Universitat de les Illes Balears

DOCTORAL THESIS

2016

TOWARDS A BETTER UNDERSTANDING OF DISTRACTION BY UNEXPECTED STIMULI ACROSS THE LIFESPAN

Alicia Leiva Mir

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Doctoral Programme of Cognition and Human Evolution

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Alicia Leiva Mir

Thesis Supervisor: Fabrice Parmentier

Thesis Co- supervisor: Pilar Andrés

Doctor by the Universitat de les Illes Balears

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Preface

The present dissertation is composed of 5 experimental series, all of them published or accepted to be published in international journals (see the list of publications presented below). This work was produced under the supervision of Dr Fabrice Parmentier and Dr Pilar Andrés.

All studies were carried out at the Cognitive Psychology Laboratory of the University of the Balearic Islands, except the fourth study, which was carried out at the Cognition Group's Laboratory of the University of Exeter under the supervision of Professor Frederick Verbruggen.

The 5 experimental series provide new and original evidence in the field of attention research and that of the cognitive mechanisms underpinning distraction in particular. Concretely, we examined (1) whether deviance distraction is observed irrespective of modality boundaries (*Publication 1*: Leiva, Parmentier, Andrés, 2015a); (2) the effects of ageing on auditory and visual deviance distraction (*Publications 2* and *3*: Leiva, Parmentier, & Andrés, 2015b; Leiva, Andrés, & Parmentier, 2015); (3) the link between attentional reorienting and response inhibition (*Publication 4*: Leiva, Parmentier, Elchlepp, & Verbruggen, 2015); (4) the modulation of deviance distraction across the lifespan as well as (5) the extent to which working memory and response inhibition contribute to deviance distraction and to what extent they can account for its age-related variation (*Publication 5*: Leiva, Andrés, Servera, Verbruggen, & Parmentier, in press).

List of publications included in the dissertation

Leiva, A., Parmentier, F. B. R., & Andrés, P. (2015a). Distraction by deviance: Comparing the effects of auditory and visual deviant stimuli on auditory and visual target processing. *Experimental Psychology*, *62*(1), 54-65. doi: 10.1027/1618-3169/a000273. Impact factor: 2.076

Leiva, A., Parmentier, F. B. R., & Andrés, P. (2015b). Aging increases distraction by auditory oddballs in visual, but not auditory tasks. *Psychological Research*, *79*(3), 401-402. doi: 10.1007/s00426-014-0573-5. Impact factor: 2.863

Leiva, A., Andrés, P., & Parmentier, F. B. R. (2015). When aging does not increase distraction: Evidence from pure auditory and visual oddball tasks. *Journal of Experimental Psychology: Human Perception and Performance*. *41*(6), 1612-1622. doi: 10.1037/xhp0000112. Impact factor: 3.358

Leiva, A., Parmentier, F. B. R., Elchlepp, H., & Verbruggen, F. (2015). Reorienting the mind: The impact of novel sounds on go/no-go performance. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(5), 1197-202. doi: 10.1037/xhp0000111. Impact factor: 3.358

Leiva, A., Andrés, P., Servera, M., Verbruggen, F., & Parmentier, F. B. R. (in press). The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study. *Developmental psychology*. Impact factor: 4.141

Abstract

Selective attention is the ability to filter out task-irrelevant stimuli in order to concentrate on the task at hand. Other mechanisms ensure that unexpected but potentially important stimuli can however break through attention and capture our attention. While adaptive, these mechanisms can have one downside when the attention capturing stimulus is of no relevance: distraction. Past research explored the mechanisms involved in this type of distraction and its behavioural impact but evidence is limited, especially with respect to its variation with age. Therefore, the main objective of this dissertation is to reach a better understanding of the cognitive mechanisms underpinning distraction by unexpected stimuli through the lifespan.

A total of 5 experimental series form part of this dissertation. *Publication 1* provides original evidence questioning the hypothesis of deviance distraction as a modality-independent mechanism. In this study, we orthogonally contrasted the sensory modalities of the irrelevant and relevant stimuli in oddball tasks. The results showed deviance distraction for auditory deviants irrespective of the targets' modality. Visual deviants, in contrast, produced no deviance distraction (for visual or for auditory target stimuli), except in the specific situation in which participants were forced to attend to the irrelevant stimuli and under specific conditions related to the spatial properties of the stimuli.

Following the evidence that our cognitive system seems to be more vulnerable to distraction when deviant stimuli are presented in the auditory modality than when presented in the visual modality (at least when irrelevant and target stimuli do not form part of the same object), in *Publication 2* we used this modality to study, for the first time, the effect of ageing on deviance distraction in cross-modal (auditory-visual) and uni-modal (auditory–auditory) oddball tasks (within-participant). The results showed an effect of age on distraction in the cross-modal task but not in the uni-modal task. In *Publication 3* we studied the effect of age on deviance distraction using uni-modal oddball tasks, visual and auditory, in which irrelevant and relevant information formed part of the same perceptual object. Our results showed deviance distraction in the auditory and visual modalities, but the amount of distraction did not vary with age. Hence, together, *Publications 2* and *3* provide strong evidence that the effect of ageing on deviance distraction is specific to the cross-modal oddball task and that deviance distraction in purely auditory or visual oddball tasks does not increase in old age.

In *Publication 4* we studied the link between response inhibition and attentional reorienting. Response inhibition and attentional reorienting are usually studied separately but recent research has proposed that both processes might rely on similar cognitive and neural mechanisms. In two experiments, we contrasted the "circuit breaker" account (which assumes that unexpected events produce global suppression of motor output) and the "stimulus detection" account (which assumes that attention is reoriented to unexpected events). Our results supported the "stimulus detection" account, highlighting the importance of reorienting our attention in order to detect the unexpected signals and consequently cancel or update our actions.

In *Publication 5,* we adopted a more global perspective. We explored deviance distraction across the lifespan (comparing children, young and older adults) as well as

the role of working memory capacity (WMC) and response inhibition in deviance distraction across the lifespan. The results revealed deviance distraction in all age groups, but more so in older adults compared to young adults and children (who did not differ from each other). Response inhibition did not account for deviance distraction in any of the age groups while WMC correlated positively with deviance distraction in children, negatively in older adults, and not at all in young adults.

Resumen (Castellano)

La atención selectiva es la habilidad de filtrar estímulos irrelevantes para la tarea en curso con el fin de concentrase en ella. Al mismo tiempo, otros mecanismos aseguran que estímulos inesperados pero potencialmente importantes puedan capturar nuestra atención y ser procesados. Estos mecanismos, aunque adaptativos, tienen una desventaja: la distracción. Estudios anteriores han explorado los mecanismos involucrados en la distracción comportamental, pero la evidencia es limitada. Por lo tanto, el principal objetivo de esta tesis es el de alcanzar un mayor conocimiento de los mecanismos cognitivos que fundamentan la distracción por estímulos inesperados a través del ciclo vital.

Un total de 5 series experimentales conforman esta tesis doctoral. La *Publicación 1* proporciona evidencia original que cuestiona la hipótesis de la distracción por estímulos inesperados como un mecanismo independiente de la modalidad de presentación del estímulo. En este estudio, contrastamos ortogonalmente las modalidades sensoriales de los estímulos relevantes e irrelevantes en tareas oddball. Los resultados muestran distracción para los estímulos auditivos desviados independientemente de la modalidad de los estímulos diana. En cambio, los estímulos desviados visuales no produjeron distracción (para estímulos diana visuales o auditivos), excepto en la situación específica en que los participantes fueron forzados a atender a los estímulos irrelevantes y bajo condiciones específicas relacionadas con las propiedades espaciales de los estímulos.

Siguiendo la evidencia de que nuestro sistema cognitivo parece ser más vulnerable a la distracción cuando los estímulos desviados son presentados en la modalidad auditiva que cuando son presentados en la modalidad visual (al menos cuando los estímulos irrelevante y diana no forman parte del mismo objeto perceptivo), en la *Publicación 2* utilizamos esta modalidad para estudiar, por primera vez, el efecto del envejecimiento en la distracción por estímulos inesperados en tareas oddball cross-modal (auditivo-visual) y uni-modal (auditivo-auditivo). Los resultados mostraron un efecto de la edad en la distracción en la tarea cross-modal pero no en la uni-modal. En la *Publicación 3*, estudiamos el efecto de la edad en la distracción por estímulos desviados utilizando tareas oddball uni-modales, visual y auditiva, cuya información relevante e irrelevante formaba parte del mismo objeto perceptivo. Nuestros resultados mostraron distracción por estímulos inesperados en las modalidades auditiva y visual, pero ésta no varió en función de la edad. Por consiguiente, de forma conjunta, las *Publicaciones 2* y *3*, proporcionan una fuerte evidencia de que el efecto del envejecimiento en la distracción por estímulos inesperados es específico de las tareas oddball cross-modal y que ésta no se ve incrementada en la vejez en tareas oddball puramente auditivas o visuales.

