deviant sound while listening to a repetitive sequence of sound, a negative potential peaking 100 to 200 ms from the onset of the stimulus is observed. This ERP component is called mismatch negativity (MMN) and has been interpreted as an indication that brain is involuntarily processing a novel or deviant sound (Näätänen & Alho, 1995; Näätänen, Paavilainen, Rinne, & Alho, 2007; Schröger, 2007). After the novel or deviant sound is registered (as indexed neurally by the MMN), it may be attended to if further investigation is needed (Friedman et al., 2001; Horváth, Winkler, & Bendixen, 2008). The neural correlates of such an attentional process include the novelty-P3 or P3a, a frontally-distributed positive potential that peaks later than the MMN (as early as 280 ms after the onset of the stimulus; Friedman et al., 2001).

The MMN shows that audition is sensitive to unusual sound and novelty-P3 demonstrates that the attention is directed toward the novel sound when it is deemed to be worthy of further investigation. The latter ERP component is thought to be the neural manifestation of the orienting response or OR (Escera, Alho, Schröger, & Winkler, 2000; Friedman et al., 2001; Knight & Scabini, 1998). The OR is an adaptive behavior of organisms in reaction to a slight change in their environment, initially described as an orienting of their “appropriate receptor organ” (Pavlov, 1927, p. 12) to investigate the novel stimulus. More recent accounts have emphasized the OR’s psychological aspects, such as the immediate investment of mental effort to evaluate the situation. According to Kahneman (1973), the OR involves allocation of cognitive resources in order to enhance the perceptual analysis of the novel stimulus. Such effort enables the individual to evaluate the significance of stimulus in question.

While the OR is a vital function for an organism, it can come with a cost. Individuals have limited attentional capacity (Kahneman, 1973; Matthews, 2000; Styles, 2006), implying that although attention may help to amplify the information processing of a novel stimulus, this act could deplete these limited resources. An important stimulus could therefore be missed; indeed, during an OR, ongoing activities are inhibited while an individual is evaluating the novel stimulus (Kahneman, 1973). This account is similar to explanations of the "dark side" of attention, in which perceptual failures can be attributed to insufficient attention on a given stimulus because it has been directed elsewhere (Chun & Marois, 2002).

Consistent with the ERP findings and cognitive theories of the OR, behavioral studies show that the presentation of an unusual sound causes auditory distraction, as indexed by poorer primary task performance. For example, when a deviant sound (e.g., a sound that has different frequency from other stimuli in the experiment) is presented before a task-relevant target, the deviant sound captures auditory attention and induces delay in responding to the designated target (Dalton & Lavie, 2004; Horváth & Winkler, 2010; Roeber, Berti, & Schröger, 2003; Schröger, 1996) or a deficit in the primary task's accuracy (Escera et al., 1998; Horváth & Burgyán, 2011; Schröger, 1996). Furthermore, the presentation of a novel sound (e.g., sound of drill among other sinusoidal tones) can increase reaction times of the primary task (Escera et al., 1998).

The various observed behavioral costs show that participants are “surprised” by the deviant or novel sound (Parmentier, 2014). The experience of surprise is induced by encountering a stimulus that deviates from one’s expectancies and when one lacks knowledge about the deviant stimulus (Horstmann, 2015; Meyer, Niepel, Rudolph, & Schützwohl, 1991; Niepel et al., 1994). Surprise results in a stimulus-driven change of attentional control, behaviorally evidenced by poorer performance on an ongoing task. It is found in both the visual domain (Asplund, Todd, Snyder, Gilbert, et al., 2010; Meyer et al., 1991) as well as in the auditory domain (Niepel et al., 1994).

In the visual domain, Meyer et al. (1991) showed that the presentation of an unexpected visual stimulus caused increased reaction times (RT) for the primary task. Importantly, this behavioral cost was most pronounced when the surprising stimulus and target were 0.5 seconds apart but not when the stimulus onset asynchronies (SOAs) were 0, 1, or 2 seconds. This result is consistent with the findings of surprise-induced blindness (SiB; Asplund, Todd, Snyder, Gilbert, et al., 2010), in which the most pronounced effects were found when the target followed the surprise stimulus (SS) by 300-400 ms, and emphasizes the importance of the temporal aspect of surprise.

Another temporal aspect of surprise is also demonstrated in the surprise-induced blindness (SiB) paradigm. The effect rapidly habituates after 2-6 surprise presentations, akin to habituation observed in the OR (Kahneman, 1973; Pavlov, 1927; Sokolov, 1990). A second line of evidence that the attentional response to novel stimuli diminishes is provided by ERP work. Repeated exposures to a novel stimulus attenuates the novelty-P3 component at frontal sites (Courchesne, Hillyard, & Galambos, 1975; Friedman et al., 2001; Friedman & Simpson, 1994).

The effect of surprise on behavioral performance was also evidenced in the auditory domain (Niepel et al., 1994). Similar to the result of Meyer et al. (1991), there was a significant delay in RT when a novel and task-irrelevant auditory stimulus was presented. Moreover, consistent with other surprise studies, such phenomenon was observable only when the SOA between the SS and the target tone was short (i.e., 200 ms) but not long (i.e., 1,500 ms). Other auditory distraction studies also have shown that the RT cost (Schröger, 1996) or accuracy deficit (Horváth & Burgyán, 2011) is more pronounced when the deviant sound and target are temporally proximate.

Taken together, these studies show that the behavioral cost of surprise can be observed across modalities. This is consistent with the claim that a surprising event captures central attention (Horstmann, 2015), but it is also consistent with modality-specific limitations that operate similarly across vision and audition. Given these previous findings, I hypothesize that a paradigm that systematically measures various aspects of auditory surprise can be established. Specifically, I intend to extend SiB into the auditory domain. Using a rapid auditory presentation (RAP), I anticipate that surprise-induced deafness (SiD) can be demonstrated and explored. It is hoped that, similar to SiB paradigm, SiD enables us to investigate the temporal characteristics of a stimulus-driven limitation in auditory selective attention – i.e., How does temporal proximity between the SS and target modulate deficit in target detection accuracy? – as well as the timecourse of habituation.

Given the nature of auditory attention as an early warning system and various previous findings, I hypothesize that the presentation of SS will induce a deficit in target detection, with properties similar to the visual counterpart. For example, I hypothesize that surprise-induced deafness will be more pronounced for SOAs that are relatively short (e.g. around 300-400 ms; (Asplund, Todd, Snyder, Gilbert, et al., 2010; Horváth & Burgyán, 2011; Meyer et al., 1991; Niepel et al., 1994; Schröger, 1996), and that it will habituate after repeated presentations (Asplund, Todd, Snyder, Gilbert, et al., 2010; Friedman et al., 2001; Kahneman, 1973; Pavlov, 1927; Sokolov, 2002). I expect that the habituation rate will be grossly similar to SiB's, as auditory surprise ERPs largely attenuate after six exposures (Friedman & Simpson, 1994).

The two experiments in this chapter explore the stimulus-driven limitation of auditory selective attention. In the first experiment, I attempt to establish SiD. Once SiD has been established, in the second experiment, I further investigate the nature of SiD. Specifically, I explored the factors that affect the timecourse of habituation and magnitude of SiD.

Experiment 1: Establishing surprise-induced deafness (SiD)

The first experiment tested whether surprise-induced deafness (SiD) would be evidenced with a design similar to surprise-induced blindness (SiB). Specifically, I investigated whether conscious perception of a designated target is transiently impaired when it is preceded by an unexpected, task-irrelevant auditory stimulus. If so, a second goal was to determine the extent to which the characteristics of SiB (especially the temporal ones) applied to stimulus-driven attention in the auditory domain. The task was similar to the SiB's paradigm, here involving the search for a target in a rapid auditory presentation (RAP) stream of distractors. The target and distractors were drawn from the same auditory category of pure tones, but the 'Surprise' stimuli (SS) were instead spoken letters (see Figure 1). During 36 of the 360 trials, the SS appeared with various stimulus onset asynchronies (SOAs) before the target or in its absence.

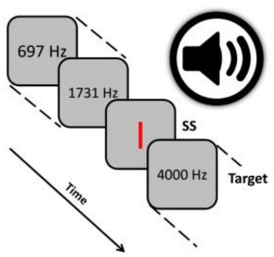

Figure 1. Illustration of the stimuli used in the RAP for Experiment 1. SS was a spoken letter embedded in the RAP of pure tone distractors.

Given the auditory system's enhanced processing of novel sounds (Escera et al., 1998; Friedman et al., 2001; Niepel et al., 1994), we expected that the presentation of a SS would cause auditory distraction and induce a behavioral cost. Because the primary costs in surprise-induced blindness, the attentional blink, and the auditory attentional blink are detection deficits (Arnell & Jolicœur, 1999; Asplund, Todd, Snyder, Gilbert, et al., 2010; Mondor, 1998; Raymond et al., 1992), I anticipated similar costs here. Nevertheless, as a secondary analysis, I also investigated whether longer reaction times (RT) would be associated with auditory surprises. Since numerous studies of auditory distraction and auditory attentional capture report RT cost upon presentation of novel or deviant sound (Dalton & Lavie, 2004; Escera et al., 1998; Horváth & Winkler, 2010; Niepel et al., 1994; Roeber et al., 2003; Schröger, 1996) I have included the speeded component to explore the possible link between the findings of these studies to SiD. Similar to SiB (Asplund, Todd, Snyder, Gilbert, et al., 2010) or auditory distraction by a novel sound (see Friedman et al., 2001 for a review), I expected to observe the dissipation of behavioral costs upon repeated presentation of surprising stimuli.

Method

Participants. Forty-nine National University of Singapore (NUS) undergraduates (20 men, 4 gender not reported) with normal hearing participated for either payment ($5) or course credit. The NUS Institutional Review Board approved of the protocol for this experiment and all subsequent experiments.

Stimuli and apparatus. The stimuli were pure tones of log-related frequencies ranging from 639 to 4000Hz (639, 697, 760, 829, 904, 944, 986, 1029, 1122, 1224, 1335, 1456, 1587, 1731, 1888, 2059, 2245, 2448, 2670, 2911, 3175, or 4000 Hz) and spoken letters of the alphabet except W, N, F, S, and X (due to their lack of intelligibility and confusability; see also Arnell & Jolicœur, 1999; Van Der Burg, Olivers, Bronkhorst, Koelewijn, & Theeuwes, 2007). Letters were each recited by a female English native speaker and digitally recorded using a Bose microphone and an Olympus IC recorder set at 32 bits of resolution for amplitude, at a sampling rate of 44.1 kHz. The best effort was made to utter each letter clearly, quickly, and consistently throughout the recording session. Each recorded letter was then compressed to span 110 ms for presentation (or 120 ms for practice trials), without altering its original pitch by using Audacity ® recording and editing software (AudacityTeam, 2014). The stimuli were presented at approximately 70-dB sound pressure level (SPL) as maximum intensity. Although the maximum amplitudes of the stimuli in the RAP were equalized, I expected that the pure tones would yield higher perceived volume due to their dense wave forms compared to spoken letters (see Figure 2). This expectation was backed up by pilot participants' reports that pure tones and spoken letters sounded roughly equivalent only when the ratio of the volume had been adjusted to 0.15/1.00. Therefore, the intensity of pure tones was attenuated accordingly.

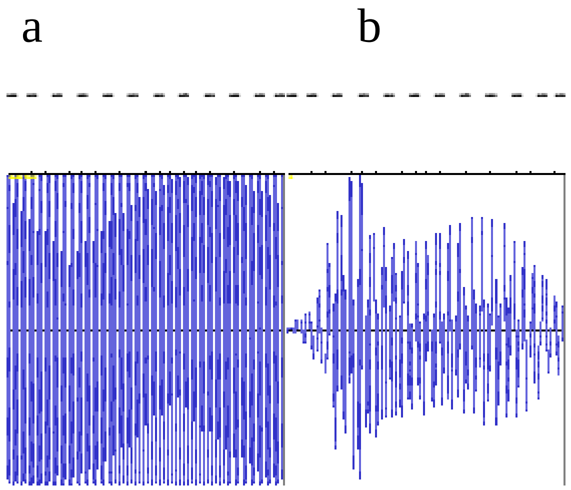

Figure 2. Illustration of the wave forms. Panel a: Illustration of the wave form of 639 Hz pure tone. Panel b: Illustration of the wave form of spoken letter 'A'. Although the maximum amplitudes are equalized, the wave of pure tone reaches the maximum value far more frequently than spoken letter does.

Each trial consisted of a rapid auditory presentation (RAP) of pure tones (639 to 3175 Hz) in which a 4000 Hz pure tone target was presented. Surprises (i.e., novel, unexpected stimuli) were spoken letters of the alphabet except W, N, F, S, and X. The target was present in 75% of the trials, whereas a surprise stimulus (SS) appeared in only 10% of the trials (i.e., surprise trials). Furthermore, for each experimental block, three SS were presented either 120, 360, or 960 ms before the target and one SS was presented during a target absent trial. This design was consistent with the target probability of 75%. Three SOAs mentioned above correspond to Lag 1 (where the SS is presented immediately before the target), Lag 3 (where there are 2 distractors in between the SS and target), and Lag 8 (where there are 7 distractors in between the SS and target), respectively. The surprise trials without the target served as catch trials for calculating false alarm rate when SS is presented. For each surprise trial, a spoken letter was randomly chosen without replacement as the SS from the set of sounds described above.

The four types of surprise trials as well as the two types of non-surprise trials (six Conditions total) were randomized inside each block with three restrictions. First, for each block, surprise trials only appeared after presentations of five to ten non-surprise trials. This restriction was intended to help participants build up the schema of the standard trial as opposed the surprise trial (see Niepel et al., 1994). Second, there were at least three non-surprise trials in between the presentation of surprise trials. This restriction was intended to attenuate the potential immediate carryover effect of post-surprise trial (such as delay in RT; Asplund, Todd, Snyder, & Marois, 2010) or inter-trial priming effects (such as speeding of RT when trials with singleton are presented in succession; Maljkovic & Nakayama, 1994). Third, the first four surprise trials included one of each Condition (3 SOAs and one without a target), with an order that was counterbalanced across participants. This consideration allowed me to assess the surprising effects of each lag condition despite the expected rapid habituation of these effects. For example, the counterbalancing equalized the number of participants who had Lag 3 surprise trial as their first exposure to SS and the number of participants who had Lag 1 surprise trial as their first exposure to SS.

During the experiment, the stimuli were presented binaurally through TDK headphones (ST 100) using 16 bits of amplitude resolution. PsychoPy software (Peirce, 2007) and a Dell computer (OPTIPLEX 990) were used to present the stimulus and record the data. Participants made their responses through a standard computer keyboard.

Sounds were played at a sampling frequency of 44100 Hz. All stimuli were 110 ms (or 120 ms for practice trials) in duration. The onset and offset of each sound included 2-ms linear amplitude ramps so that the occurrence of onset/offset clicks could be eliminated. Between any pair of tones, a 10-ms interstimulus interval (ISI) of silence was inserted. Each stimulus in the RAP had the SOA of 120 ms. Therefore, approximately 8.33 pure tones were presented per second.

Procedure. Each participant completed the experiment individually. Each experiment consisted of 360 trials divided into 9 blocks of 40. Most participants completed the session within 60 mins.

All participants were asked to go through at least 6 practice trials before starting the 9 blocks of experimental trials. Each practice block had 6 trials; before proceeding to the experimental trials, participants were required to repeat the practice block until they reached satisfactory (i.e., 66.67% accuracy) level of performance. During the practice trials, no surprises were presented.

Participants were instructed to report their detection of the 4000 Hz pure tone as soon as they had detected it, or to indicate at the conclusion of the trial if no target had been presented. Participants initiated each new trial by pressing the spacebar on the keyboard.

Before every presentation of RAP, the target tone was played to refresh participants' pitch memory, while a white fixation cross was displayed in the center of the screen. During each trial, participants were presented with a sequence of 30 tones. The target was presented following 17 to 27 non-target items on every trial (see Figure 3). If participants did not make a response during the RAP, they were prompted by a question (i.e., "Target?") presented on the computer screen 300 ms after the end of RAP. Participants pressed the '1' key if the target had been detected and the '0' key if not. Both accuracy and speed were emphasized, with the former given slight priority in the instructions: "Please respond as quickly as it is possible but not at the expense of accuracy". Between each block, participants were encouraged to take a short break if necessary. During this break, they could refresh their memory of the target pitch as many times as they wished by pressing '1'.

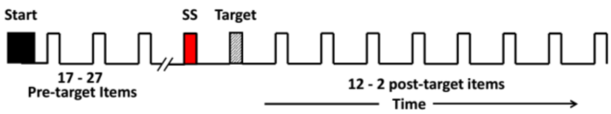

Figure 3. Illustration of the rapid auditory presentation (RAP) stream. A Lag 1 (120 ms SOA) surprise trial is shown.

Results

Accuracy was calculated separately for each Condition (six total) in each block. Conditions were categorized as surprise trials with a target (Lag 1, 3, and 8), surprise trials without a target (surprise only), non-surprise trials with a target (Target only), or non-surprise trials without a target (Target absent). For reaction time (RT) statistics and analyses, only target-present trials for which the participant gave a correct response were considered.

Statistical reports. Throughout the entire series of experiments in this thesis, the analysis of results conformed to the followings: (1) For the results of analysis of variance (ANOVA), Greenhouse–Geisser correction was used when the assumption of sphericity was found to have been violated. Reports include uncorrected degrees of freedom and corrected F-values and p-values. (2) For post-hoc comparisons, Bonferroni correction is used where appropriate; the cut-off p-values (i.e., $p < .05$) are kept constant while the actual p-values are multiplied by the number of comparisons. (3) For the results of independent-samples t-test where the equality of variance has been violated, uncorrected degrees of freedom and corrected t-values and p-values are reported. (4) For displaying the effect size of significant main effect or interaction, partial eta-squared values (denoted as "η_p^2") are presented after the p-values.

Data exclusion. The data from who could not reach a reasonable level of task performance were removed from further analyses. Whether a participant was detecting the presence/absence of the target was examined via Fisher's exact test using the number of hits, misses, false alarms, and correct rejections in a contingency table. This method produced exclusions that were virtually identical to using a d-prime criterion of 1 (e.g. 99% match in Experiment 4).

Participants whose scores were not distinguishable from random responding – i.e., yielding $p >= .05$ – were excluded from further analyses (N = 12). This method and criterion was used throughout the entire series of experiments involving target detection. Fisher's exact test was chosen over other methods (e.g., d' or A') because methods such as d' or A' do not work well when detection performance is close to 1 or 0 (Stanislaw & Todorov, 1999), and I could then use conventional cutoff criteria (i.e., $p < .05$). Nevertheless, qualitatively similar exclusions were obtained when d' was used instead.

In addition to poor detection performance in some individuals, the data also showed that some participants pressed the response key multiple times per trial despite the instruction to press it only once. The excessive responses were summed up per participant and were subjected to box plot analysis. The summed values of 4 participants were identified as extreme values (*mean* = 82.50, *SD* = 104.39) having summed excessive responses above the upper inner fence of 10.00 (interquartile range = 4.00, third quartiles = 4.00). We speculated that those participants were not focusing on making the speeded response to detect the target. Out of 4 participants, one also showed non-significant p-value using Fisher's exact test introduced above. Taken together, a total of 15 participants (out of 49, 31%) were removed from further analyses.

Accuracy. In order to test the effects of surprises on target detection, accuracy was investigated trial by trial, in a manner similar to Asplund et al. (2010). The performance for each surprise trial was compared with performance for the immediately preceding non-surprise trial (Surprise trial – 1). If the immediately preceding non-surprise trial was a target absent trial, then a Surprise trial – 2 or – 3 with the target was used for the comparison. Mean accuracy rates as a function of Condition (Surprise trial - 1, vs. Surprise trial) and SS presentation number (1 to 4) appear in Figure 4. To examine whether SiD showed rapid habituation similar to SiB (Asplund, Todd, Snyder, Gilbert, et al., 2010), I first explicitly focused on the habituation rate during the block 1 (i.e., the first four surprise trials).