En la *Publicación 4* estudiamos el enlace entre inhibición de respuesta y la reorientación atencional. La inhibición de respuesta y la reorientación atencional son generalmente estudiados de forma separada, pero estudios recientes han propuesto que ambos procesos podrían basarse en mecanismos cognitivos y neurales similares. En dos experimentos, contrastamos la explicación del “circuit breaker” (el cual asume que los eventos inesperados producen una supresión global de la respuesta motora) y de la explicación de la “detección de estímulo” (la cual asume que la atención es reorientada hacia los eventos inesperados). Nuestros resultados apoyan la explicación de la

“detección del estímulo”, destacando la importancia de reorientar nuestra atención con el fin de detectar las señales inesperadas y como consecuencia, cancelar o actualizar nuestras acciones.

En la *Publicación 5,* adoptamos una perspectiva más global. Exploramos la distracción por estímulos inesperados a lo largo de la vida (comparando niños, jóvenes y ancianos) así como el papel de la capacidad de memoria de trabajo (WMC) y de la inhibición de respuesta en la distracción a lo largo de la vida. Los resultados revelaron distracción por estímulos inesperados en todos los grupos de edad, pero ésta fue mayor en el grupo de los ancianos comparado con el grupo de jóvenes adultos y niños (quienes no difirieron entre sí). La inhibición de respuesta no explicó la distracción en ninguno de los grupos de edad mientras que la WMC correlacionó positivamente con la distracción en niños, negativamente en ancianos y no correlacionó en los jóvenes adultos.

Resum (Català)

L’atenció selectiva es la habilitat de filtrar estímuls irrellevants per a la tasca en curs amb la finalitat de concentrar-se en ella. Al mateix temps, altres mecanismes asseguren que estímuls inesperats però potencialment importants puguin capturar la nostra atenció i ser processats. Aquests mecanismes, encara que adaptatius, tenen un desavantatge: la distracció. Estudis anteriors han explorat els mecanismes involucrats en la distracció comportamental, però l'evidència és limitada. Per tant, el principal objectiu d'aquesta tesi és el d'aconseguir un major coneixement dels mecanismes cognitius que fonamenten la distracció per estímuls inesperats a través del cicle vital.

Un total de 5 sèries experimentals conformen aquesta tesi doctoral. La *Publicació 1* proporciona evidència original que qüestiona la hipòtesi de la distracció per estímuls inesperats com un mecanisme independent de la modalitat de presentació de l’estímul. En aquest estudi, vam contrastar ortogonalment les modalitats sensorials dels estímuls rellevants i irrellevants en tasques oddball. Els resultats van mostrar distracció per als estímuls auditius desviats independentment de la modalitat dels estímuls diana. En canvi, els desviats visuals no van produir distracció (per a estímuls diana visuals o auditius), excepte en la situació específica en que els participants van ser forçats a atendre als estímuls irrellevants i sota condicions específiques relacionades amb les propietats espacials dels estímuls.

Seguint l'evidència de que el nostre sistema cognitiu sembla ser més vulnerable a la distracció quan els estímuls desviats són presentats en la modalitat auditiva que quan són presentats en la modalitat visual (almenys quan els estímuls irrellevant i diana no formen part del mateix objecte perceptiu), en la *Publicació 2* vam utilitzar aquesta modalitat per estudiar, per primera vegada, l'efecte de l'envelliment en la distracció per estímuls inesperats en tasques oddball cross-modal (auditiu-visual) i uni-modal (auditiu-auditiu). Els resultats mostraren un efecte de l'edat en la distracció en la tasca cross-modal però no en la uni-modal. En la *Publicació 3*, vam estudiar l'efecte de l'edat en la distracció per estímuls inesperats utilitzant tasques oddball uni-modals, visual i auditiva, en la informació rellevant i irrellevant la qual formava part del mateix objecte perceptiu. Els nostres resultats van mostrar distracció per estímuls inesperats en les modalitats auditiva i visual, però aquesta no va variar en funció de l'edat. Per tant, de forma conjunta, les *Publicacions 2* i *3*, proporcionen una forta evidència de que l'efecte de l'envelliment en la distracció per estímuls inesperats és específic de les tasques oddball cross-modal i que aquesta no es veu incrementada en la vellesa en tasques oddball purament auditives o visuals.

En la *Publicació 4* estudiem l'enllaç entre inhibició de resposta i la reorientació de l’atenció. La inhibició de resposta i la reorientació de l’atenció són generalment estudiats de forma separada, però estudis recents han proposat que ambdós processos podrien basar-se en mecanismes cognitius i neurals similars. En dos experiments, contrastem l'explicació del “circuit breaker” (el qual assumeix que els esdeveniments inesperats produeixen una supressió global de la resposta motora) i de l'explicació de la “detecció d'estímul” (la qual assumeix que l'atenció és reorientada cap als esdeveniments inesperats). Els nostres resultats recolzen l'explicació de la “detecció d'estímul”, destacant la importància de reorientar la nostra atenció amb la finalitat de

detectar els senyals inesperats i com a conseqüència, cancel·lar o actualitzar les nostres accions.

En la *Publicació 5*, adoptem una perspectiva més global. Vam explorar la distracció per estímuls inesperats al llarg de la vida (comparant nins, joves i ancians) així com el paper de la capacitat de memòria de treball (WMC) i de la inhibició de resposta en la distracció al llarg de la vida. Els resultats van revelar distracció per estímuls inesperats en tots els grups d'edat, però aquesta va ser major en el grup d'ancians comparat amb el grup de joves adults i nens (els qui no van diferir entre si). La inhibició de resposta no va explicar la distracció en cap dels grups d'edat mentre que la WMC va correlacionar positivament amb la distracció en nens, negativament en ancians i no va correlacionar en els joves adults.

Dedication

Hay muchas personas a las que me gustaría agradecerles su apoyo durante el proceso del doctorado. Primero me gustaría empezar por mi director y codirectora de tesis, Fabrice Parmentier y Pilar Andrés, sin los cuales esto no hubiese sido posible o al menos no habría sido lo mismo. No tengo palabras para describir el apoyo que he recibido de estos dos grandes profesionales y mejores personas. Muchas gracias por apoyarme durante estos años, por el enorme trabajo que habéis hecho, por las horas dedicadas, por vuestra profesionalidad, por ser mis guías durante estos años, por confiar y creer en mí, por hacerme amar la investigación, por potenciar mi interés, por hacer fácil lo difícil y por darme la oportunidad de investigar junto a vosotros, muchas gracias por todo.

En segundo lugar me gustaría dar las gracias a todo el equipo de investigación que conocí y con el que trabajé durante la estancia que realicé en Exeter. Many thanks Frederick and Heike (and all the Cognition lab members: Myriam Mertens, Tobias Stevens, Maisy Best, Will Bowditch…) for helping me, for all the work that has been done, for your professionalism, for being so kind and to make me feel like at home.

En tercer lugar quiero dar las gracias a Rafael Jiménez y a Alex Garcia por introducirme en este mundo mientras estaba estudiando la licenciatura. Muchas gracias por haber despertado mi interés por la investigación, inicio del camino que después de varios años ha resultado en este trabajo. También quiero agradecer a los profesores del grupo de Evocog su apoyo durante la tesis por preocuparse de mi progreso y por apoyarme. También me gustaría agradecer al profesor Mateu Servera su colaboración durante la tesis que ha resultado en una publicación conjunta.

En cuarto lugar, quiero agradecer el apoyo y los momentos divertidos, las comidas que hemos compartido, por los momentos compartidos día a día, conferencias y momentos “locos”, a todas las personas, compañeros y amigos del laboratorio o que en algún momento han pasado por allí. Gracias Toñi Pacheco, Conchi Padilla, Laura Pérez, Cristina Acedo, Javier Villacampa, Laura Prada, Ana Pérez, Julia Frimodt Christensen, Albert Flexas, Lluís Barceló-Coblijn, Antonio Olivera, Gerardo Gómez, Guido Corradi, Pamela Barone, Carme Isern, Emilio López, Irune Fernández y Myriam Oliver (espero no dejarme a nadie pero si es el caso espero que mis agradecimientos lleguen a todos ☺).

Como no podía ser de otro forma, me gustaría dar las gracias a mi familia y amigos, especialmente a mis padres y a mi hermano. Quiero dar las gracias a mi madre por su apoyo incondicional durante esta gran aventura y durante toda mi vida. Por el cariño, el amor y el empuje durante los buenos y no tan buenos momentos que he vivido estos cuatro años. Gracias por confiar en mi persona más que yo misma, por levantarme en los momentos más duros, por tu paciencia, por entenderme y por tener una sonrisa que ofrecerme en cualquier momento que lo he necesitado. Gracias a mi padre que aunque hace años que no está entre nosotros, ha estado y está muy presente en cada uno de mis actos.

Finalmente, y no por eso menos importante, quiero agradecer a Javi su apoyo incondicional durante la tesis. Gracias por apoyarme durante estos años, por darme tu cariño, por entenderme, por soportar los momentos de nervios, por intentar hacerme la vida más fácil, por lidiar con mis frustraciones, por estar cuando lo he necesitado, por creer en mí, gracias.

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Additionally I was awarded a 3 months research grant from the Spanish Ministry of Education, Culture and Sport for a stay in Exeter (United Kingdom) at the School of Psychology under the supervision of Professor Frederick Verbruggen.

Abbreviations

Greek symbols

B	Regression beta coefficient
η_p^2	Partial eta–squared, effect size

English symbols and abbreviations

AA; AV; VA; VV	Auditory-auditory; auditory-visual; visual-auditory; visual-visual
AB	Attentional blink
ANOVA	Analysis of Variance
ASR	Acoustic startle response
BF	Bayes factor
cd/m^2	Candela per square metre, unit of luminance
CIs	Confidence intervals
Cm	Centimetres
d	Cohen's d; effect size
D	Deviant
d_{av}	Cohen's d_{av}, effect size
dB/dBA/SPL	Decibels; A-weighted decibels; sound pressure level
df	Degrees of freedom
EEG	Electroencephalogram
ERP	Event-related potential
F	F–ratio (test statistic used in ANOVA)
gav	Hedges' *gav*, effect size
Go|Go	Go trial after Go trial

Go|NoGo	Go trial after NoGo trial
Hz	Hertz, frequency
ISE	Irrelevant speech effect
LHeffect	Likelihood of the data given the effect, Bayes factor indices
LHnull	Likelihood of the data given the null hypothesis, Bayes factor indices
M	Mean
Max.	Maximum
MEPs	Motor evoked potentials
MMN	Mismatch negativity, electrophysiological response
ms	Milliseconds
MSE	Mean square error (ANOVA)
N, n	Sample size; N = total sample size; n = sample size of a particular group
N2p	N2 component, electrophysiological brain response
OSPAN	Operation span task
p	Probability; significance of a statistical test
P3; P3a; P3b	P300 event-related brain potential; P3a and P3b are components of P300
p(Correct)	Probability of correct responses on go trials, stop-signal task
p(miss)	Probability of missed go responses
p(resp | no-go)/ p(resp|signal)	Probability of responding on a no-go trial/signal trial
r	Pearson’s correlation coefficient
R^2; R^2 change	Coefficients of determination for regression analyses
RGB	Red, green and blue (colour intensity on computer display).
RON	Reorientation negativity, electrophysiological response

RSVP	Rapid serial visual presentation task
RT	Reaction time; Average reaction time for correct go responses
S	Standard
SD	Standard Deviation
SOA	Stimulus onset asynchrony
srRT	Mean time to respond incorrectly in the stop trials
SSD	Stop signal delay
SSRT	Stop signal reaction time
t	Test statistic for Student's t–test
T1	Target 1
T2	Target 2
TMS	Transcranial magnetic stimulation
WAIS-III	Wechsler Adult Intelligence Scale-III
WM/WMC	Working memory; Working memory capacity

Certificate of thesis supervisor

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I HEREBY DECLARE

That the doctoral thesis entitled TOWARDS A BETTER UNDERSTANDING OF DISTRACTION BY UNEXPECTED STIMULI ACROSS THE LIFESPAN, presented by Ms Alicia Leiva Mir so as to obtain a doctoral degree, has been completed under my supervision and meets the requirements the candidate needs to apply for an European Doctorate mention.

Signed,

Dr Fabrice Parmentier

University of the Balearic Islands

Palma de Mallorca, 17/11/2015

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That the doctoral thesis entitled TOWARDS A BETTER UNDERSTANDING OF DISTRACTION BY UNEXPECTED STIMULI ACROSS THE LIFESPAN, presented by Ms Alicia Leiva Mir so as to obtain a doctoral degree, has been completed under my supervision and meets the requirements the candidate needs to apply for an European Doctorate mention.

Signed,

Dr Pilar Andrés
University of the Balearic Islands

Palma de Mallorca, [24/11/2015]

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I, Dr Fabrice Parmentier, as co-author of the following articles,

Leiva, A., Parmentier, F. B. R., & Andrés, P. (2015a). Distraction by deviance: Comparing the effects of auditory and visual deviant stimuli on auditory and visual target processing. *Experimental Psychology*, *62*(1), 54-65. doi: 10.1027/1618-3169/a000273

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Leiva, A., Andrés, P., Servera, M., Verbruggen, F., & Parmentier, F. B. R. (in press). The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study. *Developmental psychology*.

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That I acknowledge Ms Alicia Leiva Mir as the main author of the above-mentioned articles and therefore grant her permission to present them as part of her doctoral thesis, on the understanding and that the said articles cannot be used again in any other thesis by publication.

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Frederick Verbruggen

Signed,

Dr Frederick Verbruggen

Exeter, 19/05/2016

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Leiva, A., Parmentier, F. B. R., Elchlepp, H., & Verbruggen, F. (2015). Reorienting the mind: The impact of novel sounds on go/no-go performance. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(5), 1197-202. doi: 10.1037/xhp0000111

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Dr Heike Elchlepp

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Universitat de les Illes Balears

I, Dr Mateu Servera, as co-author of the following articles,

Leiva, A., Andrés, P., Servera, M., Verbruggen, F., & Parmentier, F. B. R. (in press). The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study. *Developmental psychology.*

HEREBY DECLARE:

That I acknowledge Ms Alicia Leiva Mir as the main author of the above-mentioned articles and therefore grant her permission to present them as part of her doctoral thesis, on the understanding and that the said articles cannot be used again in any other thesis by publication.

Signed,

Dr Mateu Servera

Palma de Mallorca, 20/05/2016

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The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study
Developmental Psychology

Dear Mrs Leiva,

Thank you for submitting your revised manuscript, The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study, manuscript number, DEV-2015-0950R2 to Developmental Psychology. I find your responses to the previous critiques to be satisfactory. Therefore, I am happy to inform you that the manuscript has been tentatively accepted for publication, pending your completion of the necessary author forms. Please note that we must be in receipt of signed author forms prior to formal acceptance of the manuscript. Please download the forms at APA's Forms for Journals Publication at: http://www.apa.org/pubs/authors/forms.aspx.

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Thank you for submitting your work to us, and congratulations on a valuable contribution to the literature.

Sincerely,

Bert Hayslip, Jr.
Associate Editor
Developmental Psychology

1. INTRODUCTION

This dissertation is the outcome of four years of work with the aim of better understanding the cognitive mechanisms of distraction by unexpected stimuli through the lifespan. I present here five experimental series expanding the knowledge in this field and aiming to:

- Learn more about how the cognitive system works in the face of distraction by unexpected sounds.
- Identify and study some factors modulating deviance distraction (such as sensory modalities or ageing).
- Study the potential links between deviance distraction on the one hand, and working memory, response inhibition and ageing on the other.

Before reporting each experimental series, I will present the general framework in which my research was set (section 1.1). In section 1.2, I will briefly describe the different publications included in this dissertation as well as the connection between them and their coherence as a body of work. In section 2, I will highlight the aim of each experimental series. Section 3 includes the publications forming the empirical part of my thesis. Finally, in section 4, I will discuss the work as a whole, leading to some general conclusions reported in section 5.

1.1. The framework

Imagine that you are reading this dissertation in a quiet room, trying to ignore the conversation between people nearby, and that you suddenly hear a noise coming from outside (e.g., a police siren). Your attention would orient to that noise, which might signify danger, but may in this instance be completely irrelevant to you and therefore simply distract you away from the task you were engaged in (reading). This example illustrates the importance of the balance between selective attention mechanisms (the ability to filter out task-irrelevant stimuli in order to concentrate on the task at hand, shielding attention from irrelevant stimuli) and the detection of unexpected but potentially important stimuli in our immediate environment. A cognitive system able to shut out task-irrelevant stimuli in order to concentrate on a task could have negative implications from an adaptive point of view. One can speculate that mechanisms allowing unexpected stimuli to break through attention filters may be advantageous from an evolutionary point of view. For example, early hominids picking fruits from trees would have benefited from their cognitive ability to detect and react to a sudden noise in their vicinity, considering that this noise could signify a potential danger. Detecting and reacting to this noise may have been important for survival. The balance between selective attention and change detection is important in daily situations. A shield from irrelevant stimuli helps avoid distraction and increase task performance but at the risk of missing potentially important information in our environment. Detecting task-irrelevant stimuli that could be potentially relevant in other respects is useful but comes with a cost when attention-grabbing stimuli are genuinely irrelevant (Dreisbach, 2006; Dreisbach & Goschke, 2004).