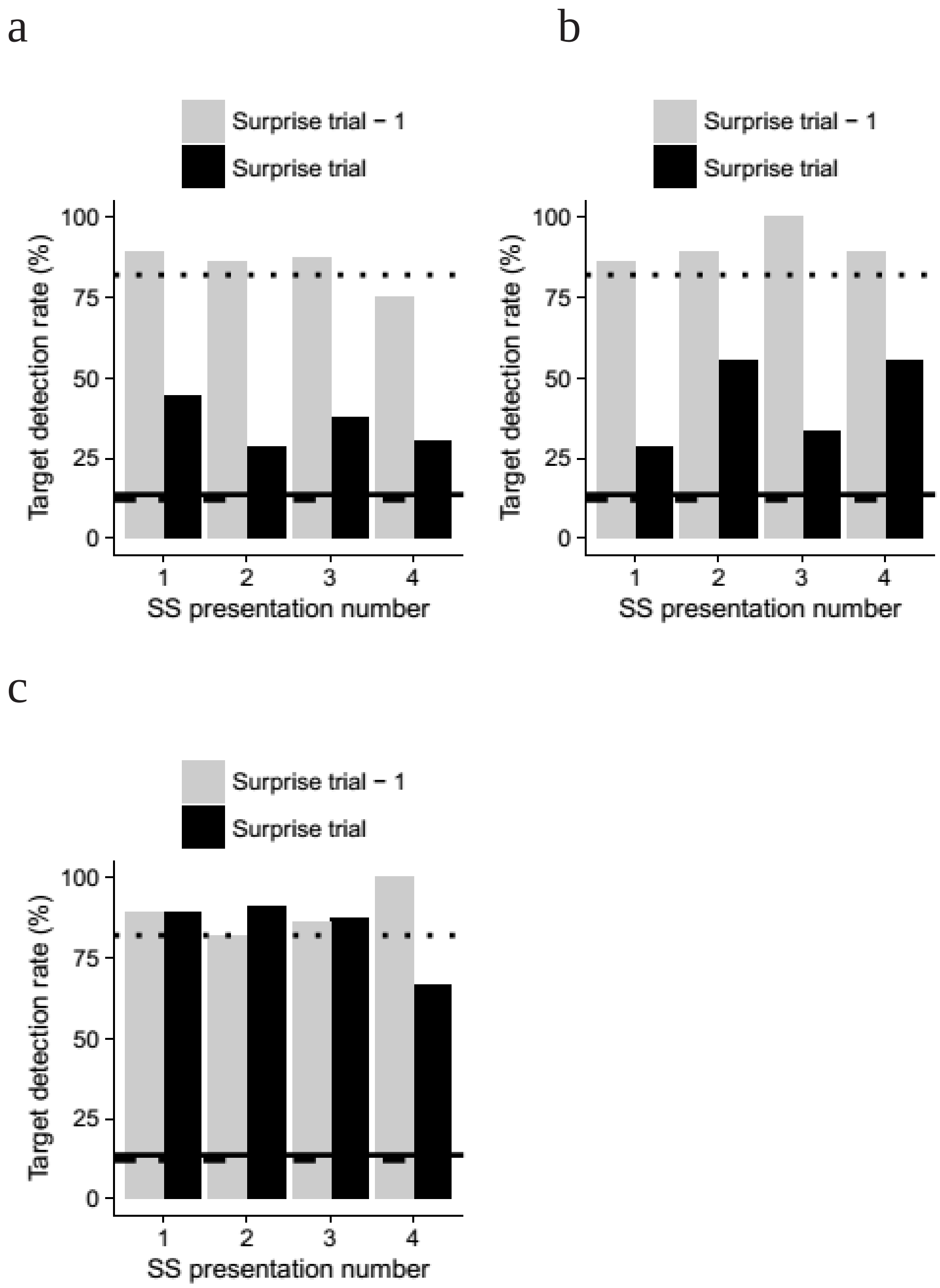

Figure 4. Effect of SS presentation number on group target detection performance at the 120 ms (Panel a), 360 ms (Panel b), and 960 ms (Panel c) SS-to-Target SOA in the first block of Experiment 1. Black bars represent performance for Surprise trials; gray bars represent trials preceding Surprise trials. Dotted line indicates Target-only trial performance, while dashed and solid lines indicates false alarm rates at Target-absent and SS-only trials respectively.

As I expected rapid habituation of any surprise effects, I first analyzed the timecourse of the target detection rate for the Lag 3 condition in the first block, during which participants were exposed to four surprises. The Lag 3 condition was specifically chosen for the analysis because it had a quick habituation rate in SiB (Asplund, Todd, Snyder, Gilbert, et al., 2010). However, a Cochran Q test here revealed that there was no significant difference of target detection rate depending on SS presentation number (Q(3) = 2.07, $p = .56$). This test was used for analyzing the trial-by-trial data because each data point was binary (i.e., 0 or 1; see Asplund, Todd, Snyder, Gilbert, et al., 2010). Furthermore, the effects of surprise appear to habituate far more slowly in SiD than in SiB: While the mean accuracy of Lag 3 trials for the first block (*mean* = 44.12, *SD* = 50.40) were significantly lower than that of Surprise – 1 trials (*mean* = 91.18, *SD* = 28.79), $t(33) = -4.46$, $p < .001$, this was even true when whole 9 blocks were used for the analysis, $t(33) = -3.91$, $p < .001$. In order to investigate these effects while increasing statistical power, the target detection rate was aggregated per block for the subsequent analyses.

Mean accuracy rates as a function of Condition (Lag 1, 3, 8, vs. Target only) and Time (Block 1, 2, 3, 4, 5, 6, 7, 8, vs. 9) appear in Figure 5. A 4 (Condition: Lag 1, 3, 8, vs. Target only) × 9 (Block 1, 2, 3, 4, 5, 6, 7, 8, vs. 9) two-way repeated-measures ANOVA was conducted. The main effect of Condition ($F(3, 99) = 34.98$, $p < .001$, $\eta_p^2 = .52$) and Time ($F(8, 264) = 2.04$, $p = .04$, $\eta_p^2 = .06$) as well their interaction ($F(24, 792) = 1.82$, $p = .048$, $\eta_p^2 = .05$) were all significant.

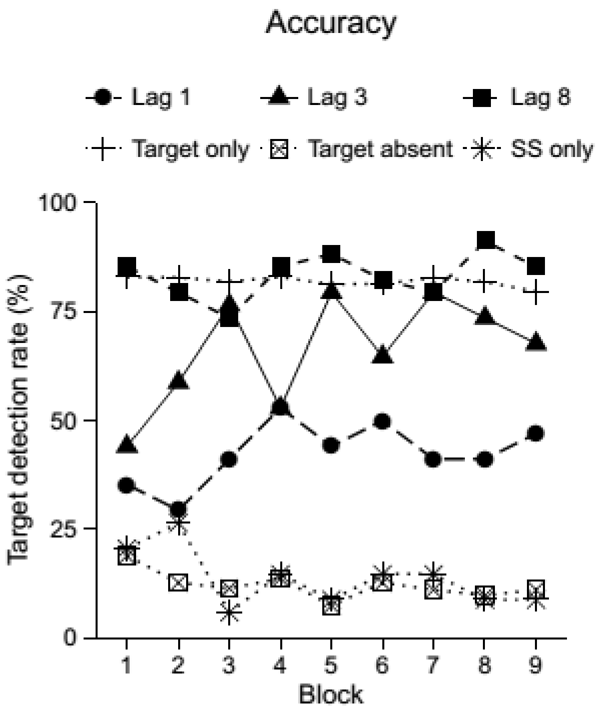

Figure 5. Mean target detection rate for each Condition as a function of time in Experiment 1. Solid line with ▲ represents the performance for Lag 3 trials. Dashed lines with ● and ■ represent the performance for Lag 1 and 8 trials respectively. Dotted lines with +, ⊠, and ✳represent the performance for Target only, Target absent (false alarm rate at non-surprise trials), and SS only (false alarm rate at surprise trials) trials respectively. Note: Error bars are omitted for clarity.

Following up on the significant main effect of the Condition, paired-samples t-tests revealed that the accuracy of Target only (*mean* = 81.93, *SD* = 12.99), Lag 1 (*mean* = 42.48, *SD* = 32.65), Lag 3 (*mean* = 66.34, *SD* = 30.03), and Lag 8 (*mean* = 83.33, *SD* = 18.20) were all significantly different from one another except for Target only vs. Lag 8 comparison ($t(33) = -0.71$, $p = 1.00$).

Most importantly, following up on the significant Condition × Time interaction, planned comparisons (i.e., Target only vs. Lag 1, 3, and 8 trials across 9 blocks) using paired-samples t-tests revealed that the accuracy for Lag 1 trials was significantly lower than for

Target only trials for all 9 blocks (*p*s $< .01$). Lag 3 trials had significantly lower accuracy than Target only trials for Block 1 (*mean* = 44.12, *SD* = 50.40 and *mean* = 82.90, *SD* = 13.62 respectively; $t(33) = -4.57$, $p < .001$). This difference was marginally significant for Block 2 ($t(33) = -2.95$, $p = .05$) but it disappeared at Block 3 onwards (*p*s $> .32$) except for Block 4 ($t(33) = -3.85$, $p = .01$). Lag 8 trials' accuracy was not significantly different from Target only trials across all 9 blocks (*p*s $> .50$).

The results described above suggest that the target detection impairment depends on the SOA between the Surprise and target stimuli, with poorer group performance for 120 (Lag 1) and 360 ms SOA (Lag 3) compared to the 960 ms SOA (Lag 8) trial. Performance for the 960 ms SOA trials was comparable to the Target only trials, suggesting that target detection was no longer impaired by Lag 8.

For the 360 ms SOA, participants recovered from the deficit in target detection by the time they reached the third block – i.e., starting around ninth exposure to the SS. Since there was no effect of time for the accuracy of Target only trials ($F(8, 264) = 0.56$, $p = .73$), target detection practice cannot account for performance on the Surprise trials. Conversely, if the participants simply learned to associate the SS with target presentations, the target false alarm rate for surprise trials (i.e., Surprise only trials) should have increased as they progressed through blocks. However, this was not the case since Surprise only trials did not show any main effect of time ($F(8, 264) = 1.37$, $p = .23$). Furthermore, the target false alarm rate for the Surprise only trials (*mean* = 13.73, *SD* = 15.00) was much lower than the target hit rate for Lag 1, 3, and 8 trials (ps < .001).

Lastly, the mean accuracy scores for Lags 1, 3, and 8 were compared using the performance on the first surprise trials (Figure 6). The first surprise trials alone were used for this analysis to examine effects before any habituation took place. There was a significant effect of lag on target detection rate (Cochran Q(2) = 6.58, p = .04), with Lag 3 (*mean* = 28.57) performance lower than Lag 8 (*mean* = 88.89) performance (Fisher exact test, p = .02). There were no significant differences between Lag 1 (mean = 44.44) and 8, or Lag 1 and 3 (Fisher exact tests, ps > .13), though these comparisons were all rather underpowered.

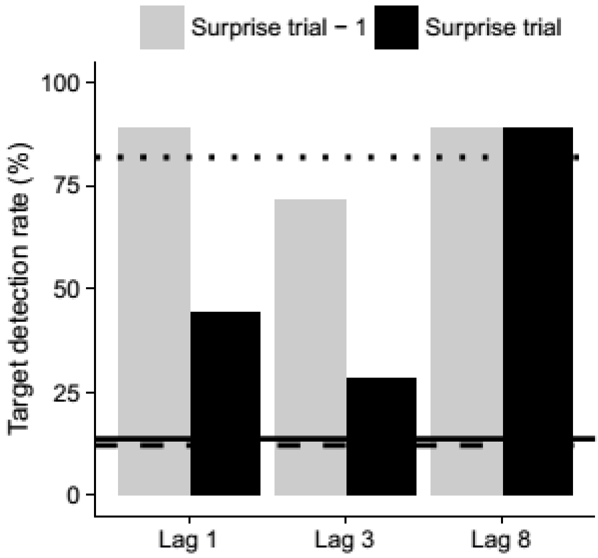

Figure 6. Mean target detection rate as a function of Condition comparing the surprise trial and surprise trial – 1 in Experiment 1. Gray bars represent the target detection rate of target only trial preceding the surprise trial. Black bars represent the target detection rate of surprise trials. Dotted, dashed and solid lines represent the mean target detection rate for target only trials, false alarm rate for the non-surprise trials, and false alarm rate for the surprise trials respectively.

Note: Most of the Surprise-1 performance reflect target detection rate of target only trial immediately preceding a surprise trial. However, when Surprise-1 happened to have no target, then performance of a target only trials 2 or 3 trials prior to the surprise trial was used.

The result of these analyses suggests that even when participants are exposed to the SS for the first time, it only affects the primary task for a short duration, well below a second.

RT. In addition to the analysis using accuracy measures, as a secondary analysis, I examined reaction times (RT) for correct responses when targets were present. To minimize the effects of outlier values, median RTs were calculated for each participant and condition combination (Condition and Block). The means across subjects of these conditional median RT scores appear in Figure 7.

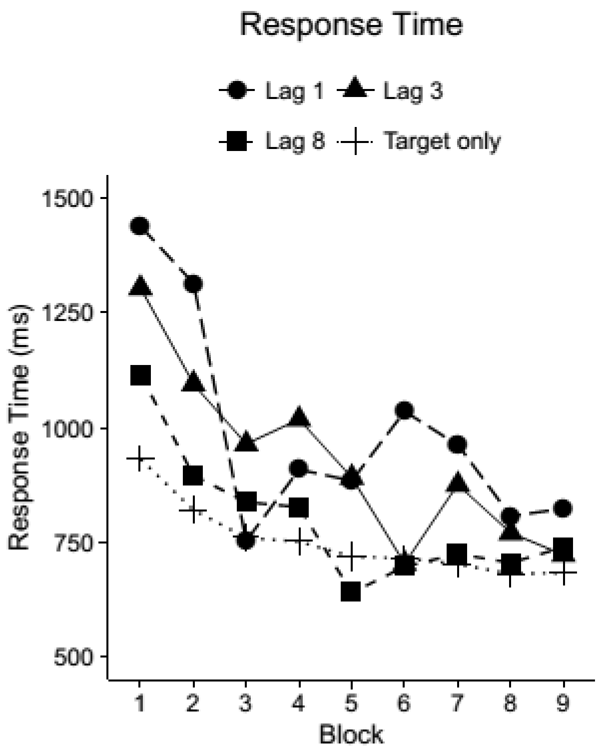

Figure 7. Mean RT for each Condition as a function of Time in Experiment 1. Solid line with ▲ represents the performance for Lag 3 trials. Dashed lines with ● and ■ represent the performance for Lag 1 and 8 trials respectively. Dotted line with + represents the performance for Target only trials.
Note: Error bars are omitted for clarity.

For the analysis of RT, the performance was averaged across the blocks in order to compensate for substantial amount of missing data points after excluding the performance of incorrect trials. One-way repeated-measures ANOVA revealed a significant main effect of the Condition (Lag 1, 3, 8, vs. Target only), $F(3, 78) = 15.73$, $p < .001$, $\eta_p^2 = .38$.

Following up on the significant main effect of the Condition, paired-samples t-tests revealed that the accuracy of Target only (*mean* = 752.30, *SD* = 384.84), Lag 1 (*mean* = 1104.40, *SD* = 544.01), Lag 3 (*mean* = 997.20, *SD* = 552.84), and Lag 8 (*mean* = 829.70, *SD* = 460.93) were all significantly different from one another except for Target only vs. Lag 8 as well as Lag 1 vs. Lag 3 comparisons (*p*s > .13).

The analysis above suggests that presentation of the SS delayed RT to the presentation of the target only when the SOA was short (i.e., 120 to 360 ms) but not long (i.e., 960 ms). Unlike the accuracy performance, the RT performance of Lag 1 and Lag 3 trials did not show significant difference.

Speed-accuracy tradeoff. The results of accuracy and RT analyses show that the speedy response did not necessarily improve the accuracy. Instead, participants showed low accuracy during the Conditions where delayed RTs were also observed. Therefore, this evidence suggests that a speed-accuracy tradeoff does not explain the accuracy results in this experiment.

Discussion

This first experiment demonstrated that Surprise-induced Deafness (SiD) could be observed when unexpected stimuli preceded a target. In general, the basic features of SiD appear to be comparable to those observed in Surprise-induced Blindness (SiB; Asplund, Todd, Snyder, Gilbert, et al., 2010). For example, the impairment in target detection depended on the proximity between the SS and target, with a stronger deficit at Lags 1 and 3. The effects in these two conditions were distinguished by the habituation rates, as the Lag 3 effects were strong but relatively short-lived, evaporating by the third block. In contrast, Lag 1 effects did not habituate across the nine blocks. The timecourse of habituation suggests that the behavioral cost induced by OR (Kahneman, 1973; Pavlov, 1927; Sokolov, 2002) and surprise (Asplund, Todd, Snyder, Gilbert, et al., 2010) is most likely represented by the former, Lag 3, effects.

The target detection deficit effects at Lag 3 condition (i.e., Lag 3 deficit) is further explored in the subsequent experiment. The overall strength and habituation rate of SiD are considered in Experiment 2 using Lag 3 alone.

Similar to its effects on accuracy, the presentation of an SS induced longer reaction times for the short lags. However, unlike the result observed in accuracy deficit, there was no difference in RT performance between Lag 1 and Lag 3 condition. Moreover, the nature of RT data (including large number of missing values) makes it difficult to investigate the presence or rate of habituation. Thus, the differentiation between SiD and other paradigm such as auditory attentional capture still remains inconclusive. Future study should directly compare two paradigms to address this issue.

Follow-up experiments

Although the SiD deficit has a rather large magnitude, it is also estimated from rather few trials. A large sample size can partially compensate for this aspect of SiD experiments, and subsequent experiments investigating higher-order manipulations (habituation rate, condition-based differences in SiD, and correlations) therefore required a substantial number of participants. In order to accommodate the need to implement large-scale studies in a reasonable timeframe, I chose an online platform to conduct the experiments. Before relying on this approach, I first compared the results of lab and web-based experiments to investigate whether the two platforms yield comparable behavioral data. I next tested the effects of SS heterogeneity on habituation rates. The duration of the experiments was shortened to 3 blocks from 9 because habituation was observed as quickly as 8^{th} exposure to the SS in Experiment 1. .

Lab-based experiment (Experiment 1L)

Method. Experiment 1L was identical to Experiment 1 with the following exceptions: Twenty-two participants (7 males) were presented with SS consisting of randomly chosen homogeneous spoken letters – they were chosen according to the participant number (e.g., 'A' for the first participant, 'B' for the second participant etc.). Each session lasted for approximately 20 mins, and consisted of 120 trials divided into 3 blocks of 40. Lag 1 and 8 conditions are omitted from the design of Experiment 1. Before each trial, participants were allowed to repeat playing the demo target as many times as necessary. Due to the excessive responses observed in the previous experiments, participants are given warning in red font – PLEASE DO NOT PRESS THE ANSWER MORE THAN TWICE! – every time responses are made more than twice while RAP is playing. In the current experiment, instead of equalizing the maximum amplitude of the RAP stimuli, each stimulus was equalized by calculating the mean of summed absolute amplitude values at every time point for each sound and then equalizing those mean values across all the RAP items.

Results and Discussion

Data exclusion. Participants whose scores were not distinguishable from random responding were excluded from further analyses (N = 2, 9%). Incorporating warning function against excessive response dramatically reduced the targeted behavior (maximum value = 4). Therefore, no participants had to be removed according to this criterion.

Accuracy. Mean accuracy rates as a function of Condition (Lag 3 vs. Target only) and time (Block 1, 2, vs. 3) appear in Figure 8. A two-way within-subjects ANOVA (Condition: Lag 3 vs. Target only), versus (time: Block 1, 2, vs. 3) was conducted. No significant main effects were obtained (all *p*s > .13). However, there was significant Condition × time interaction ($F(2, 38) = 9.69$, $p < .001$, $\eta_p^2 = 0.34$). The accuracy of Lag 3 trial was lower than the accuracy of Target only trial at Block 1 (*mean* = 66.67, *SD* = 34.20 and *mean* = 81.67, *SD* = 16.67 respectively) with marginal significance ($t(19) = -2.50$, $p = .07$). But such trend was no longer observable at Block 2 and 3 (*p*s > .46).

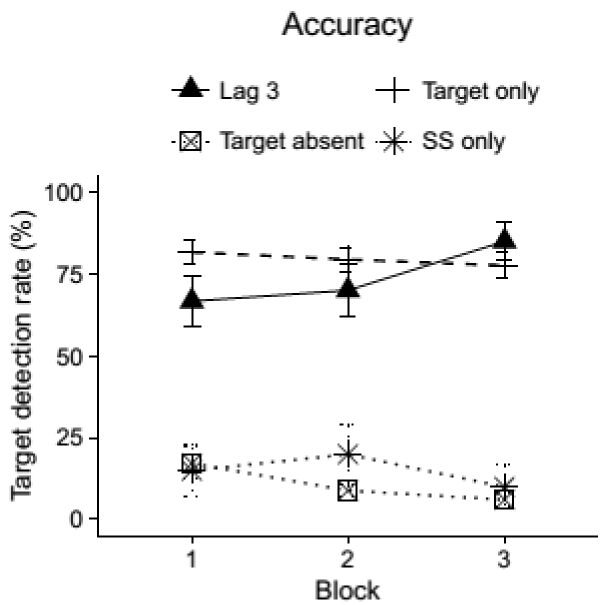

Figure 8. Mean target detection rate for each Condition as a function of time in Experiment 1L. Solid line with ▲ represents the performance for Lag 3 trials. Dashed line with + as well as dotted lines with ⊠, and ✳ represent the performance for Target only, Target absent (false alarm rate at non-surprise trials), and SS only (false alarm rate at surprise trials) trials respectively.

Compared to the result of Experiment 1, the magnitude of accuracy deficit observed at the current experiment was milder at Block 1. The result suggests that the homogeneity of SS accelerated the speed of habituation since SiD already recovered at Block 2 – i.e., starting around fifth exposure to SS. This potential difference is explored formally in Experiment 2. Regardless, the result of the current experiment showed similar general SiD features as were observed in Experiment 1, namely an overall accuracy deficit that habituates.

Web-based experiment (Experiment 1W)

Method. Experiment 1W was identical to Experiment 1L with the following exceptions: Thirty-four participants (19 men) were presented with randomly chosen spoken letter ‘I’ as SS via online crowdsourcing service – i.e., Amazon Mechanical Turk (AMT).

AMT allows researchers to efficiently acquire human subject data. Via AMT, experimenters (introduced as "requesters" in the platform) may post human intelligence tasks (HITs) to potential participants (known as "workers" in the platform). The anonymous online workers can then select which web-based tasks to complete for small sums of money. Previous studies show that AMT-based studies can replicate cognitive behavioral experiments such as the attentional blink, which itself uses an RSVP task (Crump, McDonnell, & Gureckis, 2013). Given that RAP tasks such as SiD are similar, I reasoned that the AMT platform would be feasible, thereby allowing me to collect a large amount of data quickly. From AMT platform, workers were redirected to an online survey system (Qualtrics, 2005) which presented stimuli and controlled the flow of RAP task.

In contrast with Experiment 1L, three more modifications were made for the current experiment. First, since the platform – e.g., type or brand of computers – differed across participants, it was impossible to strictly equalize the volume of RAP stream. Therefore, participants were instructed to adjust the volume to their level of comfort and were suggested to use headphone over speaker if possible. Second, due to the time constraints, participants were not required to reach 66.7% of accuracy during the practice block. Instead, they were instructed to go through 6 practice trials of slow RAP task (i.e., 120 ms SOA per stimulus) and another 6 practice trials of fast RAP task (i.e., 110 ms SOA per stimulus), both with feedback. Third, since the results from Experiment 1 showed that the accuracy deficit in the

Lag 3 condition most clearly represents SiD, the current experiment focused on accuracy, and the speeded component was removed from the design. Thus, participants were asked to report the target without time pressure, entering their response at the end of each RAP stream. Owing to the limitation of randomization function in Qualtrics, the trial order was randomized once, participants in the same condition experienced the same trial order.

To ensure the quality of data, participants were required to have 90% of their previous HITs approved by the requester and to have at least 1,000 HITs completed in the past in order to participate to the current experiment (see Grysman, 2015; Peer, Vosgerau, & Acquisti, 2014; D. N. Shapiro, Chandler, & Mueller, 2013; Summerville & Chartier, 2013). Participants were told that they would receive $1 USD and that the study would take no more than 30 minutes. They then clicked on a link that took them to the experiment, which was managed by Qualtrics online survey system. At the end of the experiment, participants received instructions to enter a unique code generated by Qualtrics in the AMT HIT to verify that they completed the study to receive payment. Qualtrics restrictions were set to allow one response per AMT worker ID to provide protection against participants completing the study multiple times.

Results and Discussion

Data exclusion. Participants whose scores were not distinguishable from random responding were excluded from further analyses (N = 4, 12%). Due to the removal of speeded component, participants were only allowed to make one response per trial. Thus, excessive responses were no longer possible for subsequent series of Experiment 2.

Accuracy. Mean accuracy rates as a function of Condition (Lag 3 vs. Target only) and time (Block 1, 2, vs. 3) appear in Figure 9. A two-way within-subjects ANOVA (Condition: Lag 3 vs. Target only), versus (time: Block 1, 2, vs. 3) was conducted. Significant main effects of Condition ($F(1, 29) = 12.43$, $p = .001$, $\eta_p^2 = 0.30$) time ($F(2, 58) = 3.97$, $p < .02$, $\eta_p^2 = 0.12$) and interaction ($F(2, 58) = 5.56$, $p = .01$, $\eta_p^2 = 0.16$) were obtained. The accuracy of Lag 3 trial was significantly lower than the accuracy of Target only trial at Block 1 (*mean* = 53.33, *SD* = 34.57 and *mean* = 81.60, *SD* = 16.17 respectively), $t(29) = -4.70$, $p < .001$, and became marginally significant at Block 2 ($t(29) = -2.54$, $p = .05$). But such trend was no longer observable at Block 3, ($t(29) = -0.83$, $p = 1.00$).

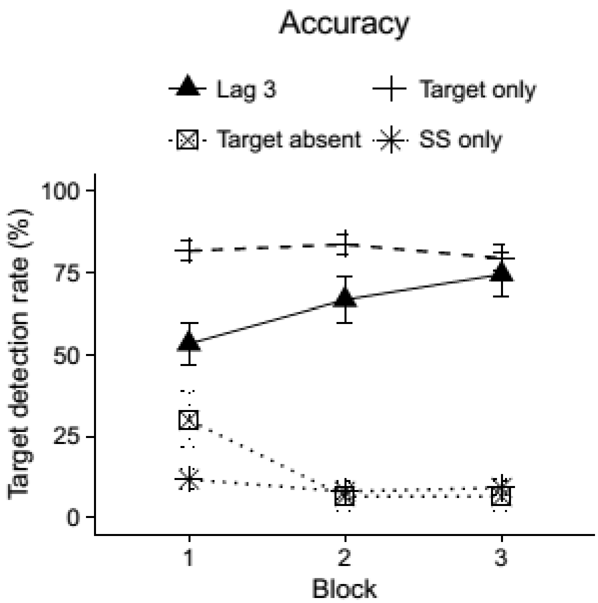

Figure 9. Mean target detection rate for each Condition as a function of time in Experiment 1W. Solid line with ▲ represents the performance for Lag 3 trials. Dashed line with + as well as dotted lines with ⊠, and ✳ represent the performance for Target only, Target absent (false alarm rate at non-surprise trials), and SS only (false alarm rate at surprise trials) trials respectively. Error bars represent ±1 standard error of the mean (SEM).

Although the accuracy deficit was more pronounced at Block 1 (Figure 9), the result of current experiment is consistent with the result of Experiment 1L – i.e., occurrence of habituation at Block 2. Therefore, the current experiment showed that the results of SiD task run via AMT platform and lab are comparable. These results suggest that despite decreased experimental control – e.g., lack of immediate supervision by experimenters, variations in experimental setting – AMT platform can closely replicate the experimental setting.

Experiment 2: Exploring Surprise-induced Deafness' habituation rate and strength

From the results of Experiment 1, the Lag 3 deficit appears to represent an auditory analogue of Surprise-induced Blindness (SiB) that I term Surprise-induced Deafness (SiD). A salient feature of the Lag 3 deficit is its rapid habituation rate, which also connects it conceptually to both SiB and the orienting response (OR). In the current experiment, I further investigate the nature of SiD by exploring two factors, the heterogeneity of the surprise stimuli and the relative frequency of surprise trials that might affect SiD's habituation rate and magnitude.

Previous studies suggest that these two factors could be important influences on SiD's characteristics. First, Asplund et al. (2010) showed that the completeness of habituation can be manipulated by controlling the heterogeneity of SS's identities. Namely, making each SS highly distinct by the usage of colorful visual images which are easily distinguishable from other SS was shown to make the habituation incomplete, at least over six SS presentations. Second, surprise studies have shown that substantially increasing novel stimulus' presentations can abolish the effects of surprise (Meyer et al., 1991; Niepel et al., 1994). Given these findings, we systematically investigated how manipulating the variety of SS and changing the density of surprise trials would modulate the habituation rate and magnitude of SiD.

In Experiment 2, we ran 4 different types of RAP task. The key differences across

RAP tasks were heterogeneity and density of SS (see Table 1). For each RAP task, the SS were either homogeneous or heterogeneous (i.e. all the same or markedly different from surprise trial to surprise trial), and SS trials appeared at different frequencies relative to non-SS trials. The density of SS varied by two-fold across conditions (i.e., 10% vs. 20% density condition).

Table 1.
Four different condition combinations for the RAP task

SS / SS density	Homogeneous	Heterogeneous
10%	Homogeneous 10%	Heterogeneous 10%
20%	Homogeneous 20%	Heterogeneous 20%

Method

Participants. One hundred seventy-one participants (92 men) with normal hearing participated for payment ($1) via an online crowdsourcing service – i.e., Amazon Mechanical Turk (AMT).

Stimuli and apparatus. The stimuli used for the current experiment was identical to that of Experiment 1W with the following exceptions: For increasing the variation of the SS, new sounds were added to this experiment (i.e., alarm, balloon popping, car horn, cat meowing, cough, cowbell, dog barking, giggle, hiccup, hi-hat cymbal, lightbulb breaking, mosquito, plunger, slide whistle, slurping, snare drum, sneeze, and tongue popping; spoken digits one and two). The sounds were sampled from freesound.org (Font, Roma, & Serra, 2013) and were compressed to 110 ms each. Similar to Experiment 1W, AMT was used as a platform to run the current experiment.

Procedure. The procedure of the current experiment was identical to that of Experiment 1W with the following exceptions: First, for the homogeneous conditions, the same SS (i.e., a spoken letter ‘I’) was used for the entire experiment, whereas for the heterogeneous conditions, various sounds were randomly chosen without replacement as the SS from the set of sounds described above. Second, for the 10% density condition, the SS appeared during only 10% of the trials; the frequency was doubled for the 20% density condition. Third, while the method of randomization was identical to that of Experiment 1 for the 10% density condition, at least two – instead of three – non-surprise trials were inserted in between surprise trials for the 20% density condition, due to increased occurrence of SS trials.

Results and Discussion

Data exclusion. Similar to the previous experiments, participants whose scores were not distinguishable from random responding (N = 57, 33%) based on Fisher’s exact test were excluded from further analyses.

Accuracy. Mean accuracy rates as a function of Condition (Lag 3 vs. Target only) and time (Block 1, 2, vs. 3) for 4 different conditions (i.e., Homogeneous 10%, Homogeneous 20%, Heterogeneous 10%, and Heterogeneous 20%) appear in Figure 10. All 4 conditions revealed significant main effect of Condition (ps < .01). The main effect of time was not significant for all conditions (ps > .16). Only Homogeneous 10% condition revealed significant Condition × Time interaction ($F(2, 50) = 8.38$, $p = .003$, $\eta_p^2 = .25$). Paired-samples t-test comparing the mean accuracies of Lag 3 vs. Target only trials for each block revealed that accuracy deficits were observed for all conditions, however only Homogeneous 10% condition showed recovery from the deficit – i.e., convergence of Lag 3 and Target only mean accuracy at Block 3, $t(25) = -0.77$, $p = 1.00$ (see Table 2 for summary). In addition to the analysis above, the accuracy for the first surprise trials across four different conditions (*mean* = 60.71, *mean* = 67.74, *mean* = 57.69, and *mean* = 44.83 for Homogeneous 10%, Homogeneous 20%, Heterogeneous 10%, and Heterogeneous 20% respectively) were compared. Cochran's Q test revealed that there was no significant difference across four conditions (Cochran Q(3) = 3.36, $p = .34$) suggesting that the accuracy performance for the surprise trials were comparable at the beginning of the experiment across all conditions.

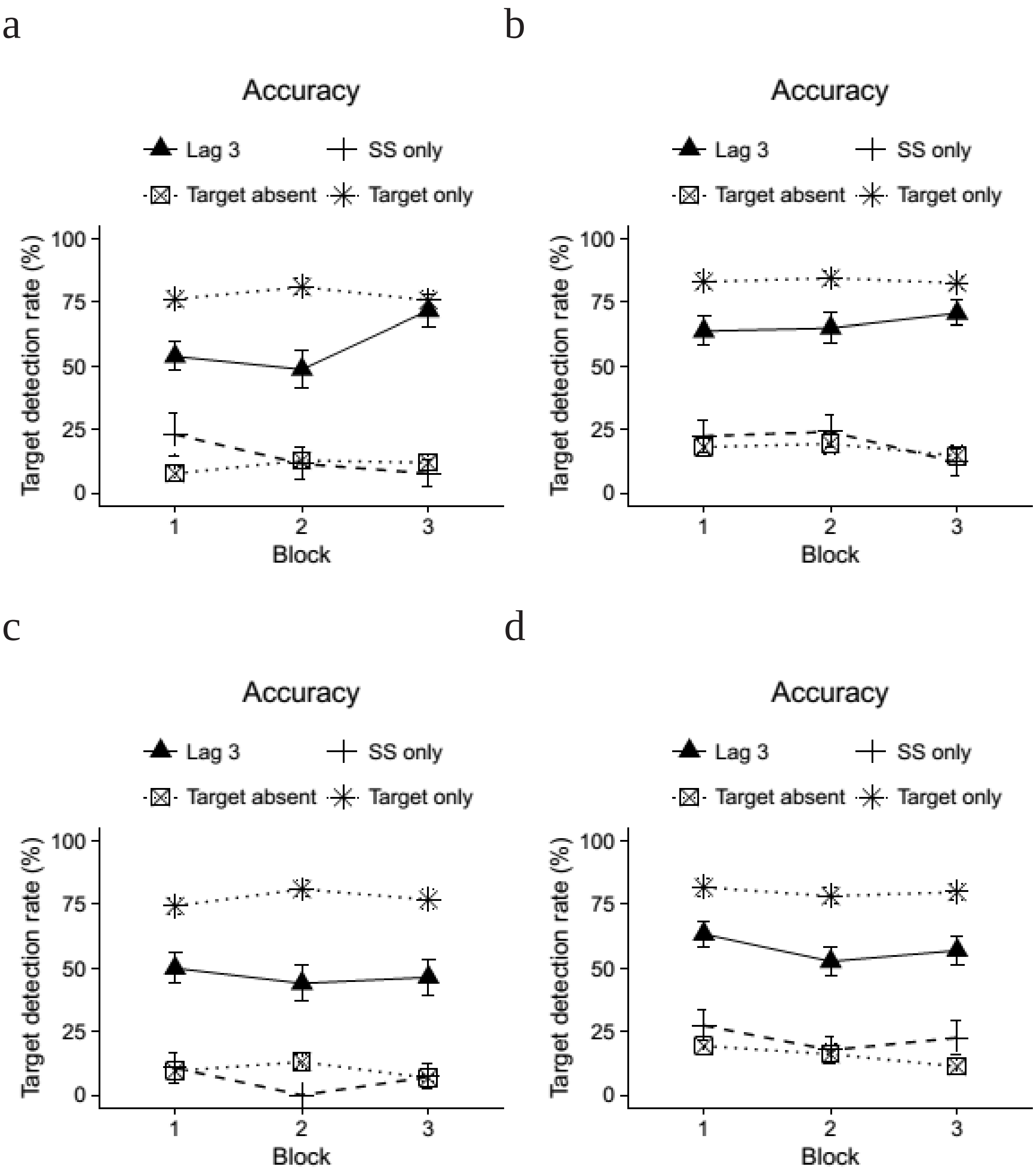

Figure 10. Mean target detection rate for each Condition as a function of time in Experiment 2. Solid line with ▲ represents the performance for Lag 3 trials. Dashed line with + as well as dotted lines with ⊠, and ✳ represent the performance for Target only, Target absent (false alarm rate at non-surprise trials), and SS only (false alarm rate at surprise trials) trials respectively. Error bars represent ±1 standard error of the mean (SEM). Panel a, b, c, and d represents Homogeneous 10%, Homogeneous 20%, Heterogeneous 10%, and Heterogeneous 20% conditions respectively.

Table 2.

Habituation rate for 4 different conditions in Experiment 2

SS density \ SS	Homogeneous	Heterogeneous
10%	Block 3	Incomplete habituation
20%	Incomplete habituation	Incomplete habituation

Note. Each cell represents the block where the habituation was observed.

The Homogeneous 10% condition and Experiment 1W showed similar accuracy deficits and habituation rates, which is expected given their procedural similarity. Furthermore, the results of Homogeneous 10% and Heterogeneous 10% conditions suggest that the heterogeneity of the SS delayed habituation. However, the effect of the SS density on the magnitude of the deficit remains inconclusive. To tease out the effect of the SS heterogeneity and density on habituation rate as well as the magnitude of the deficit, I have collapsed the orthogonal conditions (i.e., heterogeneity and density) and further investigated how they modulate SiD.

Heterogeneity. For the initial analyses described above, the mean accuracy of Target only and Lag 3 trials were calculated separately for investigating the habituation rate – i.e., the convergence of accuracy deficits between Target only and Lag 3 trials. However, for the current analysis, the "SiD magnitude" was calculated by subtracting the target detection rate of the surprise trials from the target detection rate of non-surprise trials to control for the individual differences in baseline target detection performance (see Kelly & Dux, 2011).

Figure 11 shows the group mean percentage of SiD magnitude for homogeneous and heterogeneous condition as a function of block (Time). The data were submitted to a mixed 2 × 3 ANOVA with Heterogeneity (homogeneous vs. heterogeneous) as a between-subject variable and Time (Block 1, 2, vs. 3) as a within-subject variable. A significant main effect of Time (F(2, 224) = 6.96, p = .001, η_p^2 = .06) and marginally significant main effect of Heterogeneity (F(1, 112) = 3.54, p = .06, η_p^2 = .31) emerged. Most importantly, the interaction between Heterogeneity and Time was significant (F(2, 224) = 4.75, p = .01, η_p^2 = .04).

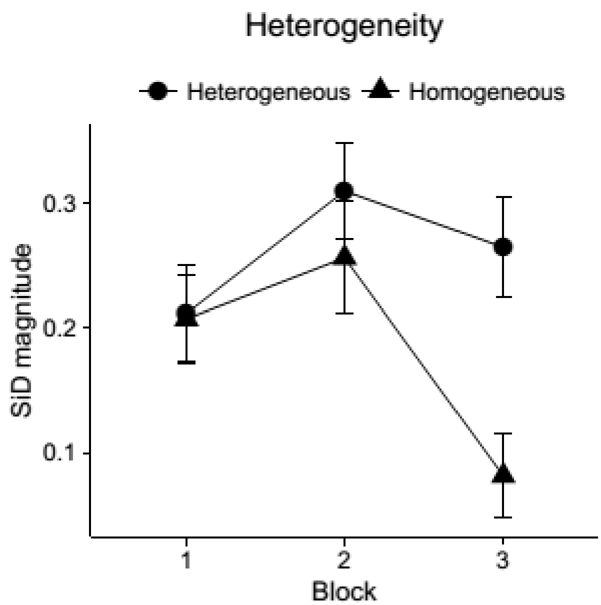

Figure 11. Mean SiD magnitude for homogeneous and heterogeneous condition as a function of Time in Experiment 2. Solid lines with ● and ▲ represent the SiD magnitude of heterogeneous and homogeneous condition respectively. Error bars represent ±1 standard error of the mean (SEM).