Pavlov defined the orienting reflex as the instant response to a change in the environment (Pavlov, 1927). For Sokolov (1966), the concept of orienting response is a nonspecific response to novel stimuli. Following this concept, new events are compared to neuronal models formed from past, repeated, stimuli. The mismatch between the new input and these representations produces an orienting response. This response is thought to vary depending on the characteristics of the novel stimulus, such as its intensity or significance. Past research defined two distinct ways of orienting attention: covert and overt. The overt shift of attention is guided by the input to the sensory receptors (e.g., when we turn our head in the direction a car horn sound is coming from). The covert shift is detached from the sensory receptors (e.g., when we are looking at a cinema screen, but our visual attention is oriented to what the person seated next to us is doing). Another important distinction is that between responding to stimuli that are inside and to those that are outside our focus of attention. We can distinguish between two mechanisms for selection: the endogenous or goal-driven attention guided by internal goals or expectations (voluntary directed, top-down control) and the exogenous or stimulus-driven attention guided by salient environmental stimuli (involuntary directed, bottom-up). We can attend to something that is of interest or relevance to us voluntarily, but a stimulus can also capture our attention involuntarily (Broadbent, 1958; James, 1890). Because attentional resources are limited, by capturing our attention the attention-grabbing stimulus affects ongoing performance. In this thesis, I will focus on the involuntary capture of attention by unexpected stimuli (mostly sounds) and study the mechanisms through which it affects behavioural performance in an ongoing task. In the next sections, I will review the current state of knowledge on this topic, including the role of certain modulators of distraction by unexpected stimuli.

1.1.1. Attention capture by unexpected stimuli

Several studies revealed that sudden changes (novel or deviant stimuli[1]) in a sequence of repeated stimuli (standard) can capture attention involuntarily, impairing the processing of the main task due to the orientation of attention to the oddball stimuli (e.g., Escera, Alho, Winkler, & Näätänen, 1998; Schröger, 1996; Schröger & Wolff, 1998).

A number of these studies provide an electrophysiological perspective showing a pattern of three specific brain responses (e.g., Berti, 2013; Berti, Roeber & Schröger, 2004; Horváth, Winkler, & Bendixen, 2008; Schröger, 1996, 1997, 2005; Schröger & Wolff, 1998): mismatch negativity (MMN), P3a, and reorientation negativity (RON). The MMN is a brain response elicited by stimuli that do not match the neuronal model or sensory traces in auditory sensory memory, measured as the difference between the ERP elicited by the standard and the deviant stimuli. The MMN marks the detection of change (e.g., Näätänen, 1992; Näätänen, Paavilainen, Rinne, & Alho, 2007) or the mismatch between an incoming sound and the prediction of the cognitive system based on a rule abstracted from past events (e.g., Schröger, Bendixen, Trujillo-Barreto, & Roeber, 2007). The MMN is a pre-attentive response as it is elicited outside the participant's control or awareness (Alho, Woods, Algazi, & Näätänen, 1992; Duncan & Kaye, 1987; Näätänen & Winkler, 1999), and usually peaks between 100 and 250 ms from the deviation onset in a frontocentral distribution. P3a is assumed to indicate the involuntary orientation of attention to a perturbing event (e.g., Berti et al., 2004; Escera, Alho, Schröger, & Winkler, 2000; Friedman, Cycowic, & Gaeta, 2001). It is widely distributed (superior temporal, dorsolateral prefrontal and parietal cortical areas, the hippocampus, and parahippocampal and anterior cingulate gyri; e.g., Alain Woods, & Knight, 1998; Knight, 1996; Mecklinger & Ullsperger, 1995) and usually peaks around 300 ms from the onset of the deviant sound. Inside the P3a window, some studies reported two peaks: the early P3a and the late P3a. The early P3a peaks around 200 ms and is associated with stimulus-specific processes and considered as a more automatic response (e.g., Horváth, Sussman, Winkler, & Schröger, 2011). The late P3a peaks around 300 ms and is associated with the involuntary orientation of attention (e.g., Escera et al., 1998). Reorientation negativity (RON) reflects the reorientation of attention to relevant information from the task at hand (e.g., Berti & Schröger, 2001, 2003; Munka & Berti, 2006; Schröger, Giard & Wolff, 2000; Schröger & Wolff, 1998). RON is frontocentrally distributed and usually peaks between 400 and 600 ms from the onset of the deviation. The RON component is thought to be comprised of two sub-components: an early sub-component associated with a switch of attention involving working memory (WM) and a late sub-component associated with a general allocation of attention to the preparation for the upcoming task (e.g., Berti, 2008; Hölig & Berti, 2010; Munka & Berti, 2006).

Behaviourally, deviant (and novel) stimuli also produce distraction, delaying responses in a primary task (e.g., Parmentier, 2014), and in some cases reduce response accuracy (Schröger, 1996) compared to standard stimuli. Deviance distraction is

[1] The term "deviant" is typically used when referring to a specific stimulus being used repeatedly as an alternative to the standard stimuli. The term "novel" is typically used when the stimulus replacing the standard stimulus keeps changing.

observed in both one-channel and cross-modal oddball paradigms. In the one-channel paradigm (e.g., Berti, 2008; Berti & Schröger, 2001, 2003, 2004, 2006; Roeber, Berti, & Schröger, 2003; Schröger & Wolff, 1998; Sussman, Winkler, & Schröger, 2003), targets and irrelevant stimuli are presented in the same modality (auditory or visual), often within the same perceptual object. For example, Schröger and Wolff (1998) asked participants to discriminate between short (100 ms) and long (200 ms) binaural tones while ignoring rare and unpredictable pitch deviations (which could be small, medium, or large). In a separate control condition, sounds consisted in a tone varying equiprobably across 10 different pitch values. Behaviourally, the results showed that response latencies in the primary task were significantly longer for deviant sounds in relation to standard sounds, which the authors interpreted as a cost induced by deviant stimuli and a benefit by standard stimuli.

In the cross-modal oddball paradigm (e.g., Escera et al., 1998; Ljungberg & Parmentier, 2012; Ljungberg, Parmentier, Leiva, & Vega, 2012; Parmentier, 2008; Parmentier, 2014; Parmentier & Andrés, 2010; Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008; Parmentier, Elsley, Andrés, & Barceló, 2011; Parmentier, Elsley, & Ljungberg, 2010; Parmentier, Ljungberg, Elsley, & Lindkvist, 2011; Parmentier, Maybery, & Elsley, 2010), target and irrelevant stimuli are presented in different sensory modalities and are temporally and perceptually decoupled. In this paradigm, the most-studied task is the auditory-visual cross-modal task, comprising the categorization or discrimination of visual target stimuli (i.e., digits) while ignoring irrelevant sounds presented shortly before each target. Negative effects of deviant sounds on visual task performance have also been observed in tasks other than oddball tasks, such as the serial recall task where participants encode sequences of verbal stimuli while ignoring a stream of task-irrelevant sounds (e.g., Hughes, Hurlstone, Marsh, Vachon, & Jones, 2013; Hughes, Vachon, & Jones, 2005; 2007). In such tasks, deviance can take the form of a salient sound or one deviating from their auditory context (e.g., Hughes et al., 2005; 2007) and has been shown to reduce serial recall accuracy.

<u>1.1.1.1. The locus of behavioural distraction</u>

Parmentier et al. (2008) studied the cognitive locus of deviance distraction in a cross-modal task. The authors contrasted two possible explanations of the distraction effect. On the one hand, the processing of a visual target could be influenced by a sound due to the competition of attentional resources between the processing of the visual target and the processing of the novel sound, thereby dividing the attention to process both stimuli (e.g., Johnston & Heinz, 1978). On the other hand, the processing of a visual target could be delayed by a sound due to an attentional bottleneck (e.g., Broadbent, 1958; Pashler, Johnston, & Ruthruff, 2001), in which processing of the target is delayed until the attention is back from the sound to the target, which delays the onset of the target processing. Parmentier et al. (2008) tested the first hypothesis in two experiments manipulating the demands placed on the visual analysis of the target stimuli or at the later stage of their categorization and the selection/execution of a response. According to the depletion of attention hypothesis, deviant sounds should consume attentional resources that are crucially needed to face the enhanced demands of the task, thereby producing a large reduction in task performance (i.e., greater deviance distraction). Instead, deviance distraction was not affected by the increase in task demands (while this increase had a sizeable main effect on response times), suggesting that deviance distraction does not reflect the slower processing of target stimuli *per se*. The results showed that the manipulation of the task demands in Experiments 1 (manipulation of complexity of the visual processing of the target stimuli) and 2 (manipulation of the complexity of the targets' categorization rules) did not increase distraction. On the contrary, in Experiment 2, the increase in complexity of the categorization demands reduced deviance distraction, which is in line with previous studies that reported a reduction of distraction when participants perform the oddball task under a WM load (e.g., Berti & Schröger, 2003; SanMiguel, Corral, & Escera, 2008). In a third experiment, Parmentier et al. found that forcing attention back to the visual modality using a visual stimulus (characterized by an abrupt motion onset) eliminated deviance distraction, thereby supporting the attentional bottleneck hypothesis. The authors concluded that behavioural distraction reflects a time penalty produced by the shifts of attention between the irrelevant stimulus and the target, delaying the onset of the target processing, an interpretation in line with that of Schröger (1996).