Following up on the significant main effect of Time, paired-samples t-tests using compiled data across homogeneous and heterogeneous condition revealed that there was a significant increase in SiD magnitude from Block 1 (*mean* = 0.21, *SD* = 0.28) to Block 2 (*mean* = 0.28, *SD* = 0.31), $t(113) = -2.49$, $p = .04$, and significant decrease from Block 2 to Block 3 (*mean* = 0.18, *SD* = 0.30), $t(113) = 3.45$, $p = .003$. There was no difference in SiD magnitude between Block 1 and 3 ($p = .83$).

Following up on the marginally significant main effect of Heterogeneity, an independent-samples t-test revealed that there was a marginally significant difference in SiD magnitude between homogeneous (*mean* = 0.18, *SD* = 0.22) and heterogeneous (*mean* = 0.26, *SD* = 0.23) condition ($t(112) = -1.88$, $p = .06$).

Most importantly, following up on the significant Time × Heterogeneity interaction, independent-samples t-tests revealed that there was a significant difference in SiD magnitude at Block 3 between homogeneous and heterogeneous (*mean* = 0.26, *SD* = 0.31) condition, ($t(112) = -3.44$, $p = .003$). Such a difference was not observable for other blocks (*p*s = 1.00). Furthermore, a one-way ANOVA with repeated-measures revealed a significant main effect of Time for the homogeneous condition ($F(2, 108) = 9.03$, $p < .001$, $\eta_p^2 = .14$) and a marginally significant main effect of time for heterogeneous condition ($F(2, 116) = 2.69$, $p = .07$, $\eta_p^2 = .04$). For homogeneous condition, there was a significant decrease in SiD magnitude from Block 1 (*mean* = 0.21, *SD* = 0.26) to Block 3 (*mean* = 0.08, *SD* =

0.25), *t*(54) = 3.11, *p* = .009, and from Block 2 (*mean* = 0.26, *SD* = 0.33) to Block 3, *t*(54) = 3.95, *p* < .001. For heterogeneous condition, there was a marginally significant increase in SiD magnitude from Block 1 (*mean* = 0.21, *SD* = 0.30) to Block 2 (*mean* = 0.31, *SD* = 0.29), *t*(58) = -2.33, *p* = .07. There were no significant differences in SiD magnitude for across other blocks, *p*s > .64.

The timecourse of SiD magnitude revealed that heterogeneity of SS plays a significant role in modulating the habituation rate of SiD phenomenon. The result suggests that habituation is significantly delayed (or possibly eliminated) when the identity of the SS keeps changing. The unexpected slight increase in SiD in Block 2 potentially warrants further exploration, though it does not affect the main conclusions about the effects of heterogeneity.

Density. The effect of the density of surprise trials was investigated by comparing the SiD magnitude across the 10% and 20% conditions (see Figure 12). The factor of Time (i.e., blocks) was not used because it was crucial to equate the number of SS presentations across different density conditions. In order to do so, the first two blocks were used for the 10% condition while only first block was used for the 20% condition, thereby yielding 8 exposures to the SS in each condition. An independent-samples t-test revealed a significant difference between the 10% (*mean* = 0.29, *SD* = 0.27) and 20% (*mean* = 0.18, *SD* =0.25) conditions (*t*(112) = 2.11, *p* = .04). This result suggests that SiD magnitude was attenuated when the density of surprise trials increased.

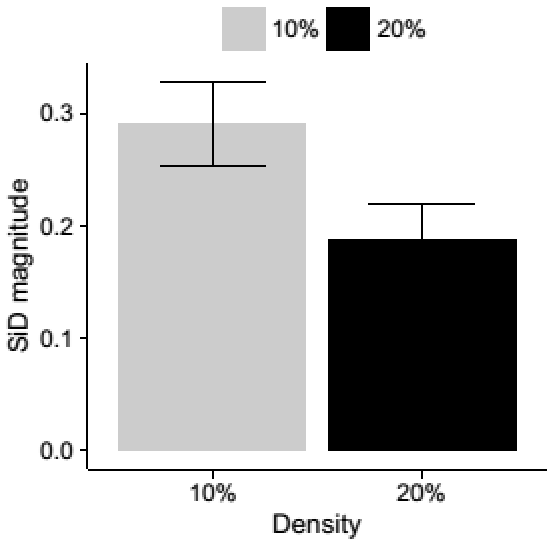

Figure 12. Mean SiD magnitude as a function of Density in Experiment 2. For the 10% density condition (gray bar), SiD magnitude was averaged across Block 1 and 2. For the 20% density condition (black bar), only the SiD magnitude of Block 1 was used. Error bars represent ±1 standard error of the mean (SEM).

Similar to heterogeneity, the result shown above revealed that the density of surprise trial in experiment plays significant role in modulating the degree of deficit induced by SiD. The result suggests that when the surprise trials become less rare, the accuracy deficit is attenuated.

General Discussion

The purpose of Experiments 1 and 2 was to investigate the temporal characteristics of a stimulus-driven limitation to selective auditory attention. The main findings derived from the series of experiments are as follows. The first experiment successfully established SiD. Similar to SiB, the deficit in target detection accuracy depended upon the proximity between the SS and target. Another similarity between the two paradigms is that relatively fast habituation was only found for the Lag 3 condition but not for the Lag 1 condition. The result of the second experiment revealed that the rate of habituation and magnitude of SiD are modulated by the heterogeneity and density of SS respectively.

The successful extension of SiB into the auditory domain is consistent with the notion that surprising events capture central attention, but that attention dwells on the event for only short period of time (e.g., not much more than 400 ms; Horstmann, 2015). Consistent with the previous studies of OR and surprise, the result of the current study suggests that unexpected auditory events strongly grab attention, compelling the individual to evaluate the novel stimulus. In the case of SiD, this investigatory act momentarily creates “deafness”. However, such a state is observable only for a fraction of second, likely because the evaluation process is completed very rapidly.

Stimulus-driven limitation of auditory selective attention

I suggest that SiD reveals a stimulus-driven limitation of auditory selective attention. First, I claim that SiD is tapping onto a stimulus-driven limitation due to the contrast with a paradigm which taps onto goal-directed limitation – i.e., the auditory attentional blink or AAB (e.g., Arnell & Jolicœur, 1999; Mondor, 1998). SiD and the AAB are almost identical paradigms except for the fact that in the latter, participants are asked to detect or identify two designated targets in an RAP stream. When the two targets are temporally proximate (less than half a second), the performance of the second target (T2) suffers. Such a behavioral cost is caused by the depletion of the limited capacity of attention since it is allocated to detecting or identifying the first target (T1). This phenomenon is similar to SiD because the results of current experiments demonstrate that the deficit in target detection accuracy is induced by the allocation of limited capacity of attention to evaluating the SS (Asplund, Todd, Snyder, Gilbert, et al., 2010; Kahneman, 1973). However, the crucial difference between the AAB and SiD is that while conscious, goal-directed processing of the T1 is specifically instructed in the former, in the latter, participants are not given any instruction to process stimuli preceding the designated target – including the SS. Although participants were not required to process the SS in the SiD paradigm, the results of the current study demonstrate that SS nevertheless grabbed attention due to its salient properties – perhaps both physically and contextually. Therefore, I believe that the presentation of the SS tapped onto a "stimulus-driven" mechanism, one which ultimately caused the accuracy deficit in primary task.

Although the perceptual saliency of the SS is likely important to inducing SiD, I argue that the mechanism of attention – rather than a perceptual mechanism such as auditory forward masking – plays a major role in this phenomenon for the following reasons. First, similar to SiB, SiD is characterized by rapid habituation. Auditory masking is a persistent phenomenon which cannot be overcome easily and requires extensive practice (e.g., 20 to 40 hours; Delahaye, Fantini, & Meddis, 1999). Second, in various ERP studies, the novelty-P3 component is interpreted as reflecting conscious attentional processes (Friedman et al., 2001) and shows attenuation (i.e., shift from frontal to posterior site) when the novel stimulus is presented repeatedly (i.e., sixth presentation; Friedman & Simpson, 1994). The roughly consistent habituation timecourse between the attenuation of novelty-P3 and accuracy deficit found in the current study is consistent with both reflecting attentional components, perhaps the same ones.

Heterogeneity and density of the SS

While rapid habituation is an important characteristic of SiD, our result showed that it can be modulated by the heterogeneity of the SS. This finding is consistent with corresponding features in the visual domain (Asplund, Todd, Snyder, Gilbert, et al., 2010). The heterogeneity of the SS slowed habituation, perhaps indicating that the identity of the novel stimulus was constantly evaluated. I speculate that although the novel stimulus captures attention in a stimulus-driven fashion, the novelty of the stimulus is constantly cross-referenced with the data derived from previous evaluation processes (Theeuwes, Atchley, & Kramer, 2000).

Second, surprise trials led to a larger SiD magnitude when they were less frequent, suggesting that participants were more distracted by the SS when it was rarer. This result is in line with the previous behavioral studies (Meyer et al., 1991; Niepel et al., 1994) as well as ERP studies that show that the amplitude of the P300 component (a positive potential peaking around 250 to 400 ms after the onset of novel sound) was inversely related to the density of the task-irrelevant novel sound (Katayama & Polich, 1996). Therefore, I speculate that closer succession of the SS exposure across trials attenuates the strength of attentional distraction or capture.

Although OR compels participants to evaluate the novel sound – especially when the stimulus keep changing – the amount of attentional resource invested in the evaluation process could be determined by the rarity of the stimulus. This idea needs further investigation because a recent study claims that novel sounds induce auditory distraction not because they are rare but because they violate expectations (Parmentier, Elsley, Andrés, & Barceló, 2011). Specifically, Parmentier et al. (2011) demonstrated that the degree of RT cost is primarily affected by (1) the expectation of the upcoming stimulus determined by the identities of two preceding stimuli and (2) the difference of identities between the currently presented stimulus and immediately preceding stimulus. Although the current study is not designed to clarify this question, future study could be designed to disentangle the effect of density, expectation, and perceptual change.

Lag 1 deficit

Unlike Lag 3 deficit which represents SiD, recovery from Lag 1 deficit was not observed – at least within 36 trials. Such slow habituation is not consistent with the characteristic of OR. From the result of Experiment 1, whether Lag 1 deficit shows habituation remains inconclusive. Although Lag 1 deficit is not the primary interest to investigate the SiD phenomenon, future study could further explore the presence of habituation by incorporating large number of Lag 1 condition in the experiment. Such an experiment should be deliberately designed so that participants will not associate the presence of target to the presentation of SS. If the habituation is not observed in such an experiment, then, there is a possibility that perceptual factor such as auditory masking is involved in the Lag 1 deficit (e.g., Brosch & Schreiner, 1997; Jesteadt, Bacon, & Lehman, 1982; Moore & Glasberg, 1981; Pastore, Harris, & Goldstein, 1980). On the other hand, if the recovery from the Lag 1 deficit is observed after prolonged exposure to SS, then the involvement of attentional factor becomes a more plausible account.

Although Lag 1 deficit requires further investigation, I speculate that involuntary processing of SS such as automatic change detection system might be interfering the process of the target detection. Schröger (1996) showed that when the deviant sound is presented 200 ms before the target, ERP result indicated that there was an impoverishment in processing the designated target – i.e., reduced early frontal negativity or N1. However, such phenomenon did not occur when the SOA was 560 ms – although MMN for the deviant sound was observed in both conditions. Since MMN is claimed to be a low level automatic change detection system which is sensitive to the physical deviance of the stimulus but not sensitive to attentional suppression (Fritz et al., 2007; Schröger, 1996), I speculate that such automatic processing of the SS might have been causing long-lasting and robust interference with target detection process when the SS and target are presented adjacent to one another. A future SiD study investigating ERP components could verify such possibility.

Further exploration of SiD

I argue that SiD represents a stimulus-driven attentional limitation, but it may not be completely (or even partially) dissociable from the goal-directed one associated with the AAB. These two deficits could have different inducing stimuli but a common underlying limitation or processing bottleneck. To test whether the limitations are common or distinct, I next used an individual differences approach to investigate the correlation between SiD and AAB magnitude across participants (see Dale, Dux, & Arnell, 2013). This experiment is the focus of the next chapter.

Chapter III

An individual differences approach to understanding the relationship between stimulus-driven and goal-directed auditory attentional limitations

Experiments 1 to 2 established surprise-induced deafness (SiD) and explored its various characteristics, such as its timecourse and habituation rate. The paradigm's setup and results suggest that SiD reflects a stimulus-driven limitation of auditory selective attention. In the remaining experiments, I attempted to explore the relationship of SiD with a similar paradigm, the auditory attentional blink (AAB). The AAB demonstrates a primarily goal-directed limitation of auditory selective attention. In Experiment 3, I developed and tested a suitable AAB paradigm that was well matched with SiD in many of its design characteristics. In Experiment 4, I employed an individual differences approach to investigate whether SiD and AAB had similar magnitudes in the same individuals; a strong association would suggest that the two deficits had a common cause, despite different evoking circumstances.

One fundamental question is whether stimulus-driven and goal-directed attention produce dissociable limitations. Although copious evidence in vision studies have explored the unique features of stimulus-driven and goal-directed attentional properties and mechanisms (see Egeth & Yantis, 1997 for a review), there are different theories to account for how those two forms of attention are related to one another. For instance, some researchers argue that two mechanisms are independent (e.g., Pinto, Leij, Sligte, Lamme, & Scholte, 2013) while others argue that they do not function in isolation (e.g., Rauschenberger, 2010). On the other hand, indirectly supporting both views, multiple sources of psychophysiological evidence suggest that the two functions are dissociable but that they do interact (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Serences et al., 2005). Although visual goal-directed and stimulus-driven attention have been found to be anatomically and functionally dissociable (i.e., dorsal vs. ventral network), Corbetta & Shulman (2002) argue that visual goal-directed and stimulus-driven attention interact for coherent attentional function to emerge, with the latter serving as a "circuit breaker" of the former. Upon presentation of an unexpected stimulus, the ventral network performs the initial evaluation, and then influences the dorsal network to engage in attentional shifts or further evaluation of a stimulus. Furthermore, similar to above account, a study using SiB paradigm suggests that specific brain region (i.e., inferior frontal junction or IFJ) is responsible for coordinating goal-directed and stimulus-driven attentional control (Asplund, Todd, Snyder, & Marois, 2010).

A different idea has been advanced by Buschman & Miller (2007), who found that the activation of lateral intraparietal area, lateral prefrontal cortex, and frontal eye fields show different time courses depending on task demands of goal-directed or stimulus-driven attention (cf. Schall, Paré, & Woodman, 2007). The brain regions involved were highly similar, but the flow of information is different.

The majority of studies exploring stimulus-driven and goal-directed attention involve the visual domain, with less exploration of the auditory domain (Alho, Salmi, Koistinen, Salonen, & Rinne, 2015). Nevertheless, stimulus-driven and goal-directed processes of auditory attention can be distinguished on a neural level: The former elicits a novelty-P3 whereas the the latter elicits a target-P3 (i.e., P300 or P3b), a parietally-distributed ERP positive deflection from 400 to 580 ms after the onset of rare, task-relevant sound (Debener, Kranczioch, Herrmann, & Engel, 2002). Despite such a dissociation, similar to vision, there is evidence that stimulus-driven and goal-directed attentional process interact. It has been shown that manipulating factors that affect goal-directed attentional processes, such as the predictability of an upcoming deviant stimulus or the cue for the primary task, also modulates behavioral costs or ERPs induced by stimulus-driven auditory distraction (Bidet-Caulet, Bottemanne, Fonteneau, Giard, & Bertrand, 2015; Sussman, Winkler, & Schröger, 2003). Similar to vision, there are evidences which suggest that the two processes overlap. Functional magnetic resonance (fMRI) studies demonstrated that common brain areas (i.e., temporo-parietal, superior parietal, and frontal areas) are activated during orientation of attention controlled by goal-directed or triggered by stimulus-driven attention (Alho et al., 2015; Salmi, Rinne, Koistinen, Salonen, & Alho, 2009).

Based on the literature reviewed above, I suggest three different possibilities for the relationship between limitations induced by manipulations of stimulus-driven and goal-directed attention. First, different paradigms could be tapping onto a common psychological limitation. This situation is more probable if there are widespread overlaps in the involved neural networks for the different forms of attention (Alho et al., 2015; Buschman & Miller, 2007; Salmi et al., 2009). A second possibility is that different paradigms tap onto largely dissociable limitations, consistent with neural evidence suggesting dissociable attentional networks (Debener et al., 2002; Pinto et al., 2013) as well as behavioral evidence (Egeth & Yantis, 1997). A third possibility is that two limitations are partially dissociable but are partially overlapping, as many studies suggest that stimulus-driven and goal-directed mechanisms work in tandem through shared components, psychological or neural (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Serences et al., 2005).

Although Experiment 5's individual differences approach bears only tangentially on the relationship of stimulus-driven and goal-directed attention themselves, it can help us understand the relationship between the AAB and SiD. If the deficits across the paradigms are strongly correlated (particularly in the absence of correlations with basic processes such as target detection), it suggests a shared cause despite different evoking conditions. Conversely, a lack of correlation across these two similar paradigms would indicate distinct neural or psychological limitations.

Experiment 3: Replicating and extending the Auditory Attentional Blink (AAB)

The auditory attentional blink (AAB) (e.g., Arnell & Jolicœur, 1999; Mondor, 1998) is a phenomenon that reflects a temporal limitation related to auditory selective attention. The paradigm extended the visual attentional blink (AB) (e.g., Chun & Potter, 1995; Raymond et al., 1992) into the auditory domain using a rapid auditory presentation (RAP). Similar to the AB, the AAB reveals that detecting, discriminating, or identifying the second target in a RAP is impaired by the goal-directed deployment of attentional resources to detecting the first target (Arnell & Jenkins, 2004; Arnell & Jolicœur, 1999; Martens, Johnson, Bolle, & Borst, 2009; Martens, Kandula, & Duncan, 2010; Martens, Wierda, Dun, Vries, & Smid, 2015; Mondor, 1998; Shen & Mondor, 2006; Soto-Faraco & Spence, 2002; Vachon & Tremblay, 2005, 2006; Vachon, Tremblay, Hughes, & Jones, 2009). Furthermore, the observed deficit is not caused by a stimulus-driven phenomenon such as auditory attentional capture or distraction: The deficit is absent both when the first target is absent (e.g., Mondor, 1998) and when participants are told to ignore it (e.g., Arnell & Jolicœur, 1999; but see Horváth & Burgyán, 2011). This characteristic stands in contrast to SiD.

In the current experiment, I attempted to obtain an AAB using a RAP task similar to those used for SiD. The key difference between the current experiment and previous ones is that participants were specifically instructed to process two targets, with only the latter target (referred to as the “probe”) the same as the one used in the SiD experiments.

Method

Participants. Forty-three National University of Singapore (NUS) undergraduates (18 men) with normal hearing participated for course credit.

Stimuli and apparatus. The stimuli used for distractors in the RAP were pure tones of log-related frequencies ranging from 639 to 2911 Hz (639, 697, 760, 829, 904, 944, 986, 1029, 1122, 1224, 1335, 1456, 1587, 1731, 1888, 2059, 2245, 2448, 2670, or 2911 Hz). This stimulus set was identical to the one in Experiment 1 except for the removal of 3175 Hz to improve task performance. Pilot experiments showed that the AAB’s dual task was substantially more difficult compared to SiD’s single detection task. Three complex tones were used as targets (T1) in the RAP streams, whereas the Probe (also referred to as T2, and referred to as the target in the SiD experiments) was the same 4000 Hz pure tone as before. Each target was comprised of five log-related frequencies – 455, 522, 600, 689, and 792 Hz for the low-pitched Target; 909, 1045, 1200, 1378, and 1583 Hz for the middle-pitched Target; 1819, 2089, 2400, 2757, and 3167 Hz for the high-pitched Target. Therefore, the sound of the Target was qualitatively distinguished (complex vs. pure) from the distractors (Figure 1). Similar to Experiment 2, the intensities of stimuli were equalized by calculating the mean of summed absolute amplitude values at every time point for each sound and then equalizing those mean values across all the RAP items.