Parmentier et al. (2008) offered different possible interpretations of the shifts of attention caused by deviant sounds in the cross-modal oddball task. First, the shifts may be spatial: the deviant triggering a shift from the spatial location where the target stimulus is expected to the sound's spatial location (the centre of the participant's head when sounds are presented binaurally). While this may occur in cross-modal tasks, the spatial shift proposition is not applicable in tasks in which targets and irrelevant stimuli are presented as part of the same perceptual object and, therefore, in the same spatial location (e.g., Berti, 2008; Berti & Schröger, 2001, 2003, 2004, 2006; Schröger & Wolff, 1998). Second, the shifts of attention could occur between sensory modalities. Deviant sounds could trigger a shift of attention from the visual to the auditory modality and the reorientation to the visual one. Third, the shifts of attention may occur between task sets where participants switch from the target set (stimulus-response mappings) to another task set (not producing a response to a deviant sound). Finally, the shifts of attention could reflect a contextual change where changes in the context could make response selection relatively difficult.

Horváth, Roeber, Bendixen, and Schröger (2008) too explored the nature of the deviance distraction effect. The authors tested two distinct hypotheses: distraction as a specific attention switch or as a general attention resetting. Under the general attention-resetting hypothesis, any unpredictable stimulus should trigger distraction, while according to the specific attention-switch hypothesis a stimulus should trigger distraction only if the stimulus deviates from past stimuli in a task-irrelevant stimulus aspect. The main task was to respond if the direction of a pair of sounds ascended or descended in pitch. Three conditions were presented: relevant deviance, irrelevant deviance, and double deviance condition. In the relevant deviance condition, deviants were defined by the magnitude of the pitch difference in each pair of sounds: a task-relevant stimulus aspect. In the irrelevant deviance condition, deviants were defined by the spectral width difference of the second tone of the pair: a task-irrelevant stimulus aspect. In the double deviance condition, deviance involved both aspects. The results showed response delay in the three conditions, but the mean reaction time prolongation in deviant trials was twice as large in the irrelevant and double deviance conditions compared to the relevant deviance condition. These results give support to the specific switch of attention hypothesis, where involuntary shifts of attention occur from the relevant task to the task-irrelevant stimulus aspect. However, the response delay in all conditions as well as the elicitation of specific brain responses (N2p, P3b) in all three conditions suggests that deviance could influence the processing of the target even in the absence of an involuntary attentional change.

1.1.1.2. Violations of predictions

Some studies have demonstrated that the unpredictability of the stimuli is a main determinant of attention capture. Standard stimuli may indeed be defined as a sequence of regular or predictive sounds and oddball stimuli (novel or deviant) as unexpected or unpredictable sounds. When a sequence of regular and expected (standard) stimuli is presented, our cognitive system builds upon this regularity to predict further repetitions. In this context, the presentation of a novel (or deviant) sound violates predictions and elicits attention capture (e.g., auditory: Bendixen, Roeber, & Schröger, 2007; Bendixen, SanMiguel, & Schröger, 2012; Schröger et al., 2007; Vachon, Hughes, & Jones, 2012; van Zuijen, Sussman, Winkler, Näätänen, Tervaniemi, 2005; Winkler, 2007; e.g., visual: see Czigler, 2010; Kimura, Schröger, Czigler, & Ohira, 2010).

Parmentier, Elsley et al. (2011) reported a study aiming to establish whether deviant sounds yield behavioural distraction because they are rare or because they violate predictions. Using a cross-modal oddball task in which participants categorized digits while ignoring irrelevant sounds presented shortly before each digit, the authors manipulated the base-rate probability and predictability of standard and deviant sounds. The key manipulation consisted in the careful sequencing of standard (S) and deviant (D) trials. Trials were arranged such that deviant trials most often (but not always) came in pairs (e.g., SSSSSDDSSSSDDSSSSSSSSDDSSSDDSSSSDSSS…). Counting on the implicit learning of stimulus contingencies by participants, the authors not only compared performance in deviant trials for predictable versus unpredictable deviant sounds, but also performance in the standard trials when the standard sound was predictable and when it was unpredictable. The results clearly showed that distraction was observed for a sound violating predictions, irrespective of whether that sound was the standard (high base-rate probability) or the deviant sound (low base-rate probability). In conclusion, this study indicated that the rarity of a sound is not enough to elicit capture attention and that what matters is that that sound violates the cognitive system's predictions. In line with these authors, Nöstl, Marsh, and Sörqvist (2012) used the oddball paradigm with sequence learning, and manipulated the pitch of the irrelevant sounds in two experiments. Participants had to respond to visual stimuli (arrows) while ignoring irrelevant sounds presented shortly before (standard and deviant tones). A training phase was presented with a repetition of 660-880-660-440 Hz tones sequence. In the experimental phase, three standard tones were presented (440 Hz, 660 Hz and 880 Hz tones) following a repetitive sequence (i.e., 660-880-660-440-660-880). In some trials, either the 440 Hz standard tone or the 880 Hz standard tone was replaced by either a low-pitch deviant tone (220 Hz) or a high-pitch deviant tone (1100 Hz). The findings showed that high-pitch deviants were more distractive when replacing low-pitch standards and low-pitch deviants when replacing high-pitch standards. The authors confirmed that novelty is not sufficient for attentional capture (Parmentier, Elsley et al., 2011), thereby emphasizing the violation of predictions as a determinant of the magnitude of attentional capture by auditory events (see also Nöstl, Marsh, & Sörqvist, 2014).

In a more general framework, Bubic, von Cramon, Jacobsen, Schröger, and Schubotz (2008) studied the detection of visual deviant stimuli in different task contexts. In one of them, the sequential order of the stimuli was violated, while in the other context the sequential order was not violated and in its place a different stimulus from the standards was presented. The results revealed different brain activations as a function of the task context, thereby showing functional differences between stimulus violations and rule violations. In another study, Bubic, von Cramon, and Schuboltz (2011) demonstrated that the context and the deviant stimuli's features (position, rhythm, object identity) influence which brain areas are activated to detect the deviant event (see Bubic, von Cramon & Schuboltz, 2010).

1.1.1.3. Discrepancies between electrophysiological and behavioural distraction

It has often been assumed that electrophysiological responses to unexpected stimuli invariably trigger behavioural distraction. Some studies provide evidence both occurring together: brain responses (e.g., P3a) and performance impairment due to the presentation of an irrelevant event (e.g., Berti et al., 2004; Escera et al 1998; Schröger & Wolff, 1998; Wetzel & Schröger, 2007). However, this assumption should be studied more carefully. For example, San Miguel, Morgan, Klein, Linden, and Escera (2010) found the same pattern of electrophysiological responses for two opposite behavioural effects of novel sounds (distraction and facilitation). Other studies found the same behavioural results despite variations in electrophysiological responses (e.g., Berti, 2012; Horváth, Czigler, Birkás, Winkler, & Gervai, 2009; Jankowiak & Berti, 2007) or a lack of correlation between both types of measures (Getzmann, Gajewski, & Falkenstein, 2013). For example, Horváth et al. (2009) observed variations in the electrophysiological responses between a group of children, young, and older adults (variations in P3a and RON between young and older adults; variation in RON between children and young adults). However, at the behavioural level, no such differences in distraction were found.

The studies cited above suggest that behavioural distraction is not a direct consequence of the electrophysiological responses to deviant sounds. At the same time, one cannot assume the variation of determined electrophysiological responses based on behavioural measures. Further research is needed in order to gain a better understanding of the cognitive mechanisms that can modulate and underpin behavioural distraction independently of electrophysiological markers of distraction.

1.1.2. Modulators of attention capture

In this section, I briefly review factors modulating deviance distraction, distinguishing between external and internal factors. External factors include sensory modalities, task characteristics, stimuli characteristics, arousal, emotional valence, irrelevant stimuli' informational value, and semantic processing. Internal factors include age, emotions, working memory and response inhibition.