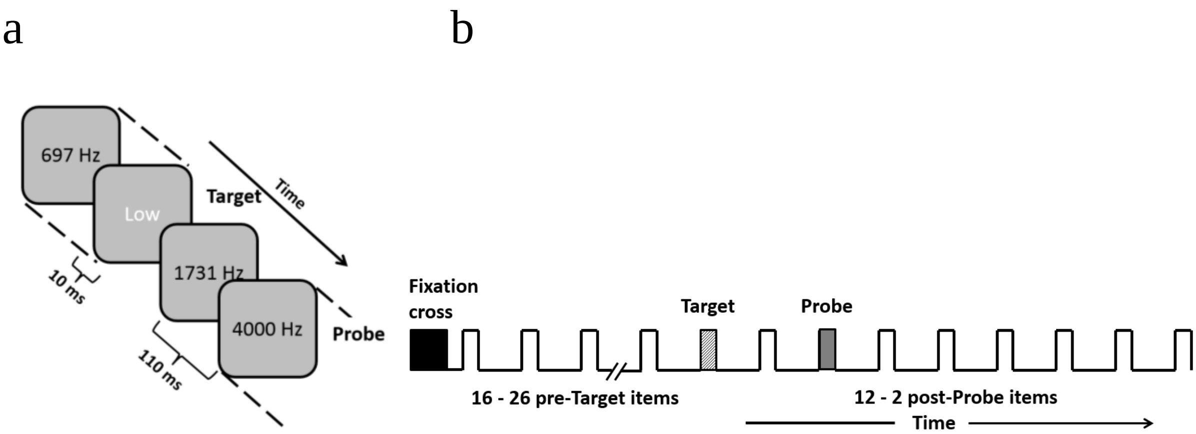

Figure 1. Panel (a): Illustration of the stimuli used in the RAP for Experiment 3. The Target and Probe were complex and pure tones embedded in the RAP of pure tone distractors. Panel (b): Illustration of RAP shown in Panel A in the temporal order.

Procedure. Each participant went through an experimental session consisting of 240 trials, and which lasted up to 60 mins. All stimuli presented were pure tones except for the Targets, which were complex tones. The Probe was a 4000 Hz pure tone that was presented on 75% of the trials. For Probe present trials, the Probe appeared 120, 240, 360, 600, or 960 ms after the onset of Target with equal probability, which corresponds to Lag 1, 2, 3, 5, and 8. For Probe absent trials, only the Target was presented in the RAP. On each trial, participants were presented with a sequence of 30 tones. The Probe was presented following 17 to 27 non-target items on every trial.

Participants in the AAB task were randomly assigned to either an experimental group or a control group. In the former group, participants were instructed to discriminate the pitches of Targets and detect the presence of the Probe, whereas in the control group, participants were only instructed to detect the presence of the Probe. The control group was used to test whether the qualitatively distinct sound of the Target would induce an involuntary capture of attention, which could lead to impaired Probe detection.

There were two tasks for the experimental group. First, participants had to report whether the 4000 Hz pure tone was present in the RAP as soon as he/she has detected it. Second, participants had to identify which one of the three possible complex tones (i.e., low, middle, and high) was presented in the RAP. If participants did not make a response during RAP, they were prompted by a question (“Probe?”) on the computer screen 300 ms after the end of the RAP. Participants then pressed the ‘<’ key if the Probe had been detected and the ‘>’ key otherwise. After entering a Probe response (either during the stream or in response to the prompt), participants were then prompted by another question (“Target?”) to press the ‘1’, ‘2’, or ‘3’ key to indicate detection of the low, middle, or high Target, respectively. For the Probe detection task, performance of both accuracy and speed were emphasized (i.e., “Respond as quickly as it is possible (but not at the expense of accuracy) using your right hand”), whereas speed was not emphasized for the Target discrimination task (i.e., “Detect the Target tones in each stream, and respond when asked using your left hand on the top row of keys 1, 2, and 3”). Participants in the control group were instructed only to monitor whether the Probe was present or absent.

Before participants in the experimental group started the 6 blocks of experimental trials, they went through at least 18 practice trials to become familiarized with the Targets and Probe. The practice session contained three phases. In the first 6 trials, participants were asked to discriminate only the Target in RAP, whereas in the next 6 trials, they were asked to detect only the presence of the Probe in RAP. Participants performed an additional 6 practice trials in which they were asked to perform both discrimination of the Target and detection of the Probe. For each phase of practice, participants were required to reach an accuracy of 66.67% before advancing to the next practice phase. Probe accuracy during the third practice phase was calculated contingent upon correct Target discrimination. For this dual task practice, the Target and Probe were separated by at least 960 ms, which is well outside the blink window in previous AAB experiments (e.g., Arnell & Jolicœur, 1999; Mondor, 1998). For the participants in the control group, they were only required to familiarize themselves with the Probe, after which they were given Probe detection practice (at least 1 set of 6 trials) before proceeding to the actual experiment. Prior to each trial, all relevant target tones (i.e., the Target and Probe for the experimental group, and only the Probe for the control group) were played to refresh participants' auditory memory. Participants were allowed to play these demo tones as many times as necessary before beginning each trial.

Results

Mean accuracy rates and the median RT for each participant in each group were calculated as a function of Lag (Lag 1, 2, 3, 5, vs. 8).

Data exclusion. For the participants in the control group, the data exclusion criteria used in previous series of experiments were applied since they were only required to perform the single Probe detection task. However, for the participants in the experimental condition, an additional exclusion criterion was used to ensure satisfactory Target discrimination performance. Participants whose Target discrimination accuracy was not distinguishable from chance performance (below 40% in this case) were removed. As a result of employing the above exclusion criteria, the data from two participants in the experimental group and the data of one participant in the control group were excluded from the further analyses.

In addition to above data exclusions, three participants in the experimental group found the dual task of AAB extremely difficult. They were not able to go beyond the practice blocks and decided to drop out from the experiment.

Target discrimination accuracy. The probability of a correct response to the Target task, averaged across all conditions, was 69.74% (*SD* = 12.56). This performance level indicated that the target discrimination task was relatively difficult for participants, though they still performed well above chance level (33.33%).

Target discrimination performance was investigated by lag. A repeated-measures ANOVA revealed that the main effect of lag (Lag 1, 2, 3, 5, vs. 8) on the Target discrimination rate was not significant, $F(4, 68) = 1.18$, $p = .33$ (see Figure 2). Furthermore, paired-samples t-test also revealed that there was no significant difference between the Target discrimination rate for the Probe present (*mean* = 69.20, *SD* = 12.94) and Probe absent trials (*mean* = 71.85, *SD* = 13.08), $t(17) = 1.58$, $p = .13$.

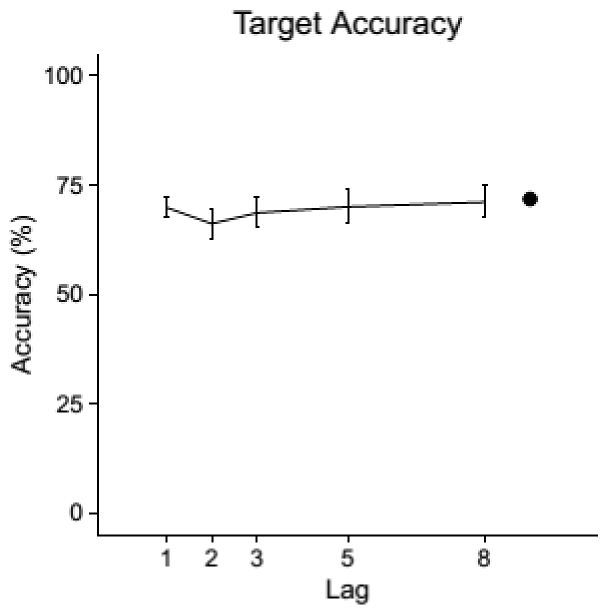

Figure 2. Mean Target discrimination rate as a function of Lag in Experiment 3. Black dot represents the mean Target discrimination rate for the Probe absent trials. Error bars represent ±1 standard error of the mean (SEM).

Probe detection accuracy. Figure 3 shows the group mean percentage of trials where the presence of the Probe was reported correctly when it had appeared (T2|T1) as a function of Lag (Lag 1, 2, 3, 5, vs. 8) and Group (control vs. experimental). For the experimental group, the means were calculated based only on trials where participants discriminated the Target correctly. The data were submitted to a mixed 5 × 2 two-way ANOVA with Lag as a within-subject variable and Group as a between-subject variable. A significant main effect of Group ($F(1, 35) = 16.20$, $p < .001$, $\eta_p^2 = .32$) as well as a significant interaction ($F(4, 140) = 6.98$, $p = .001$, $\eta_p^2 = .17$) emerged. The latter, combined with the pattern of Probe detection recovery with longer lags, is indicative of an auditory attentional blink.

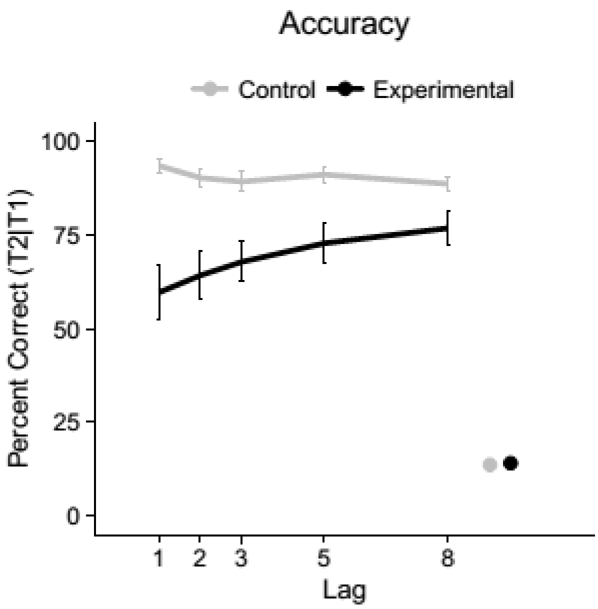

Figure 3. Mean Probe detection rate contingent upon correct Target discrimination as a function of the Lag in Experiment 3. The black line represents performance of the participants in the experimental group (discriminate the pitch of the Target and report the Probe presence or absence), and the gray line represents performance of the participants in the control group (report the Probe presence or absence only). Black and gray dots represent the false alarm rates of the participants in the experimental and control groups respectively. Error bars represent ±1 standard error of the mean (SEM).

Following up on the significant main effect of Group, an independent-samples t-test revealed that T2|T1 accuracy for participants in the experimental group (*mean* = 68.33, *SD* =

22.68) was significantly lower than the Probe detection rate of participants in the control condition (*mean* = 90.64, *SD* = 8.16), $t(35) = 3.94$, $p = .001$. While Target discrimination task impaired the Probe detection task, the mean false alarm rates between two conditions were not significantly different, $t(35) = -1.24$, $p = .90$.

Most importantly, following up on the significant interaction, independent-samples t-tests confirmed a significant blink pattern. From Lag 1 to 5, T2|T1 performance in the experimental group was significantly lower than in the control group (*p*s < .05). By Lag 8, however, the difference was no longer significant ($t(35) = 2.35$, $p = .14$). A repeated-measures ANOVAs also revealed a significant main effect of lag for the experimental group ($F(4, 68) = 5.44$, $p = .01$, $\eta_p^2 = .24$), but not for the control group ($F(4, 72) = 2.17$, $p = .11$).

Probe detection RTs. Similar to Experiment 1, RT measure was added for a secondary analysis. Figure 4 shows the mean RTs as a function of Lag and group, based on trials in which the Probe was present and reported correctly. For the experimental group, only trials for which the Target was reported correctly were included. The data were submitted to a mixed 5 × 2 ANOVA with Lag as a within-subject variable and Group as a between-subject variable. There were significant main effects of Lag ($F(4, 140) = 6.81$, $p = .002$, $\eta_p^2 = .16$) and Group ($F(1, 35) = 24.19$, $p < .001$, $\eta_p^2 = .41$), as well as a significant interaction ($F(4, 140) = 5.88$, $p < .001$, $\eta_p^2 = .14$). Although not necessarily indicative of an auditory attentional blink *per se* (though see Jolicœur & Dell'Acqua, 1999; Ruthruff & Pashler, 2001), the results provide another indication of the cost of attending to the first target.

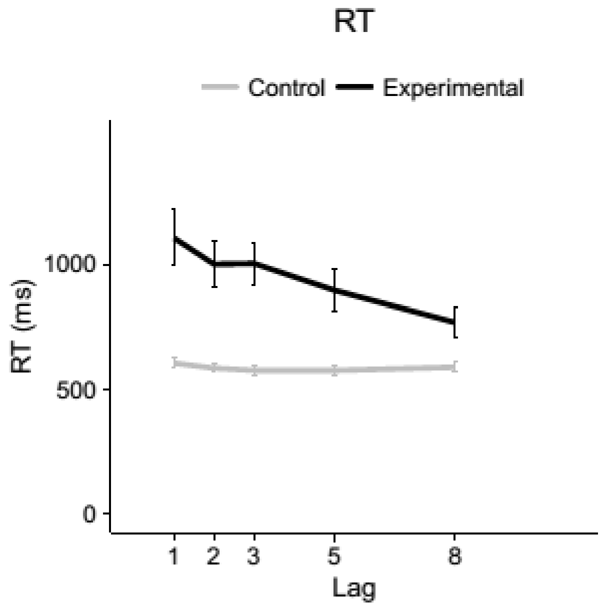

Figure 4. Mean response time (RT) contingent upon correct Target discrimination as a function of Lag in Experiment 3. Black line represents RT of the participants in the experimental group, and the gray line represents RT of the participants in the control group. Error bars represent ±1 standard error of the mean (SEM).

Following up on the significant main effect of the Group, an independent-samples t-test revealed that the RT of participants in the experimental group (*mean* = 955.26, *SD* = 316.06) was significantly higher than that of participants in the control group (*mean* = 587.11, *SD* = 79.64, $t(35) = 4.80$, $p < .001$).

A follow-up repeated-measures ANOVAs revealed that there was a significant main effect of Lag for the experimental group, $F(4, 68) = 6.08$, $p = .005$, $\eta_p^2 = .26$, as well as for the control group, $F(4, 72) = 2.63$, $p = .04$, $\eta_p^2 = .13$. Planned comparisons (Lag 1 vs. Lag 2, 3, 5, and 8) using paired-samples t-test revealed that for the experimental group, there was a significant difference between the mean RT at Lag 1 (*mean* = 1106.28, *SD* = 476.02) and Lag 8 (*mean* = 768.59, *SD* = 243.77, $t(17) = 3.22$, $p = .02$). However, all other pairwise comparisons did not show significant differences (*p*s > .18). In addition, no such differences were observed in the control group (*p*s > .13).

Following up on the significant interaction, independent-samples t-tests revealed that the RT of participants in the experimental condition were higher compared to that of participants in the control condition at all lags, *p*s > .04.

The analysis of RT showed that the Target discrimination induced the delay when participants were responding to the Probe. Furthermore, although the delay in RT for the Probe was more pronounced when it was temporally close to the Target, the RT observed for the dual task did not converge with that of single task within SOA of 960 ms. This result suggests that RT cost of the Target discrimination on Probe detection persists for a longer period of time compared to the accuracy deficit.

Discussion

Target presentation and auditory attentional capture. First, the null effects of lag on accuracy and RT for the control group suggest that the presentation of the Target did not induce auditory attentional capture in a stimulus-driven manner. Therefore, I conclude that the Probe detection deficit in this experiment can be distinguished from the target detection deficit observed in SiD experiments (Experiments 1-2).

Probe detection accuracy and RT. The pattern of Probe detection performance suggests that the current experiment reestablished AAB (e.g., Mondor, 1998). The dual-task cost on accuracy was substantial. While previous studies have showed that AAB lasted for about 450 to 540 ms (Mondor, 1998; Vachon & Tremblay, 2005) the blink lasted at least 600 ms, and possibly longer, in the present experiment. This longer blink period or increased dual-task cost may have resulted from the challenging 3 AFC Target discrimination task (see Shore, McLaughlin, & Klein, 2001; but see also McLaughlin, Shore, & Klein, 2001).

In addition to the usual investigation of an accuracy deficit (the AAB), I also considered the RT cost in responding to the Probe. Similar to the pattern of accuracy deficit, the RT cost was also greater for the shorter lags. However, the dual-task cost appeared to be even more substantial for the RT measure because it was still statistically significant at the longest lag (see Figure 4). The RT results provide additional evidence that the difficult 3AFC first task created a relatively long-lasting deficit in responding to the Probe.

Experiment 4: An individual differences approach to investigating the relationship of surprise-induced deafness (SiD) and the auditory attentional blink (AAB)

Experiment 3 successfully reestablished the auditory attentional blink (AAB), a paradigm in which the goal-directed deployment of attention leads to a deficit in probe detection. As such, the series of experiments in this thesis have demonstrated that involuntary capture by unexpected salient stimulus and voluntary, intentional processing of the designated stimulus both induce target detection deficits in RAP paradigms. Both the AAB and SiD paradigms demonstrate a deficit that is dependent upon the Probe's proximity to the surprise stimulus (SS) or Target (see Figure 5). Despite the similar timecourses for the accuracy deficits, they are elicited by rather different circumstances, with SiD designed to examine stimulus-driven attention and the AAB related more to goal-directed attention. It is unclear, however, whether the two deficits actually reflect a common processing limitation or two separate ones.

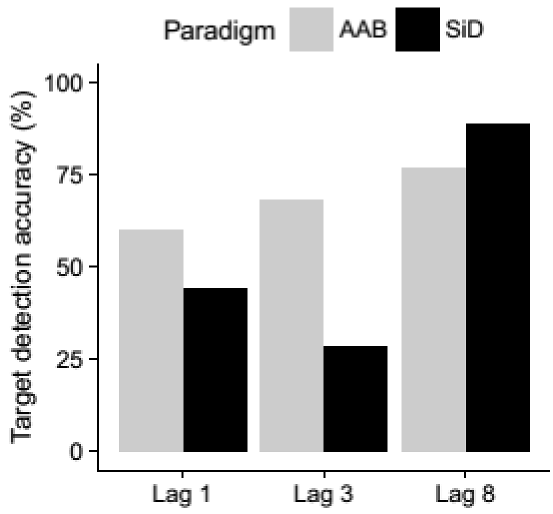

Figure 5. Mean target detection rate in the AAB (Experiment 3) and SiD (Experiment 1) paradigms as a function of lag. Gray bar represents the performance for AAB. Black bar represents the performance – first SS exposure – for SiD paradigm.

In the current experiment, I used an individual differences approach to better understand the relationship between SiD and the AAB, particularly whether they represented distinct processing limitations. Such an approach has recently been used to better understand whether different forms of the visual attentional blink (AB) paradigm reflect the same processing limitations (Dale et al., 2013). For example, a key divide in AB tasks is between those that include a task switch and those that do not (depending on the presence of task-switch component in rapid serial visual presentaion; Kelly & Dux, 2011). The individual differences approach revealed that different types of AB task share a common cognitive limitation (i.e. there were significant correlations across all tasks), but a task-switch also imposed a different limitation. That is, the correlations were stronger within AB task categories than across them (Dale et al., 2013).

In the present experiment, I first obtained the magnitude of accuracy deficits induced by the involuntary capture of the SS (SiD) and by the voluntary processing of the Target (AAB) from a large sample of participants. The data were subjected to a correlation analysis to determine the degree of covariance across individuals. In order to employ this approach successfully, each measure must show sufficient variation across individuals (see Figure 6). Fortunately, Experiments 1 and 3 suggested that there would likely be substantial variability in performance, which we could then test for internal consistency-reliability (see below).

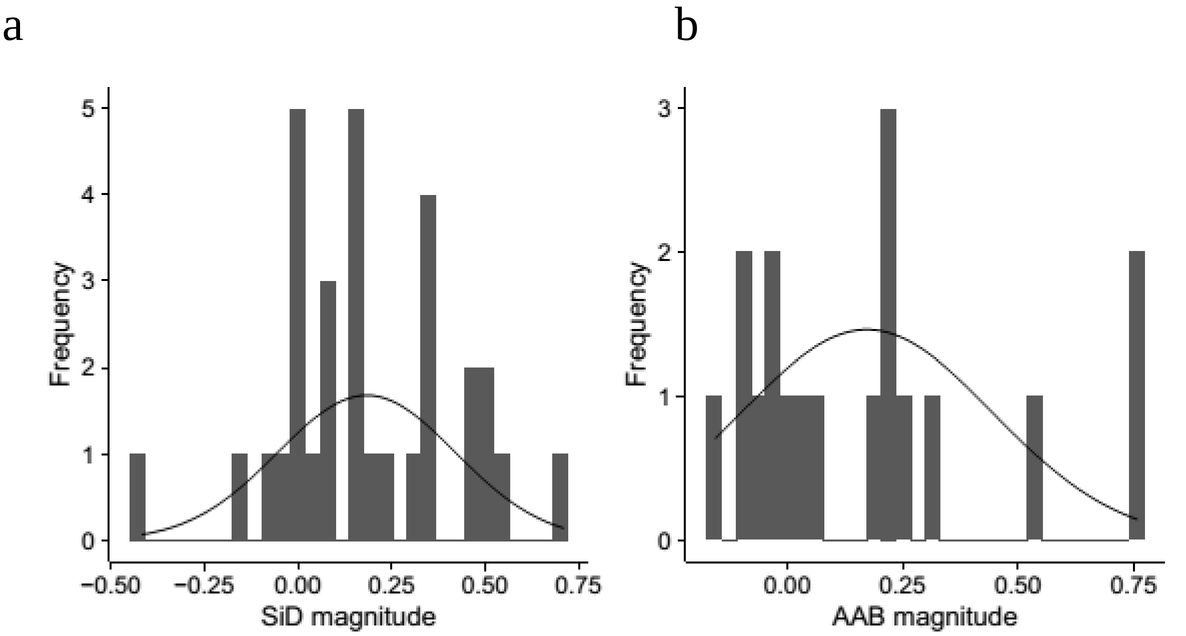

Figure 6. Panel (a): Observed frequency as a function of SiD magnitude obtained from Experiment 2 (heterogeneous, 20% density condition). Panel (b): Observed frequency as a function of AAB magnitude – calculated by subtracting the T2|T1 accuracy at Lag 1 condition from that of Lag 8 condition – obtained from Experiment 3. The overlaid curves represent best fitted curves to depict the distributions.

To achieve the aim of current experiment, we combined the SiD and AAB paradigms and created a new task called the SiD-AAB task. Using the SiD-AAB task, we obtained both SiD and AAB magnitude from each individual in a relatively brief experimental session.

Method

Participants. Two hundred participants (116 men, 4 gender not reported) completed the behavioral task combining SiD and AAB paradigm (SiD-AAB task) via Amazon Mechanical Turk (AMT). Participants received $3 USD for the study, which lasted approximately 50 to 60 minutes.

Behavioral task. The SiD-AAB task was built upon paradigms established in the previous experiments. The SiD task used in Experiment 2 (heterogeneous SS of 20% density) and AAB task used in Experiment 3 were combined into a single task with minor modifications to their stimulus features. A heterogeneous SiD task was used in order to generate a more stable level of performance in each individual, as performance in the homogenous version habituated rather quickly.

Stimuli and apparatus. The distractor stimuli in the rapid auditory presentation (RAP) were pure tones of log-related frequencies ranging from 639 to 2911 Hz (639, 697, 760, 829, 904, 944, 986, 1029, 1122, 1224, 1335, 1456, 1587, 1731, 1888, 2059, 2245, 2448, 2670, or 2911 Hz). Two complex tones were constructed for use as Targets (i.e., first target in the RAP stream). They were each made up of five log-related frequencies – 794, 891, 1000, 1122, and 1260 Hz for the low-pitched Target; 1349, 1515, 1700, 1908, and 2142 Hz for the high-pitched Target. Therefore, the sound of the Target was qualitatively distinguished (complex vs. pure) from the distractors. Out of various surprise stimuli (SS) used in Experiment 1 and 2, 24 SS were selected. They were spoken letters (i.e., ‘C’, ‘L’, ‘J’, and ‘H’), spoken digits (i.e., ‘one’ and ‘two’), and other environmental sounds (i.e., sounds of alarm, balloon popping, car honking, cat meowing, cough, cowbell, dog barking, giggle, hiccup, hi-hat cymbal, light bulb breaking, mosquito buzzing, plunger, popping tongue, slide whistle, snare drum, sneeze, slurping).

The number of complex Target tones was reduced from the three in Experiment 3 to two (i.e., low and high) for the current experiment. In addition, the intensities of the distractor pure tones, SS, and the Probe (i.e., second target in the RAP stream) were attenuated to 30%, 30%, and 45%, respectively, in comparison to the Target. These modifications were made to reduce task difficulty so that the participants could maintain better Target discrimination and Probe detection performance in an unsupervised online experimental environment.

Procedure. Each participant went through experimental session consisting of 120 trials. All stimuli presented were pure tones, except for the complex Target tones and the heterogeneous task-irrelevant sounds (surprise stimuli, SS). The Probe was a 4000 Hz pure tone that was presented on 75% of the trials. For Probe present trials, the Probe appeared 120, 240, 360, 600, 840, or 1080 ms after the onset of the Target with equal probability. These SOAs correspond to Lag 1, Lag 2, Lag 3, Lag 5, Lag 7, and Lag 9, respectively. After hearing the RAP, participants were asked first to identify the Target, pressing the ‘d’ key if the low-pitched Target had been detected or the ‘f’ key if the high-pitched Target had been detected. They next reported the presence of the Probe, pressing the ‘j’ key if the Probe had been detected and the ‘k’ key if not. All responses were unspeeded.

During 20% of the trials, a heterogeneous SS (i.e., various sounds and letters) was embedded between the Target and Probe. During these SiD trials, the Probe appeared 1080 and 360 ms after the onset of the Target and SS respectively, with 75% probability. In relation to the Probe’s position, these SOAs correspond to Lag 9 and 3 (see Figure 7). For the SiD trials, the Probe appeared outside of the primary AAB window to reduce the Target’s effect on Probe detection after the presentation of a SS. Considerable temporal distance was also inserted between the Target and SS (i.e., Lag 6 – 720 ms after the onset of the Target) to minimize the influence of the Target on the perception of the SS. Pilot testing also suggested that the SS was clearly audible (and distracting) even within these blink trials. Conversely, the Probe’s position 360 ms after the SS onset rendered it vulnerable to SiD’s effects (see Experiments 1 and 2).

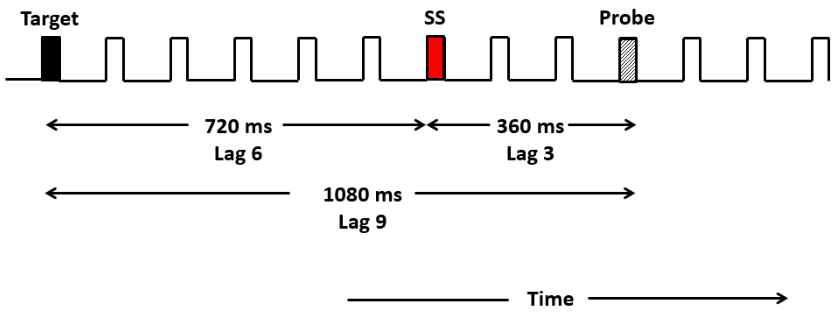

Figure 7. A schematic representation of the Probe-present SiD trial (SS + Probe trial) for SiD-AAB task. The lag between the Target and SS, the SS and Probe, and the Target and Probe are 6, 3, and 9 respectively.

In a separate control experiment, twenty-five participants (13 men) were run on an identical procedure, save they were not required to discriminate the Target. This experiment allowed us to test whether the deficits in Probe detection were due to the goal-directed deployment of attentional resources for discriminating the Target as opposed to an attentional capture effect caused by the increased intensity of the Target. In addition, this control experiment allowed us to assess the impact of the Target on SiD, assuming that it had no effects on the Probe task itself.

Before performing the main SiD-AAB task, participants were instructed to adjust the volume to their level of comfort and to use headphones instead of a speaker if possible. Participants in the main experiment completed 4 practice trials discriminating the Target, 4 practice trials detecting the Probe, and 8 practice trials performing both tasks – all with feedback. Participants in the control experiment completed 4 practice trials detecting the Probe with feedback before beginning the experiment.

Results and Discussion

In order to calculate SiD and AAB measures, the key trials for each subtask were identified (see Table 1). The mean accuracy rates of the relevant Conditions were calculated for each participant. For SiD, mean accuracies were computed for 4 types of trials: SS + Probe (i.e., Probe present trials with SS), SS only (i.e., Probe absent trials with SS), Probe only (i.e., Probe present trials without SS which is equivalent to Lag 9 condition of AAB trials), and Probe absent (i.e., Probe absent trials without SS) trials. All the SS absent trials were relevant to AAB trials. They were further categorized into Lag 1, 2, 3, 5, 7, 9, and Probe absent trials.

Table 1.
Conditions relevant to calculating AAB or SiD

SS presence / Lag between the Target and Probe	SS present	SS absent
Lag 1	N.A.	AAB
Lag 2	N.A.	AAB
Lag 3	N.A.	AAB
Lag 5	N.A.	AAB
Lag 7	N.A.	AAB
Lag 9	SiD	SiD and AAB
Probe absent	SiD	SiD and AAB

Note: This table categorizes the type of RAP trials by the Lag and presence of the SS. For the analysis for SiD, Lag 9 (with or without SS) and Probe absent trials (with or without SS) were classified as SS + Probe, Probe only, SS only, and Probe absent trials. For the analysis of AAB, all the SS absent trials were used. Each cell represents relevant task(s) (i.e., SiD, AAB, both SiD and AAB, or none) according to the Lag and SS presence.

Performance classification. Preliminary analyses of the SiD-AAB task performance revealed a wide range of behavior. Different analyses required different features within the results, so participants were classified into three groups based on the criteria explained below.

Bottom bin. A substantial number of participants (N = 79, 40%) were sufficiently poor at either the discrimination or detection tasks that it was impossible to determine the effects of the Target discrimination (AAB) or an unexpected event (SiD) on the Probe detection. Participants were put into this bin if their performance on either task component was not distinguishable from chance. For the two alternative forced choice (2AFC) Target discrimination, the threshold was 60%, as determined with a binomial test. For Probe detection, a non-significant result from a Fisher's exact test was the key criterion. Only a small number of participants failed at the Target task alone (N = 8).

Top bin. A second group of participants (N = 45, 23%) showed nearly perfect Probe detection performance regardless of the condition. As such, their data contained little useful behavioral variance for either the SiD or AAB task. Participants were classified in this group if their Probe detection accuracies, contingent upon correct Target discrimination (T2|T1), were above 90% for both short lags (i.e., Lag 1 and 2) and long lags (i.e., Lag 7 and 9).

Middle bin. The remaining participants (N = 75, 38%) could perform Probe detection and Target discrimination, but were not perfect at both in all conditions.

Data collection error. One participant's data from the main experiment were unusable due to a recording error. The final N across the three bins was thus 199.

Control experiment. For the control experiment, the data of 5 participants were excluded from further analyses since their Probe detection accuracies were not distinguishable from random responding (i.e., non-significant results of Fisher's exact test). This left 20 participants for the final analysis.

Behavioral analysis. For my initial investigation into the effects of SiD and AAB in the combined SiD-AAB task, the data from the participants in the middle plus top bin were subjected to the analyses. This is consistent with the behavioral analysis in Experiment 3, in which the data of participants who showed poor performance in either Target discrimination or Probe detection task were excluded from the further analysis.

Correlation analysis. Only the data from participants in the middle bin were used for investigating the relationship between the SiD and AAB paradigms as the top and bottom bins represented floor or ceiling performance. (Importantly, the results were qualitatively similar even when high performers were included.) The data of participants in the top bin showed variability in SiD and AAB magnitude that was substantially less compared the ones observed among participants in the middle bin (see Figures 8 and 9). Therefore, the data of the top bin was excluded from the correlation analysis; this segment of the data contains substantially less information about how the two magnitudes covary. That said, qualitatively similar results were obtained even when the top bin was added to the analyses.

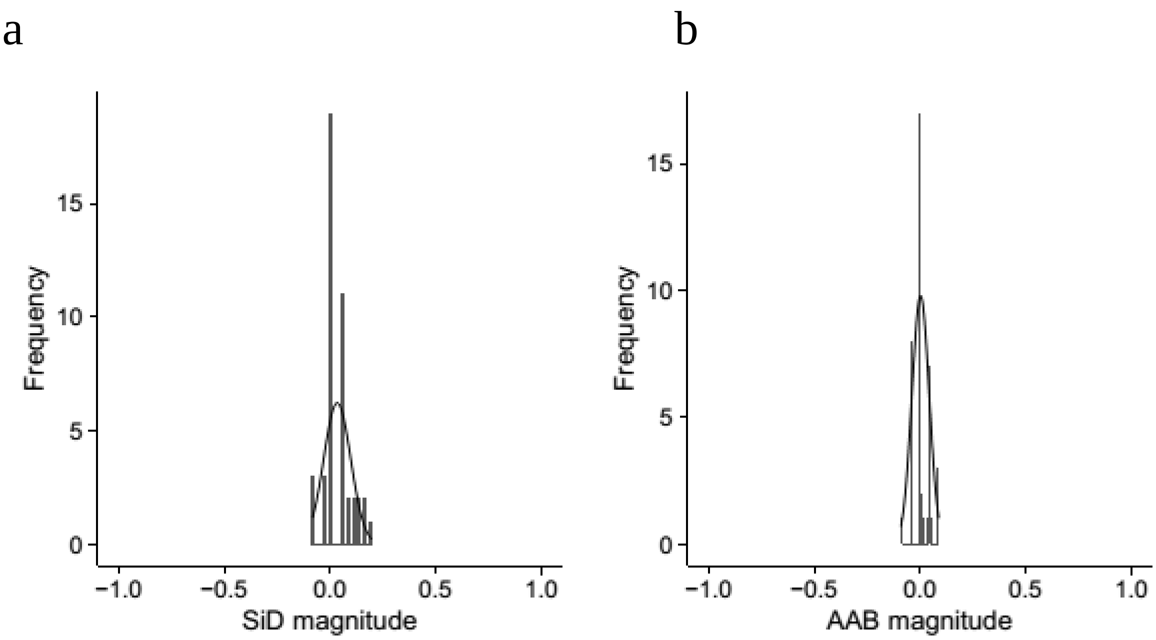

Figure 8. Panel (a): Observed frequency as a function of SiD magnitude obtained from participants in the top bin (*mean* = 0.03, *SD* = 0.06). Panel (b): Observed frequency as a function of AAB magnitude obtained from participants in the top bin (*mean* = 0.001, *SD* = 0.04). The overlaid curves represent best fitted curves to depict the distributions.

Note: SiD magnitudes are calculated by subtracting accuracy at SS + Probe trials from Probe only trials. AAB magnitudes are calculated by subtracting the mean accuracy at Lag 1 and 2 trials from the mean accuracy at Lag 7 and 9 trials.

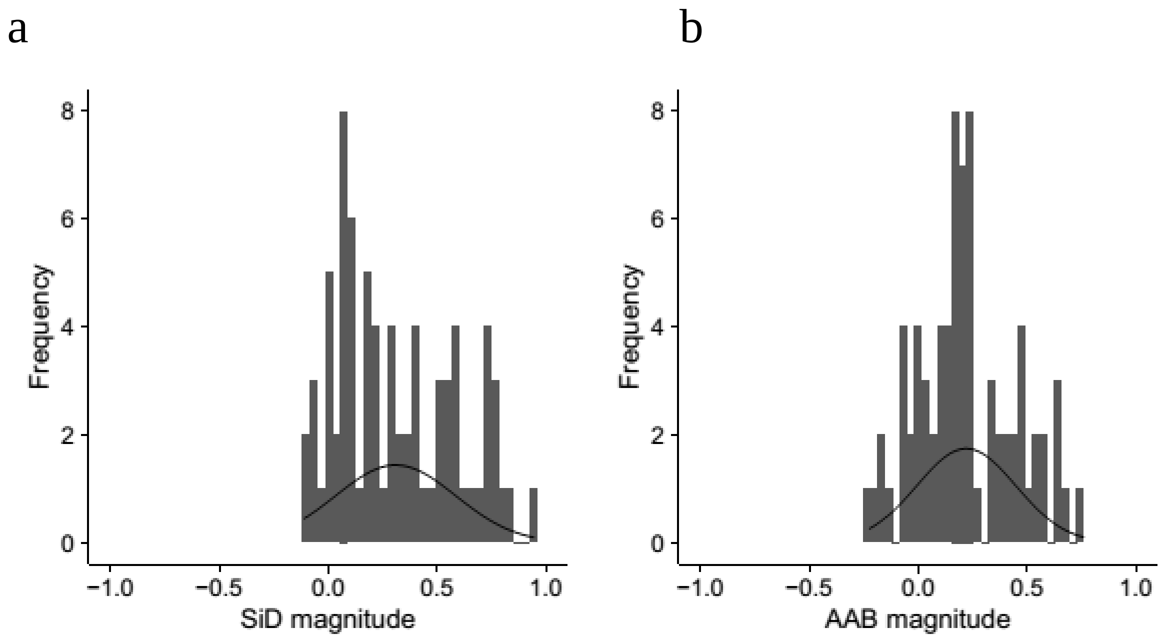

Figure 9. Panel (a): Observed frequency as a function of SiD magnitude obtained from participants in the middle bin (*mean* = 0.31, *SD* = 0.27). Panel (b): Observed frequency as a function of AAB magnitude obtained from participants in the middle bin (*mean* = 0.22, *SD* = 0.23). The overlaid curves represent best fitted curves to depict the distributions.

Probe detection accuracy on SiD trials. As stated earlier, the top and middle bins were used for analyzing the SiD and AAB behavioral performance. Mean accuracy rates as a function of Condition (SS + Probe vs. Probe only) and Time (Block 1, 2, vs. 3) appear in Figure 10. The means were not contingent upon correct Target discrimination. A two-way 2 × 3 within-subjects ANOVA with factors of Trial (Type: SS + Probe vs. Probe only) and Time (Block 1, 2, vs. 3) revealed significant main effects of Condition ($F(1, 119) = 75.40$, $p < .001$, $\eta_p^2 = .39$) and Time ($F(2, 238) = 17.36$, $p < .001$, $\eta_p^2 = .13$). The interaction was marginally significant ($F(2, 238) = 2.60$, $p = .08$, $\eta_p^2 = .02$). This result suggests that participants' accuracy was better at Probe only trials compared to SS + Probe trials, and the accuracy performance generally got better as participants progressed through blocks.

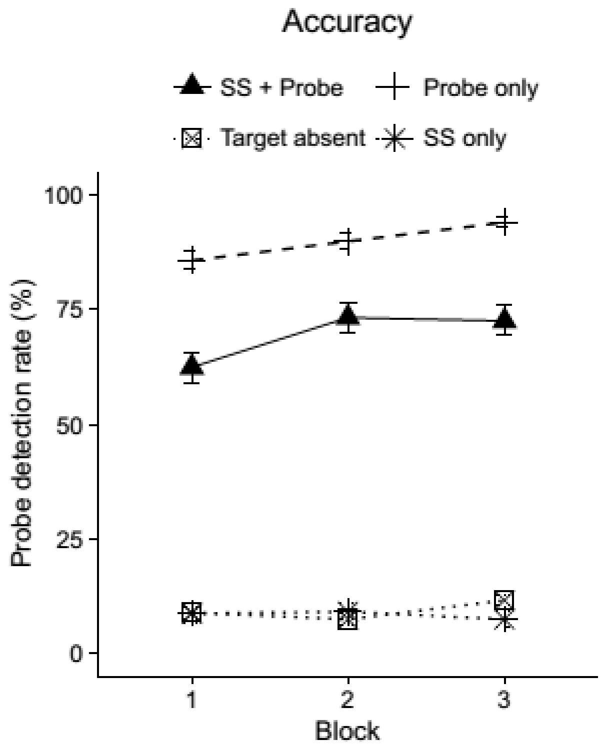

Figure 10. Mean target detection rate for each Condition as a function of time in Experiment 4 (SiD paradigm). Solid line with ▲ represents the performance for SS + Probe trials. Dashed line with + represent the performance for Target only trials. Dotted lines with ⊠, and ✳represent the performance for Target absent (false alarm rates at non-surprise trials) and SS only (false alarm rates at surprise trials) trials respectively. Error bars represent ±1 standard error of the mean (SEM).