1.1.2.1. External factors

1.1.2.1.1. Sensory modalities

Within the oddball paradigm, several studies have examined the impact of unexpected stimuli on different sensory modalities. Irrelevant stimuli and targets can be presented within the same modality or in different modalities. In one-channel tasks, targets and irrelevant stimuli are presented in the same modality, typically auditorily (e.g., Berti, 2008; Berti & Schröger, 2001, 2003; Horváth et al., 2009; Horváth et al., 2008; Horváth & Winkler, 2010; Jankowiak & Berti, 2007; Roeber et al., 2003; Schröger et al., 2000; Schröger & Wolff, 1998; Wetzel, Widmann, Berti, & Schröger, 2006). In general, targets and irrelevant stimuli are presented as distinct features of the same auditory object, such as in a duration discrimination task where deviance is defined by rare changes in pitch. Such task-irrelevant changes produce a lengthening of response latencies. This distraction effect is also observed in the visual modality (e.g., Bendixen et al., 2010; Berti & Schröger, 2001; 2004; 2006). For example, in the study by Berti and Schröger's (2001), auditory and visual distraction effects were contrasted. The main task was to discriminate the duration of the stimuli (visual in the visual condition, auditory in the auditory condition) as short or long. In the auditory condition, deviance was defined by task-irrelevant changes in pitch (1050 or 950 Hz tones in 12% of trials, 1000 Hz tone in the remaining, standard, trials). In the visual condition, the visual stimuli consisted of a square containing a small triangle and deviance was introduced in 12% of trials by shifting the location of the small triangle or rotating it. In both conditions, participants were instructed to judge the duration of the stimulus as quickly and accurately as possible. The results showed a lengthening of response times in deviant compared to standard trials as well as MMN, P3a and RON responses to deviants in both modalities (except the absence of RON for long-duration stimuli in the visual condition). Other studies have used bimodal deviants. For example, Boll and Berti (2009) presented a duration discrimination task where the main task was to discriminate the duration of combined auditory and visual stimuli as short or long, while irrelevant changes occurred auditorily (e.g., change in pitch), visually (e.g., change in position), or in both modalities at the same time (bimodal deviants). The authors reported behavioural deviance distraction in the bimodal and auditory conditions and a marginal significant lengthening of the response times caused by visual deviants. Specifically, the lengthening of response times (as well as the elicitation of MMN, P3a and RON components) by auditory and bimodal deviants were similar. In contrast, visual deviants response times costs were smaller relative to auditory or bimodal deviants.

In the cross-modal task, irrelevant stimuli and targets are presented in different modalities, with targets presented in the visual modality and irrelevant stimuli in the auditory modality (e.g., Andrés, Parmentier, Escera, 2006; Berti, 2012; Domínguez-Borràs, Garcia-Garcia, & Escera, 2008a; Escera et al., 1998; Escera, Corral, & Yago, 2002; Escera, Yago, & Alho, 2001; Gumenyuk, Korzyukov, Alho, Escera, & Näätänen, 2004; Ljungberg, Parmentier, Jones, Marsja, & Neely, 2014; Ljungberg et al., 2012; Pacheco-Unguetti & Parmentier, 2014; Parmentier, 2008; Parmentier & Andrés, 2010; Parmentier et al., 2008; Parmentier, Elsley et al., 2011; Parmentier, Elsley et al., 2010; Parmentier, Turner, & Perez, 2014; Wetzel, Schröger, & Widmann, 2013). In general, the main task is to categorize a visual stimuli (e.g., categorize digits as odd or even) while ignoring irrelevant sounds (standard and deviant) presented shortly before. Even though sounds are task-irrelevant and should be ignored, response latencies in the main task are significantly longer following deviant sounds compared to standard sounds. For example, Parmentier and Andrés (2010) used such task with task-irrelevant sounds that were standard (90% of the trials) or novel (10% of the trials). The standard sound was a 600 Hz sine wave tone and the novel sounds were short environmental sounds (e.g., drill, hammer, rain, door, telephone ringing). A silent block was also included for comparison. Participants responded faster following the standard sound compared to a silent condition. However, novel sounds increased response times and decreased response accuracy compared to standard sounds. While the majority of cross-modal oddball tasks have been auditory-visual, some studies reported deviance distraction in tactile-visual oddball tasks (e.g., Ljungberg & Parmentier, 2012; Parmentier, Ljungberg et al., 2011). In these studies the task was similar to the auditory-visual task described above except that standard and deviant vibrations delivered to the participants' hands were used in place of sounds. The findings from these studies are functionally similar to those from auditory-visual tasks: deviant vibrations yielded longer response latencies compared to standard vibrations.

Deviance distraction is also observed in the multi-deviant paradigm. For example, Grimm, Bendixen, Deouell, and Schröger (2009) presented a visual task where participants categorized visual digits as odd or even while ignoring two triangles flanking these digits. Deviance was introduced by changing the colour or location of one of the triangles, or replacing it by a different shape. Interestingly, deviant trials occurred every third trial, though the nature of the deviance (location, colour, shape) was not predictable. Deviant features prolonged reaction times in the categorization task and elicited specific ERP effects. Grimm et al. (2008) reported similar findings in an auditory equivalent multi-modal paradigm.

Thus, it seems that distraction is observed regardless of whether irrelevant and target stimuli are presented within the same or in different modalities. One may therefore wonder whether distraction by unexpected stimuli may constitute a general phenomenon independent of sensory modalities. The general notion of a time penalty relating to shifts of attention to and away from a deviant stimulus (e.g., Parmentier et al. 2008) may constitute such general, a-modal, principle. However, some findings question the concept of deviance distraction as a central a-modal mechanism. For example, Ljungberg and Parmentier (2012) contrasted cross-modal distraction in different sensory modalities. Participants performed both auditory-visual and tactile-visual oddball tasks. The results revealed deviance distraction and post-deviance distraction (small amount of distraction observed in the first standard trial following a deviant trial) in both tasks and a similar decrease in deviance distraction across the blocks. However, despite these functional similarities between the two tasks, deviance distraction did not correlate between the auditory and tactile modalities for response times (but correlated for accuracy), and post-deviance distraction showed no cross-modality correlation either. These results do not fit the hypothesis of a central mechanism responsible for deviance distraction irrespective of sensory modalities. In addition, Berti and Schröger (2001) reported that in auditory and visual duration discrimination tasks, ERP effects were functionally similar in the two modalities for short but not for long stimuli, again suggesting that deviance distraction invokes at least some modality-specific processes.

1.1.2.1.2. Task characteristics

In this section, I discuss the modulation of deviance distraction by the characteristics of the tasks, specifically by WM load and cognitive control.

1.1.2.1.2.1. Working memory load

Several studies suggest that a WM load reduces deviance distraction (e.g., Berti & Schröger, 2003; Lv et al., 2010; Otten, Alain, & Picton, 2000; SanMiguel et al., 2008;

Zhang, Chen, Yuan, Zhang, & He, 2006; but see Muller-Gass & Schröger, 2007), suggesting top-down control over involuntary attention. For example, SanMiguel et al. (2008) manipulated WM load in an auditory-visual oddball task in two conditions. In the control condition, participants discriminated whether two digits were identical (e.g., "3 3") or different (e.g., "3 2") while ignoring irrelevant sounds presented shortly before. In the 1-back WM condition, participants had to decide if the first digit of the pair was the same or not as the first digit on the previous trial while ignoring irrelevant sounds presented shortly before. The results revealed a reduction in behavioural and electrophysiological distraction in the WM load condition compared to the control condition (see also San Miguel, Linden, & Escera, 2010). Hence it appears that if attentional resources are actively involved in maintaining information in WM, deviance distraction is reduced, an effect that may reflect the reduction of attentional resources available to orient toward the deviant stimulus (e.g., Berti & Schröger, 2003; Escera & Corral, 2007; Munka & Berti, 2006; SanMiguel et al., 2008; Sussman et al., 2003; but see Lv et al., 2010).

A second connection between deviance distraction and WM emanates from the interpretation of the RON component. This component has been argued to be composed of two attentional processes: an early sub-component associated with a switch of attention involving WM and a late sub-component associated with a general reallocation of attention such as the reactivation of the task set (e.g., Berti, 2008; Hölig & Berti, 2010; Munka & Berti, 2006).

In summary, research on the impact of WM load on deviance distraction shows that under a WM load distraction reduces. When a task involves WM load, the attentional resources required to orient the attention to the irrelevant stimulus are less "available" to process the deviant sound, leading to less distraction.

1.1.2.1.2.2. Cognitive control

While the orientation of attention is regarded as an involuntary response, several studies have demonstrated that top-down mechanisms can modulate the orienting of attention by showing that providing participants with cues announcing the presentation of a deviant sound results in the reduction or suppression of distraction. For example, Sussman et al. (2003) used a duration discrimination task (short and long tones) in which participants had to respond to the longer tones while ignoring rare changes in pitch. A red square (87.5% of the trials) or a green square (12.5% of the trials) was presented shortly before each sound. In the unpredictable condition, the visual stimulus did not give information about the type of upcoming sound (standard or deviant). In the predictable condition, the red square announced standard sounds and the green square deviant sounds. The results showed behavioural and electrophysiological effects of distraction in the unpredictable condition, but not in the predictable condition (except for the presence of MMN). Similar results were reported by Wetzel and Schröger (2007) and Wetzel, Widmann, and Schröger (2009). Horváth et al. (2011) went further by examining whether cues allowed participants to prepare for deviance in general or for specific deviant stimuli. The authors modified Sussman et al.'s (2003) task to compare two conditions. In one, visual cues announced the imminent presentation of a deviant sound but did not predict which of several deviant sounds would be presented. In the other, visual cues announced the exact deviant sound to be presented. The authors found that cues reduced distraction in both conditions, though behavioural distraction was reduced further when cues not only predicted the occurrence of a deviant sound but also which sound was to be presented.

In previous studies, different conditions were compared in order to study the role of cues on deviance distraction. As an alternative, Horváth and Bendixen (2012) manipulated the presentation of cues in a single condition. Participants had to discriminate between long and short tones (responding to the longer tones) while ignoring changes in pitch. Cues (grey square) were presented before each tone, above (high cue) or below (low cue) the fixation cross. On 80% of the trials, a valid cue was presented (announcing the pitch of the tone, e.g., low cue preceding a low tone) and on the remaining trials, invalid cues were presented (e.g., low cue preceding a high tone). The results showed a reduction in the degree of distraction and P3 amplitude by deviant sounds after a valid cue (compared to the invalid cues).

While the studies described above argued that participants use cues to exert cognitive control and thereby reduce distraction, Parmentier and Hebrero (2013) tested this hypothesis against an alternative proposition. This alternative proposition was that distraction might have been reduced in earlier studies because cue processing monopolizes attentional resources that are therefore not available for the orientation of attention to unexpected stimulus. For this purpose, the authors used a task in which participants categorized the direction of the sound movement (left or right) while ignoring rare changes in pitch (standard or deviant). Three conditions were presented: unpredictable, late-cue, and early-cue conditions. In the unpredictable condition, no cues were presented and so deviant sounds were not predictable. In the late cue condition, a cue predicted the type of upcoming sound (deviant or standard) but did so very shortly before the sound. In the early-cue condition, the cue was presented early, leaving over 2 seconds for its processing before the target stimulus was presented. If cues reduce the attentional resources available for the orientation of attention to the unexpected stimulus, distraction should be reduced in the late condition but not in the early condition. Conversely, if the reduction of distraction is due to cognitive control, a reduction of distraction should be observed in both cue conditions. The results supported the latter, hence adding further support to the notion that deviance distraction can be reduced through cognitive control.

Volosin and Horváth (2014) used an auditory discrimination task where participants responded to the direction of the sound movement (left or right) while ignoring changes in pitch. Deviant pitch changes could be presented randomly (unpredictable condition) or every 7th sound (predictable condition). The results showed no differences between conditions at the behavioural level, but P3a amplitude was reduced in the predictable condition. The authors suggested that participants benefited from information about the deviant occurrence in order to reduce distraction (see also Max, Widmann, Schröger, & Sussman, 2015). While the manipulation made the presentation of deviant sounds predictable through the learning of the sequence and not through the use of cues, this study can be regarded as another example of top-down control of deviance distraction.

1.1.2.1.3. Stimuli characteristics

Several aspects of the irrelevant stimuli have been found to modulate deviance distraction. For example, Berti et al. (2004) demonstrated that the amount of behavioural and electrophysiological distraction increased as the probability of deviant stimuli decreased (see also Escera et al., 1998; Yago, Corral, & Escera, 2001). A second characteristic suggested to modulate deviance distraction is the deviant sound's significance. It has been argued that some stimuli of personal significance, such as our own name, are supposedly more prone to capture attention (e.g., Moray, 1959; Röer, Bell, & Buchner, 2013; Wood & Cowan, 1995) even when participants do not pay attention to them. Evidence regarding the distractive effect of one's own name in oddball studies is mixed, however. For example, using a passive oddball task, Eichenlaub, Ruby, and Morlet (2012) presented own name and some other name among repeated tones while participants watched a silent video with subtitles. An early P3a response was elicited by own and other names, but no late P3a component was elicited by either. Only own name elicited late components following P3. The findings showed that own name and another name were processed differently but that the own name failed to elicit more attention orienting (P3a) than the other name.

In a recent study, Ljungberg et al. (2014) used a cross-modal oddball task in two experiments in which the deviant sounds were the names of the participants, control names, or an irrelevant word, and the standard sound was a sine wave tone. All deviant stimuli yielded similar levels of distraction compared to the standard tone.

Rather than using the participant's own name as a significant deviant sound, Roye, Jacobsen, and Schröger (2007), used the participant's own SMS ringtone. In a passive oddball task, participants watched a silent film with subtitles and were instructed to ignore all sounds (standard tone, sound of their own ringtone, or sound of another ringtone). The results showed that one's own ringtone elicited MMN and P3a responses relative to standard tones. Moreover, a posterior ERP deflection following MMN, an enhanced late P3a response and a greater RON response were observed for one´s own ringtone. The authors suggested that the processing of significant personal information might occur between the detection of the change (MMN) and the orientation of attention (P3a) to the new stimulus (see also Roye, Jacobsen, & Schröger, 2013; Roye, Schröger, Jacobsen, & Gruber, 2010).

1.1.2.1.4. Arousal

Recent studies have proposed that performance in oddball tasks might reflect a mixture of distraction [cost of orienting attention to (and away from) unexpected stimulus)] and facilitation (due to an increase in arousal by novel sounds), (e.g., SanMiguel, Morgan et al., 2010; Schomaker & Meeter, 2015; Wetzel et al., 2012). Wetzel et al. (2012), using an auditory-visual cross-modal task, found that novel and deviant informative sounds (i.e., sounds that announced the imminent presentation of a target stimulus) captured attention, causing behavioural distraction. However, uninformative deviant sounds (i.e., sounds that did not announce the imminent presentation of a target stimulus) did not cause behavioural distraction, while uninformative novel sounds produced a small degree of facilitation. This facilitation effect was explained by the authors as an unspecific activation (arousal) produced by the novel sounds (more motivationally significant than deviant sounds, see also Wetzel et al., 2013). Their reasoning was that informative novel sounds trigger deviance distraction and, to a lesser extent, an increase in arousal. The first slows response times while the second speeds them up. Because the effect of the first is larger than that of the second, informative novel sounds produce distraction. However, when novel sounds are uninformative, the first effect is cancelled, making the small facilitation effect due to arousal visible.

Max, Widmann, Kotz, Schröger, and Wetzel (2015) studied the influence of negative and neutral sounds in a visual categorization task. The authors presented two conditions: informative and uninformative. In the informative conditions, the sounds presented (standard, neutral novel and negative novel sounds) predicted the occurrence of the target, while in the uninformative condition, the sounds (standard, neutral novel and negative novel sounds) did not. Only novel informative sounds elicited distraction. Moreover, independently of the condition (informative or uninformative) negative novel sounds speeded up responses relative to neutral novel sounds.

It is worth noting, however, that arousal has typically been evoked as the source of the small facilitation effect observed in some condition in a post-hoc manner. Indeed, these studies did not provide independent measures of arousal. Furthermore, some arguments put forward by authors as indicative of a role of arousal (SanMiguel, Morgan et al., 2010) have been questioned and alternative explanations proposed (Parmentier, 2014).

1.1.2.1.5. Emotional valence

Compared to emotionally neutral stimuli, stimuli with emotional value have been argued to be especially potent to capture our attention (e.g., Dolan, 2002; Öhman, Lundqvist, & Esteves, 2001; Richards & Blanchette, 2004). This characteristic can be adaptive, for example to facilitate the orientation of our attention to potentially threatening stimuli. Although the equivalent as so far not been clearly demonstrated in oddball tasks, different studies have however reported that deviance distraction can be modulated by the emotional context (e.g., Domínguez-Borràs et al., 2008a; Domínguez-Borràs, Garcia-Garcia, & Escera, 2008b; Garcia-Garcia, Yordanova, Kolev, Domínguez-Borràs, & Escera, 2010).

Domínguez-Borràs et al. (2008a), for example, explored the effect of a negative emotional context (induced by emotional pictures) on auditory novel distraction. Participants performed a cross-modal oddball task in which the main task was to categorize a pair of images (with a neutral or negative valence) as different or identical, while irrelevant sounds (novel or standards) were presented shortly before. The results showed behavioural distraction independently of the valence of the visual stimuli, but the amount of distraction yielded by novel sounds was greater when the sounds were preceded and followed by negative images as opposed to neutral ones (see also Domínguez-Borràs et al., 2008b; Garcia-Garcia et al., 2008).