Paired-samples t-tests revealed that the Probe detection performance on the SS + Probe trials were significantly lower than that of Probe only trials for all 3 Blocks (*p*s < .001).

These results suggest that the SS impaired Probe detection, and that the effect did not habituate during the course of this relatively short experiment. This pattern is consistent with the results from Experiment 2. For subsequent analyses, probe detection accuracy was collapsed across the three blocks when calculating SiD magnitude.

Target discrimination accuracy. The probability of a correct response in the Target task, averaged across all conditions, was 91.12% (*SD* = 8.59), showing that the target discrimination task was manageable for participants.

Accuracy of the Target discrimination was also investigated across lag. A repeated-measures ANOVA revealed a significant main effect of lag (Lag 1, 2, 3, 5, 7, vs. 9) on the Target discrimination rate ($F(5, 595) = 2.63$, $p = .02$, $\eta_p^2 = 0.02$; see Figure 11). This result suggests that there is a small but statistically significant effect of lag on the Target discrimination – such effect of lag on the Target performance is also reported in other AAB studies (e.g., Martens et al., 2009; Shen & Alain, 2012)

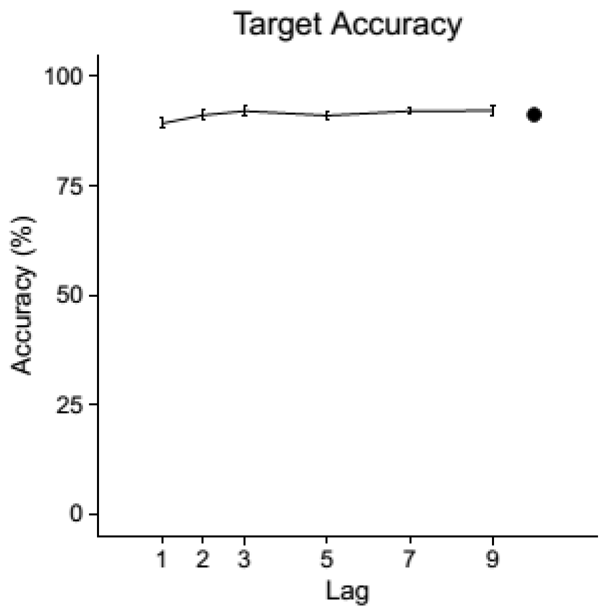

Figure 11. Mean Target discrimination rate as a function of Lag in Experiment 4. Black dot represents the mean Target discrimination rate for the Probe absent trials. Error bars represent ±1 standard error of the mean (SEM).

Probe detection accuracy during AAB trials. The mean accuracies for trials in which the Probe was present and detected (i.e., hits) are presented in Figure 12 as a function of Lag and experiment (main versus control). The means were calculated using only those trials in which participants discriminated the Target correctly. They were submitted to a mixed 6 × 2 ANOVA with Lag (1, 2, 3, 5, 7, vs. 9) as a within-subject variable and Group (Experimental vs. Control) as a between-subject variable. This analysis revealed a significant main effect of Lag ($F(5, 690) = 7.12$, $p < .001$, $\eta_p^2 = .05$), a main effect of Condition ($F(1, 138) = 5.17$, $p = .03$, $\eta_p^2 = .04$), and an interaction ($F(5, 690) = 3.54$, $p = .004$, $\eta_p^2 = .03$).

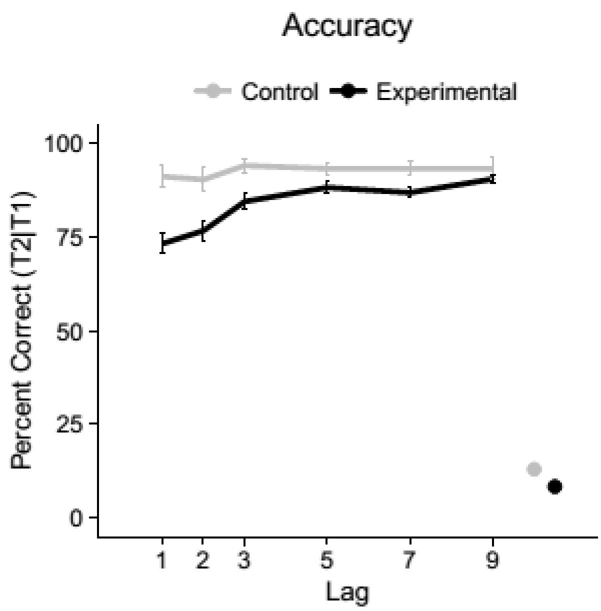

Figure 12. Mean Probe detection rate contingent upon correct Target discrimination as a function of Lag in Experiment 4. Black line represents performance of the participants in the main experiment (discriminate the pitch of the Target and report the Probe presence or absence), and the gray line represents performance of the participants in the control experiment (report the Probe presence or absence only). Black and gray dots represent false alarm rates of the participants in the experimental and control groups respectively. Error bars represent ±1 standard error of the mean (SEM).

A follow-up independent-samples t-test for the significant main effect of Group revealed that the T2|T1 rate of participants in the experimental group (*mean* = 83.40, *SD* = 17.89) was significantly lower than the Probe detection rate of participants in the control group (*mean* = 92.64, *SD* = 7.08), $t(138) = 4.06$, $p < .001$. However, while Target discrimination task impaired the Probe detection task, the mean false alarm rates between two groups were not significantly different, $t(138) = -1.28$, $p = .22$.

Most importantly, follow-up independent-samples t-tests for the significant Lag × Group interaction revealed that from Lag 1 to 3, the T2|T1 detection rate was significantly lower in the main experiment compared to the control one (*p*s < .05). However, such significant differences were not found from Lag 5 onward (*p*s > .06; difference was marginally significant at Lag 7). Furthermore, a follow-up repeated-measures ANOVAs revealed a significant main effect of lag for the experimental group ($F(5, 595) = 31.19$, $p < .001$, $\eta_p^2 = .22$), but not for the control group ($F(5, 95) = 0.51$, $p = .71$). Planned comparisons of the Lag 1 trials with each of the other lag trials in the main experiment revealed that there were significant differences between Lag 1 (*mean* = 73.27, *SD* = 29.28) and all other lags (*p*s < .001), save Lag 2 (*mean* = 76.75, *SD* = 28.28), $t(119) = -2.21$, $p = .15$).

Similar to Experiment 3, the results described above show that the Target discrimination task induced deficit in the Probe detection rate. Moreover, the degree of deficit was dependent upon the proximity between the Target and Probe. Compared to the previous experiment, the AAB deficit appeared to have a shorter duration (~360 ms), perhaps because the Target discrimination task was easier. The deficit was most pronounced at Lag 1 and 2.

Internal-consistency reliability. In order to interpret the correlations across tasks, I first determined the stability of the SiD and AAB measures themselves. To do so, I evaluated the internal-consistency reliability of each paradigm by performing a split-half reliability analysis. Only the middle bin of participants was used, as the top and bottom bins lacked useful variation across individuals (see Performance classification section above).

The data were split into odd and even trials by the trial number of the actual run. Namely, all 120 trials were given numbers according to the order of appearance and were split into either odd or even trials regardless of Condition. For these separate batches of trials, a measure of SiD magnitude for each batch of trials was obtained by regressing out the mean Probe detection accuracy in Probe only trials from the SS + Probe trials and saving the residual variability (Dale et al., 2013). Similarly, a measure of AAB magnitude was obtained by regressing out the mean Probe detection accuracy at long-lag (7 and 9) from the short-lag (1 and 2) and saving the residual variability. While calculating SiD and AAB magnitudes by simple subtraction is suitable for the comparison of means, the magnitudes calculated by using residuals from regression analyses are better for correlation analyses (MacLean & Arnell, 2012). The latter controls for unwanted variation of baseline performance across participants when the correlation of two measures are investigated. Probe + SS trials (Lag 3 trials) and short lags (Lag 1 and 2 trials) were chosen for calculating SiD and AAB magnitudes respectively for following reasons. For SiD, as evidenced by Experiment 1, Lag 3 (not Lag 1) trials best represent the phenomenon of SiD. On the other hand, consistent with the previous findings (e.g., Shen & Mondor, 2008) the accuracy deficit of AAB is more pronounced at the shortest lags for the current experiment (i.e., Lag 1 and 2 trials). Although this difference is potentially problematic for my correlation analyses, it also suggests that the two effects have slightly different time-courses even with highly similar procedures.

For the analysis, performance for the odd trials was correlated with performance on the even trials (see Table 2). The internal-consistency reliability was found to be high for both the SiD and AAB tasks, thus ensuring that both measures are stable enough to be utilized for further investigations of individual differences. The split-half r-values also provide a meaningful ceiling for interpreting the cross-task correlations.

Table 2.
Internal-consistency reliability of SiD and AAB trials.

	Split-Half *r*	Corrected *r*
SiD magnitude	0.68	0.81
AAB magnitude	0.56	0.72

All *p*s < .001
Note: Corrected r-values are calculated using Spearman-Brown procedure (Spearman, 2010) to adjust the values which are underestimated due to splitting the trials into half. However, uncorrected r-values were used for the data interpretation since odd and even trials were not truly parallel items such as test-retest measures (see Eisinga, Grotenhuis, & Pelzer, 2013).

Intercorrelations between SiD and AAB trials. To empirically test the relationship between SiD and the AAB, the deficit magnitude for each subtask was subjected to correlation analysis. As shown in Table 3, Pearson correlation coefficients were calculated to examine the relationships among four measures derived from SiD-AAB task. These measures included Target discrimination accuracy, Probe detection accuracy (a measure identical to Probe only trials for SiD task), SiD magnitude, and AAB magnitude. These final two measures were based on the residuals from the regression approach described in the internal-consistency reliability section above.

Table 3.
Intercorrelations between SiD and AAB trials

Measure	1	2	3
1. Target discrimination	–		
2. Probe detection	.28*	–	
3. SiD magnitude	-.05	>.001	–
4. AAB magnitude	-.10	.08	.24*

* p < .05, ** p < .01, *** p < .001

The result of correlation analysis showed two significant positive correlations, the (1) Target discrimination vs. Probe detection rate and (2) SiD vs. AAB magnitude. These r-values were squared and was interpreted in relation to the squared uncorrected split-half r-values in Table 2 (see Note) – i.e., 0.31 to 0.46. Such calculation was done in order to interpret the significant cross-task correlations in relation to the ceiling values obtained from the internal consistency reliability analysis. First, the significant correlation between Target discrimination vs. Probe detection rate (r^2 = 0.08) suggests that about 17% to 26% (i.e., 0.08/0.46 to 0.08/0.31) of the variation in participants' ability to discriminate the pitch of the complex tones is explained by the variation in participants' ability to detect the designated pure tone. Second, and most importantly, the latter (r^2 = 0.06) suggests that about 13% to 19% (i.e., 0.06/0.46 to 0.06/0.31) of variation across participants in SiD magnitude is explained by that of AAB magnitude. In other words, compared to the high internal consistency-reliability values, a relatively small portion of SiD variance is explained by AAB variance. The rest of the correlations revealed that the Target discrimination and Probe detection rates were not significantly correlated to SiD or AAB magnitudes. These null results suggests that our calculated SiD and AAB magnitudes are independent of participants' general tone discrimination and detection abilities. Such a lack of correlation is to be expected since overall probe detection performance was essentially regressed out of both measures.

Taken together, the significant but relatively weak correlation between SiD and AAB magnitude suggests that the SiD paradigm reveals a cognitive limitation that is partially dissociable from the one responsible for the AAB deficit. Additional discussion of this point follows at the end of this chapter.

Additional analyses. In addition to the analyses described above, I conducted cross-experimental and additional analyses to test the followings; (1) how SiD magnitude was affected by combining SiD and the AAB into a single paradigm and (2) how dual-task cost of AAB was affected by the difficulty attenuation (i.e., removal of mid-pitched Target and high-pitched distractor, boosting the intensity of the Target and Probe).

SiD paradigm. First, the SiD magnitude (calculated by simple subtraction) derived from Experiment 2 (heterogeneous SS, density 20%) and Experiment 5 were compared (Figure 13) because the designs of those two experiments were identical except for the two factors mentioned above. Independent-samples t-test revealed that there was no significant difference between the two experiments ($t(149) = -0.43$, $p = .67$), with comparable SiD magnitudes in each.

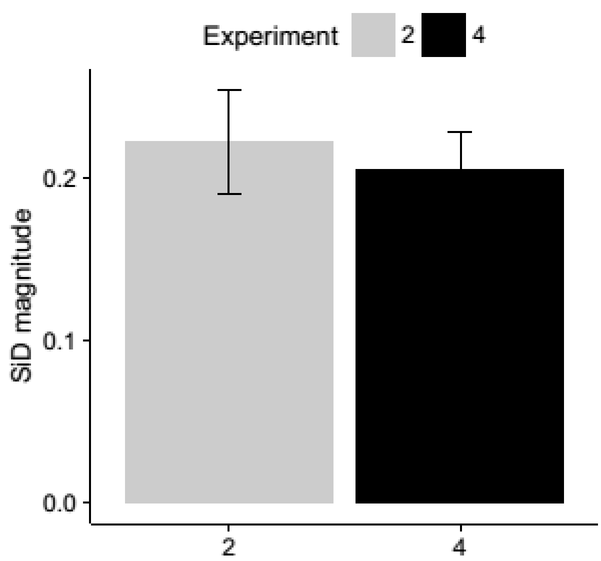

Figure 13. The group mean of SiD magnitude as a function of Experiment. Gray and black bar represent SiD magnitudes for the Experiment 2 and 4 respectively. Error bars represent ±1 standard error of the mean (SEM).

In addition to the analysis shown above, the SiD magnitude of participants in Experimental condition (*mean* = 0.21, *SD* = 0.26) was compared to that of Control condition (*mean* = 0.14, *SD* = 0.23) – to specifically investigate the influence of the Target discrimination task on SiD magnitude. This analysis also did not yield any significant difference between the two, $t(138) = 1.12$, $p = .26$, (see Figure 14).

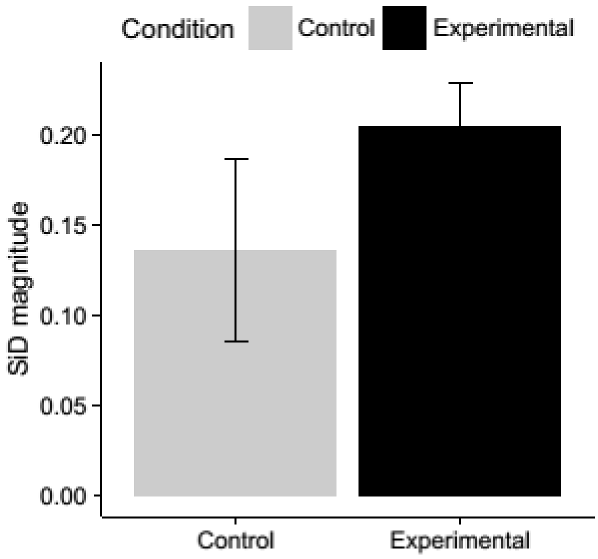

Figure 14. The group mean of SiD magnitude as a function of Condition. Gray and black bar represent SiD magnitudes for the experimental and control condition respectively. Error bars represent ±1 standard error of the mean (SEM).

The results shown above suggest that SiD magnitude was unaffected by combining the paradigms in general or the presence of a Target in particular.

AAB paradigm. Second, the dual-task costs observed in Experiment 3 and 4 were contrasted. The ANOVAs of two experiments revealed that the main effects of the Condition were both significant. However, the effect size of the two showed substantial difference – i.e., η_p^2 = .32 vs. η_p^2 = .04 for Experiment 3 and 4 respectively. These results suggest that the dual task cost was attenuated for Experiment 4. From the design of the experiment, I speculate that the reducing the Target discrimination difficulty is the most probable cause of decrease in dual-task cost.

Taken together, the cross-experimental and additional analyses support my use of the combined task for further analyses. Performance was similar for SiD in the SiD-AAB task context, and the only important difference in the AAB effects appears to have been due to an easier first task.

General Discussion

The results of Experiment 4 show that SiD represents a deficit that is partially dissociable from the AAB. Therefore, I argue that the limitations are – at least in part – specific to the forms of attention elicited by each paradigm, namely stimulus-driven and goal-directed.

The result of Experiment 4 empirically validated SiD's design because it is shown to tap onto attentional limitation which is partially dissociable from that of AAB counterpart. The result suggests that although two paradigms are both characterized by accuracy deficit, SiD paradigm is not a mere extension of AAB. It also demonstrates that even when the seeming behavioral cost is identical, the underlying processes is governed by how auditory attention was drawn away from the designated target.

On the other hand, although SiD and AAB magnitudes were shown to be partially dissociable, there was an overlap between the two. This overlap could represent an attentional switch from one stimulus to another. In the SiD paradigm, this attentional switch occurs when a participant reorients his/her attention from the SS back to Probe detection task. On the other hand, in the AAB paradigm, the switch occurs when a participant intentionally tries to shift from discriminating the Target to detecting the Probe. In ERP studies, a component called the reorienting negativity (RON) is usually observed (e.g., Sussman et al., 2003) when participants are required to reorient his/her attention back to the task-relevant tone from a task-irrelevant tone which induces auditory distraction. RON is a late negative deflection which happens around 500 ms from the onset of distracting sound. Furthermore, the RON could represent the attentional reorientation after auditory distraction as well as intentional engagement in another task-relevant sound (Hölig & Berti, 2010). Based on such evidence, my interpretation is that the small overlap between SiD and AAB magnitude may represent the attentional reorientation or switch required in both paradigms.

While the dissociability of SiD from the AAB is addressed in this chapter, it remains unclear whether the stimulus-driven process of auditory selective attention is dissociable from its goal-directed counterpart. The result demonstrating that SiD and the AAB have a relatively modest overlap indirectly supports the idea that stimulus-driven and goal-directed processes of auditory selective attention are largely dissociable, with just a partial interaction. This view is consistent with the findings in vision studies which claim that the two processes are dissociable but they do interact (Asplund, Todd, Snyder, & Marois, 2010; Corbetta & Shulman, 2002; Serences et al., 2005). It would be useful to explore the neural correlates or implementation of these two forms of auditory selective attention, thereby providing more information about their degree of dissociation or similarity. Furthermore, to test whether such a dissociation is indeed common across modalities, a study incorporating both visual and auditory paradigms can be performed.

The SiD paradigm in the context of attentional capture

While I argue that SiD represents a stimulus-driven limitation in auditory selective attention, other paradigms such as auditory attentional capture or auditory distraction have also been used for exploring such limitations. Dalton & Lavie (2004) used a RAP task to show that a deviant tone having outstanding intensity or frequency captures auditory attention and results in longer reaction times to a target. Similarly, Horváth & Burgyán (2011) used a different RAP task to demonstrate that an AAB-like accuracy deficit can be induced by auditory distraction using tones with deviant frequency. The deviant tones or singletons used in these studies share commonality with rest of the stimulus in a RAP (e.g., sinusoidal waveform) but is made different by modulating one specific dimension (e.g., frequency, intensity).

The question remains whether these findings and SiD are due to the same limitation or qualitatively (or neurally) different limitations. Despite the differences in experimental designs, the RT cost Dalton & Lavie (2004) observed is consistent with the result of current study. The result of Experiment 1 showed that the SS significantly delayed RT. Although these similar patterns do not strongly suggest similar mechanisms, they are consistent with them.

The long-lasting accuracy deficit Horváth & Burgyán (2011) observed is different from the short-lived SiD. Their study's accuracy deficit was most pronounced at Lag 1, especially when there was a large frequency discrepancy between the deviant tone and other tones in the RAP. We hypothesize that their finding could be more similar to the Lag 1 effects in the current study. In Experiment 1, accuracy improved with increasing lag when performance was averaged across blocks (ignoring the habituation effects). This pattern of deficit is similar to what Horváth & Burgyán (2011) observed.

Despite the similarities between SiD and auditory attentional capture or auditory distraction studies described above, it is still not possible to draw a conclusion because the rate or presence of habituation is not reported in those studies. If no habituation is observed among studies using deviant tones, I speculate that there is a possibility that featural commonality between the deviant tone and target or distractor is making the capture immune from dissipation. A finding from vision study using RSVP task (Folk, Leber, & Egeth, 2008) suggest that attentional capture happen only when a deviant stimulus or singleton possessed a critical feature that also distinguishes the target from distractors (e.g., color red). This finding supports the "contingent capture" account by demonstrating that goal-directed component plays an important role in involuntary attentional capture. Although deviant tones were not characterized by the critical factor that defined targets in auditory attentional capture or auditory distraction studies, the fact that they still shared basic element such as sinusoidal wave form still leaves a possibility that it is more difficult to ignore deviant tones compared to the radically different novel tones. I speculate that whether deviant sounds tap onto goal-directed limitation compared to novel ones could possibly be investigated via habituation rate since the involvement of goal-directed processes is shown to prolong the behavioral cost as evidenced by AAB.

As a matter of fact, Escera, Alho, Winkler, & Näätänen (1998) distinguished the neural mechanisms of involuntary attention reacting to the deviant (reflected in the MMN ERP component) and novel tone (reflected in the N1 ERP component) – i.e., a pure tone which has slightly higher frequency from distractor pure tones and environmental sounds such as sound of a drill respectively. Furthermore, their experiment dissociated the behavioral costs, with the former related to an accuracy deficit and the latter to increased RTs cost. These results are different from our findings, but that could reflect Escera et al. (1998)'s use of a cross-modal task.

Future studies could disentangle the effects of deviant tones and SS on target detection performance using a RAP task. The study should equalize the density and heterogeneity of the deviant tone and SS – and focus on the habituation rate and magnitude of the Lag 3 deficit. I hypothesize that such a systematic comparison would allow surprise paradigm to be properly contextualized in existing literature about auditory attentional capture and auditory distraction.

Chapter IV

Conclusion

Summary of findings

In this thesis, a new paradigm named surprise-induced deafness (SiD) was established and explored via series of experiments (see Table 1). In Experiment 1, I discovered a transient target detection deficit following an unexpected sound, which habituated over the course of the experiment (the SiD phenomenon). In Experiment 2, I explored the magnitude and habituation rate of SiD when the heterogeneity and relative frequency of surprises were manipulated. The results showed that increased heterogeneity slowed the habituation rate, and lower density increased the magnitude of SiD. In Experiment 3, I constructed and tested an auditory attentional blink (AAB) paradigm that was as similar to the SiD paradigm in all respects except for the goal-directed first target discrimination. In Experiment 4, I combined the AAB and SiD paradigms into a single experiment and used an individual differences approach to determine whether the two deficits had common psychological components. The SiD-AAB task results suggested that the deficits were partially dissociable. Taken together, these four experiments established and explored SiD as an interesting paradigm that evidences a stimulus-driven limitation of auditory selective attention.

Table 1.

Primary purpose and findings of 4 experiments

Experiment	Primary purpose	Findings
1	Establish SiD	1. Lag 3 deficit shows quick habituation 2. Lag 1 deficit did not show habituation
2	Explore SS heterogeneity and density	1. Heterogeneous SS delays habituation 2. Higher SS density attenuates SiD magnitude
3	Reestablish AAB	1. AAB is reestablished 2. Difficult Target discrimination increased the dual-task cost
4	Compare SiD and AAB	1. SiD paradigm is tapping onto limitation partially dissociable from the one AAB paradigm taps onto 2. SiD and AAB paradigm can be combined

Theoretical implications

I believe that SiD could be a useful tool for advancing attention research. Selective temporal attention has been studied across modalities and forms (goal-directed versus stimulus-driven), but SiD fills in a previously missing piece (see Table 2). As such, we now have a more complete set of tasks to explore, thereby allowing us to investigate the relationships of different attentional processes across sensory modalities using comparable paradigms.

Table 2.
Currently available paradigms

Modality \ Limitation	Stimulus-driven	Goal-directed
Vision	Surprise-induced blindness	Attentional blink
Audition	Surprise-induced deafness	Auditory attentional blink

Previous studies have shown that the goal-directed limitations could be modality-specific (Martens et al., 2009; Martens et al., 2010). On the other hand, a small but significant correlation between SiD and AAB was evidenced in the current study. While how different forms of attentional limitation across visual and auditory modalities interact with one another is only partially known at the moment, the completion of matrix described above bears a possibility to enhance our knowledge about selective attention. I hypothesize that the value of establishing SiD will be fully appreciated by running a large-scale correlational study utilizing both SiD-AAB as well as SiB-AB task (a study that is presently underway). Specifically, such a study allows researchers to investigate bivariate correlations of six different combinations (i.e., SiB-SiD, AB-AAB, SiB-AB, SiD-AAB, SiB-AAB, and SiD-AB).

Furthermore, the newly established SiD paradigm can be extended into direct comparisons across modalities by combining the RAP and RSVP tasks to investigate “cross-modal surprise”. Such a study would more directly address Horstmann’s (2015) claim that surprise reactions involve central, amodal attentional processes. It would also allow us to further contrast SiD with blink experiments. The presence of amodal or central goal-directed limitation remains controversial for the AB and AAB; cross-modal attentional blinks combining RAP and RSVP tasks have yielded divergent findings (Arnell & Jolicœur, 1999; Potter et al., 1998; Soto-Faraco & Spence, 2002).

Clinical implications

Earlier, I proposed that the relationship between stimulus-driven vs. goal-directed limitation should be further investigated using a neural measure in conjunction with behavioral measures such as the SiD and AAB paradigms. However, the behavioral results alone may also have clinical applications. The result of Experiment 4 suggested that the amount of limited attentional resource a person deploys to a certain sound depends on whether the sound was the source of surprise or target of focus during a given task. In a general term, this result suggests that even if a person is easily distracted by an unexpected sound, it does not necessarily mean that the person cannot exert goal-directed focus on specific sound. If this is a valid insight, then it sheds a new light for understanding how we define and understand “attentional problems”. For example, such a problem is apparent among people with attention-deficit/hyperactive disorder (ADHD).

ADHD is a disorder primarily characterized by the symptoms of inattention, hyperactivity, and impulsivity (American Psychiatric Association, 2013). Multiple cognitive processes are associated with the disorder or claimed to be its cause. These include (i.e. behavioral inhibition, sustained attention, and executive functions; Barkley, 1997; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), goal-directed processes of visual selective attention (usage of AB paradigm; Hollingsworth, McAuliffe, & Knowlton, 2001; Li, Lin, Chang, & Hung, 2004), and impoverishment of auditory signals (usage of auditory oddball paradigm; Gomes et al., 2012; Orinstein & Stevens, 2014; Puente, Ysunza, Pamplona, Silva-Rojas, & Lara, 2002; Stevens, Pearlson, & Kiehl, 2007). Experiments utilizing the SiD-AAB and/or SiB-AB paradigms could potentially help clinical researchers to better understand the mechanism behind the disorder, and perhaps could even support better diagnoses of ADHD subtypes.

Practical implications

In our daily lives, auditory distraction is experienced frequently by most of us. At times, this distraction has a useful function: Audition can act as an early warning system. However, in the contemporary time, this function also has a cost. Particularly in dense and busy cities, we are exposed to noise continually. Despite this fact, the need for goal-directed selective auditory attention has not diminished, as it is evident from the fact that communication still remains as the important high-level activity for human being. The result of Experiment 2 suggests that our attentional resource is constantly used for evaluating unusual sound. This result could be implying that the intensity of noise *per se* is not the sole determinant of how much the cognitive resource is depleted by a noise. Instead, whether or not the content of noise keeps changing could affect how much the cognitive resource is drained. Therefore, I speculate that minimizing the heterogeneity of noise in the immediate surrounding will improve our goal-directed performance.

Limitations of the current study

Although the current study successfully established SiD paradigm, substantial amount of data were lost in this study because some participants had difficulty performing the task. This result calls the generalizability of SiD task into question. A pilot study was run (see Appendix A) to explore whether SiD is still observable using RAP task with substantially attenuated difficulty. A weak SiD was observed but the result was strongly affected by the ceiling effect. The current series of experiments demonstrated that there is a substantial performance differences across individuals when it comes to pitch discrimination. Future studies should try out various types of RAP tasks to search for the one that yields reasonable performance yet capture the SiD effect.

The importance of auditory selective attention study

Although auditory selective attention has been explored for decades (Styles, 2006), the number of studies are still substantially fewer than those of its visual counterpart (Jones, 1993). An opportunity is created by this unequal rate of exploration, as many visual paradigms can be tested in their auditory forms and then compared across modalities. As it is shown above, replicating SiB into the auditory domain expanded the horizon of possible future research because filling in the "missing piece" substantially increased realm of future exploration.

In the contemporary world, we believe that there is a great necessity to understand how auditory and visual selective attention interact. As technology has advanced, physical labors are being automated and how we thrive in a society that is becoming more and more dependent upon information processing. We are required to perform high-level tasks via verbal communication and reading, and there are many demands for our attention and pressure to multi-task. Understanding how auditory stimuli interfere with or facilitate visual selective attention is therefore crucial for optimizing our productivity and happiness. Therefore, we believe that various possibilities to investigate how selective attention across those two important sensory modalities interact provide fertile ground to harvest the knowledge we need for maximizing the high-level information processing. I hope that one small advancement in the knowledge of how auditory selective attention works had a meaningful contribution to the existing study of attention.

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Appendix A

Follow-up experiment: Exploring the generalizable SiD

We believe that series of experiments successfully established and validated SiD as a paradigm tapping onto stimulus-driven limitation of auditory selective attention. However, main limitation of the SiD paradigm is the generalizability of the RAP task using pure tones. As it was evident, quite a number of participants had to be screened out due to their poor performance. This result revealed that there is a big variation across individuals when it comes to the accuracy of pitch discrimination. Another domain that was unexplored in the series of SiD experiments is the effect of SS's identity on SiD magnitude. In our previous experiments, auditory objects such as spoken letter or sound of alarm were used as SS. The best effort was made to select the sounds which remains intelligible after compressing them to 110 ms. However, whether intelligibility of the sound plays critical role in inducing SiD is yet to be explored. Taking the two outstanding questions into consideration, the current follow-up experiment explored two possibilities: (1) whether SiD could still be observed by using simple detection RAP tasks with substantially attenuated difficulty and (2) whether SS has to be intelligible to induce the accuracy deficit. In the current experiment, the difficulty of the Probe detection was attenuated by removing high-pitched distractors. Furthermore, unintelligible sounds were added to the existing SS as non-auditory objects – as opposed to auditory objects.

Method

The current experiment was identical to that of Experiment 4 with the following exceptions: Eighteen participants (14 men) with normal hearing participated for payment ($1) via Amazon Mechanical Turk (AMT). The intensities of distractors and the Probe were attenuated to 30% and 45% in comparison to the intensities of the SS. The stimuli used for distractors in RAP were pure tones of log-related frequencies ranging from 639 to 2448 Hz (639, 697, 760, 829, 904, 944, 986, 1029, 1122, 1224, 1335, 1456, 1587, 1731, 1888, 2059, 2245, or 2448 Hz). Auditory and non-auditory objects were used as the SS. As auditory objects, 6 surprise stimuli (SS) were sampled from Experiment 1 to 5. They were spoken letter (i.e., ‘I’), spoken digit (i.e., one), and various sounds (i.e., sounds of alarm, cough, dog barking, hiccup). As non-auditory objects, 6 complex tones composed of 5 different log-related frequencies were used. Two of them were low (454, 522, 600, 689, and 791 Hz), mid (909, 1044, 1200, 1378, and 1583 Hz), and high-pitched (1818, 2089, 2400, 2756, and 3166 Hz) Targets from Experiment 3. Two of them were low (794, 891, 1000, 1122, and 1260 Hz) and high-pitched (1349, 1515, 1700, 1908, and 2142 Hz) Targets from Experiment 4. One of them was a newly made complex tone (944, 1190, 1500, 1889, and 2381 Hz). Before moving on to the main experiment, participants went through 8 trials of slow RAP task (SOA = 130 ms) and 8 trials of normal speed RAP task (SOA = 120 ms). No surprise trials were presented during the practice blocks and 75% of the trials contained the Probe. For the main experiment, participants went through 60 RAP trials which were divided into 2 blocks of 30 trials. Participants were only required to detect the presence of the Probe. Unlike SiD-AAB task in Experiment 5, the Targets were not presented in the RAP.

Results

RAP trials were categorized into two surprise trials – i.e., Lag 3 and SS only (SS present without the Probe) – and two non-surprise trials – i.e., Probe only (Probe present without SS), and Probe absent (Probe absent without SS). Lag 3 trials are further categorized into two types depending on the identity of the SS – i.e., Auditory vs. non-Auditory object. Using only the Probe present trials, mean accuracy rates were calculated for each participant as a function of Condition (Lag 3 vs. Target only). Furthermore, using only Lag 3 trials, mean accuracy rates were calculated for each participant as a function of SS (Auditory vs. non-Auditory object).

Data exclusion. Participants whose scores were not distinguishable from random responding (N = 3) were excluded from further analyses using Fisher's exact test.

Accuracy. Mean accuracy rates as a function of Condition (Lag 3 vs. Target only) appear in Figure 1. A paired-samples t-test revealed that participants' mean accuracy at Lag 3 trials (*mean* = 82.96%, *SD* = 31.95) was lower than that of Target only trials (*mean* = 99.07%, *SD* = 2.01) and the difference was marginally significant, $t(14) = -2.04$, $p = .06$.

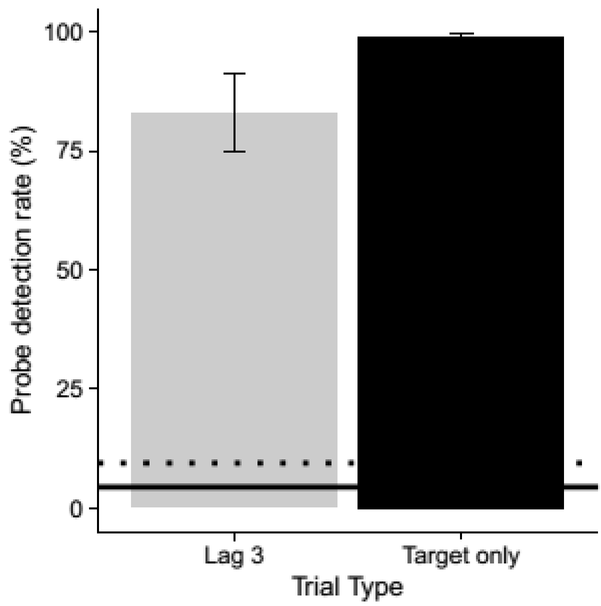

Figure 1. Mean Probe detection rate as a function of Condition in the follow-up experiment. Gray and black bar represent accuracy at Lag 3 and Target only trial respectively. Dotted and solid line represent false alarm rate at non-surprise and surprise trial respectively. Error bars represent ±1 standard error of the mean (SEM).

Furthermore, the SiD magnitudes were calculated for each participant by subtracting their Probe detection rate at Lag 3 trials from that of Target trials. Figure 2 depicts the distribution of SiD magnitudes across participants.

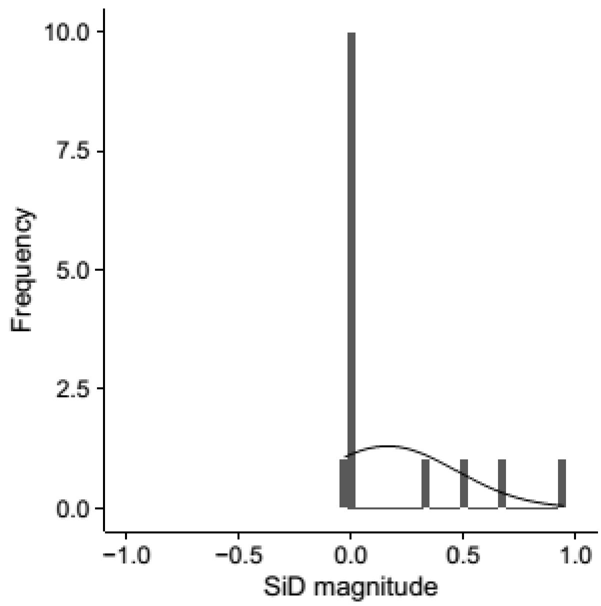

Figure 2. Observed frequency as a function of SiD magnitude obtained from participants in the follow-up experiment (*mean* = 0.16, *SD* = 0.31). The overlaid curves represent best fitted curves to depict the distributions.

Mean accuracy rates as a function of SS (Auditory vs. non-Auditory object) appear in Figure 3. Furthermore, a paired-samples t-test revealed that participants' mean accuracy at Lag 3 trials with Auditory objects (*mean* = 88.89%, *SD* = 23.29) did not significantly differ from that of non-Auditory objects (*mean* = 83.33%, *SD* = 30.21), $t(14) = -0.84$, $p = .42$.

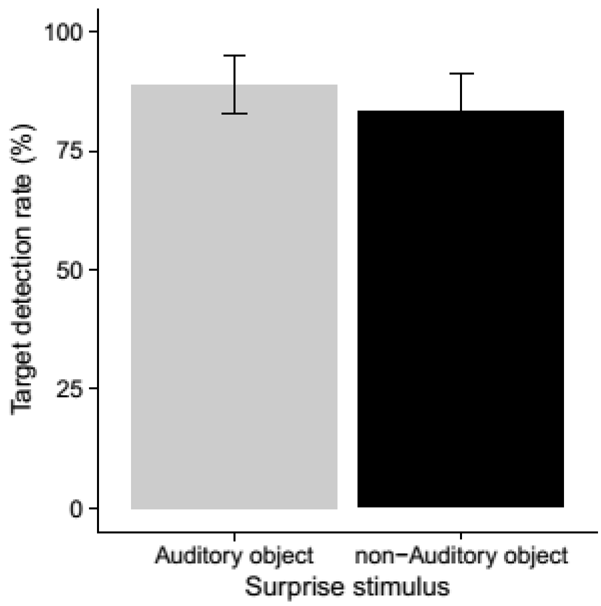

Figure 3. Mean Probe detection rate as a function of surprise stimulus (SS) in the follow-up experiment. Gray and black bar represent accuracy at surprise trials with Auditory and non-Auditory object respectively. Error bars represent ±1 standard error of the mean (SEM).

Discussion

The result of current experiment suggests that compared to the previous experiments, substantially less participants were screened out due to random responses. For heterogeneous 20% SS condition in Experiment 2 the screen out rate was 39.22%. But for the current experiment, the rate was less than half – i.e., 16.67%. SiD was still observable with the current RAP task, but the significance dropped to marginal most probably due to ceiling effect as it is evident from the near-perfect baseline accuracy.

Despite the fact that the attenuation of RAP task difficulty resulted in less pronounced SiD effect, the individual differences was still observable. As a matter of fact, the spread of SiD magnitude obtained from the current experiment was still quite comparable to the one observed at Experiment 4 – i.e., *SD* = 0.31 and *SD* = 0.27 respectively. This result has a practical implication because it suggests that studies utilizing SiD magnitude could be conducted with manageable RAP tasks which prevents substantial data loss.

The comparison of performance between surprise trials with auditory and non-auditory object revealed that the accuracy deficit could be induced by the latter. This has a substantial theoretical implication since numerous auditory attentional capture and auditory distraction studies utilize non-auditory objects as deviant pure tones to investigate the neural-correlates and behavioral cost (see Friedman et al., 2001 for a review).

A practical implication of discovering the efficacy of non-auditory object to induce SiD is that it allows researchers to explore the longer habituation rate when heterogeneous SS is used. The series of SiD experiments have revealed that the heterogeneity of SS significantly delays habituation. Although we found out that the habituation is still incomplete when participants were exposed to 24 heterogeneous SS, the complete timecourse of the recovery from SiD is yet to be known. The major practical difficulty in coming up with more than 24 SS was that sounds which maintain their intelligibility after compressing them to 110 ms were limited in number. However, the current experiment revealed that any task-irrelevant sound could be used as the SS. Future studies should take advantage of this finding and explore the complete timecourse of habituation when heterogeneous SS are utilized.