1.1.2.1.6. Irrelevant stimuli' informational value

One characteristic of the oddball paradigm long gone unnoticed is the fixed contingency between irrelevant and relevant stimuli. Reviewing studies using the cross-modal oddball task, Parmentier, Elsley et al. (2010) pointed out that all prior studies presented a visual target stimulus a fixed amount of time after the auditory irrelevant sound. These authors argued that in such conditions the so-called irrelevant sound was perhaps not that irrelevant but might have acted as an unspecific warning allowing participants to prepare for action. The warning effect of the irrelevant sounds can for example be observed when comparing performance in standard trials and silent blocks: response latencies are slower in the latter (Andrés et al., 2006; Parmentier & Andrés, 2010). Parmentier, Elsley et al. (2010) set out to test whether the warning value of the irrelevant sounds in the cross-modal oddball task might be a condition for deviance distraction to emerge. To test this, they manipulated the warning value of the sound using a cross-modal oddball task in three conditions. In the informative condition, every sound was followed by a target after a fixed sound-to-target interval (similar to the traditional cross-modal oddball task). In the uninformative condition, half the sounds (standard and deviant) were followed by a target (the other half was followed by a cross), and so after one of three possible temporal intervals. Hence in this condition sounds no longer announced whether or when a target stimulus would be presented. Finally, in the informative deviant condition, the standard sound was uninformative (using sound-to-target contingencies identical to those of the uninformative condition) but the deviant was informative (i.e., it was always followed by a target stimulus after a fixed interval). Distraction was observed in the informative condition but not in the uninformative condition. Furthermore, deviants yielded faster responses than the standard sound in the informative deviant condition. The authors concluded that when the sounds' informational value acts as a warning of the forthcoming event the cognitive system takes advantage of it to prepare for action and that, in such circumstances, deviant sounds yield distraction. Work by Wetzel, Widmann, and Schröger (2012) and Wetzel et al. (2013) produced similar results with deviant sounds, and some small degree of facilitation for novel sounds in the uninformative condition (an effect that the authors speculated to reflect some degree of enhanced alertness specific to novel sounds). It is also worth pointing out that Wetzel et al.'s (2013) study also revealed that while behavioural distraction by deviant sounds was eliminated in the uninformative condition, the P3a response was elicited as in the informative condition. The authors suggested that the cognitive system seems to be capable of dealing with the evaluation of the irrelevant stimulus and, at the same time, to shield its processing when the sounds do not provide information.

In a more detailed behavioural study, Ljungberg et al. (2012) went one step further by disentangling the role of event (the extent to which sounds announce whether or not a target will follow) and temporal (the extent to which sounds announce when a target might occur) information. Manipulating these conditions orthogonally, the authors demonstrated that deviance distraction was observed when sounds provided event information and not otherwise (temporal information had no impact). Li, Parmentier, and Zhang (2013) reported converging results in a purely auditory task.

The studies described above support the proposition that deviance distraction is eliminated when sounds do not act as useful warning signals. This conclusion was challenged in a recent study by Parmentier (2016), however. In this study, participants performed an auditory-visual oddball task in one of two conditions: informative or uninformative. In the informative condition, sounds were always followed by a visual target. In the uninformative condition, only half of the sounds were followed by a visual target. The critical aspect of this study was in the distinction between two types of trials in the uninformative condition: those following a trial in which a target had been presented (Go trial following Go trial, or Go|Go) and those following a trial in which no target had been presented (Go trial after NoGo trial, or Go|NoGo). Parmentier (2016) hypothesized that the apparent absence of distraction reported in previous studies in the uninformative condition may in fact reflect two opposite effects of the deviant sounds in Go|Go and Go|NoGo trials. More specifically, the author argued that NoGo trials might leave the cognitive system in a state of response inhibition and that a deviant sound on the next trial might have the effect of facilitating the cancellation of this state, such that deviant sounds may be expected to reduce response times instead of lengthening it.

When analysing the effect of the deviant sound in the uninformative condition as a function of the type of preceding trial (Go vs. NoGo) two opposite effects were indeed observed: distraction following a Go trial and facilitation following a NoGo trial. The reanalysis of the data from three prior studies (Li et al., 2013; Ljungberg et al., 2012; Parmentier, Elsley et al., 2010) confirmed these findings. Finally, Parmentier (2016) modelled the data of the four studies combined and reported a strong fit of the response time data using five predictors: the participants' mean response time (to capture individual differences), the time penalty induced by deviant sounds, post NoGo slowing (reflecting the tendency for slower response when participant inhibited responding on the previous trial), release from this post-NoGo slowing, and the warning value of the sound. Parmentier (2016) concluded that contrary to past conclusions, deviant sounds impact behaviour irrespective of the sounds' value as warning signals and that the apparent absence of distraction reported elsewhere (Li et al., 2013; Ljungberg et al., 2012; Parmentier, Elsley et al., 2010; Wetzel et al., 2013; Wetzel et al., 2012) was due to authors inadvertently mixing two opposite effects of deviant.

1.1.2.1.7. Semantic Processing

As explained in the section on *stimuli characteristics*, some features of the irrelevant sounds such as their personal significance appear to modulate attentional capture, suggesting that the irrelevant sounds must undergo some level of automatic semantic processing. Regarding the semantic processing of the irrelevant stimuli, Wetzel and Schröger (2007) suggested that change detection is elicited by the physical deviance and that this in turn triggers some semantic processing of the deviant stimulus. In line with Wetzel and Schröger (2007), some authors (Roye et al., 2007) suggested that the processing of significant personal information could occur between the detection of the change (MMN) and the orientation of attention (P3a) to the new stimulus or after an attentional switch to the new event (Escera, Yago, Corral, Corbera, & Nuñez, 2003).

In order to determine whether deviant sounds are semantically processed, Parmentier (2008) used a cross-modal task in which participants performed a visual categorization task (arrows pointing to the left or to the right) while ignoring irrelevant sounds preceding each arrow. The key manipulation implemented across several experiments was the use of two deviant words ("left" or "right"), which were congruent or incongruent (in equal proportions) with the upcoming visual arrows. The results showed deviance distraction (lengthening of response times on deviant trials) whether congruent or incongruent, compared to standard trials. More importantly, response times were longer in the incongruent condition compared to the congruent condition (semantic effect). While manipulations of the contrast between the standard sounds and the deviants (whether they differed acoustically, lexically, or in source: artificial versus human voice) affected deviance distraction, this manipulation did not affect the semantic effect. Moreover, while deviance distraction decreased with task practice, the semantic effect remained constant. Parmentier (2008) argued that the semantic effect represents "the crosstalk interference between conflicting activations and marks the involuntary analysis of the novel's lexical and semantic characteristics" (Parmentier, 2008, p. 360). Parmentier, Turner, and Elsley (2011) further showed that increasing the temporal interval between sound and visual arrow increased the semantic effect but not deviance distraction, and provided supporting evidence for Parmentier's (2008) proposition that incongruent activations triggered by the involuntary semantic analysis of the deviant sounds are subject to inhibition. In sum, the results of Parmentier (2008;

see also Parmentier et al., 2014) and Parmentier, Elsley et al. (2011) suggest that deviant sounds affect behaviour in part due to the time penalty associated with the orientation to and from the deviant sound (deviance distraction) and, in cases where the semantic processing of deviant sound and target clash, crosstalk interference (semantic effect). Overall, the involuntary semantic processing of deviant stimuli in the oddball paradigm can be understood as the crosstalk interference between conflicting semantic and lexical activations originating from, on the one hand, the involuntary processing of the deviant sounds and, on the other hand, the voluntary processing of the target stimuli. The semantic processing of the deviant sound is itself partly (but not entirely; Parmentier et al., 2014) triggered by the capture of attention by the deviant on the basis of its acoustic features (deviance distraction).

1.1.2.2. Internal factors

1.1.2.2.1. Age

1.1.2.2.1.1. From childhood to adulthood

The development of the ability to ignore irrelevant information requires brain maturation (principally the prefrontal cortex; e.g., Casey, Giedd, & Thomas, 2000; Fuster, 2002) and continues from childhood to young adulthood (e.g., Stroop task: Comalli, Wapner, & Werner, 1962; dichotic listening task: Berman and Friedman, 1995; Karns, Isbell, Giuliano, & Neville, 2015; Go/no go task: Jonkman, 2006; oddball tasks: Wetzel, 2014; Wetzel, 2015; Wetzel & Schröger, 2014). In a review, Heim and Keil (2012) examined the development of attention control and suggested that the ability to control attention is present early in development. They also added that the ability to adequately manage this attentional resources develops from early school age until late adolescence (e.g., Ridderinkhof & van der Stelt, 2000; flankers: Ladouceur, Dahl, & Carter, 2007; attentional blink paradigm: Heim, Wirth, & Keil, 2011).

Several studies have examined the development of auditory distraction by unexpected stimuli across childhood from an electrophysiological and/or behavioural perspective. At the electrophysiological level (see Wetzel & Schröger, 2014, for a review), the mismatch (MMN) response can be observed before birth (e.g., Draganova et al., 2005) and matures until adolescence (Bishop, Hardiman, Barry, 2011; Martin et al., 2003; Oades, Dittman-Balcar, & Zerbin, 1997; Ruhnau et al., 2013; but see Csépe, 1995; Mahajan & McArthur, 2015). Processes underlying the P3a component seem to develop from childhood to adulthood (Mahajan & McArthur, 2015; Oades et al., 1997; Wetzel et al., 2006). The RON component seems to develop progressively during early adolescence (Mikkola et al., 2010; Wetzel, Berti, Widmann, & Schröger, 2004; Wetzel et al., 2006).

Behaviourally, results from developmental studies on distraction by unexpected stimuli are mixed. On the one hand, some studies report less distraction effects with increasing age throughout childhood (e.g., auditory: Wetzel & Schröger, 2007; Wetzel et al., 2006; auditory-visual: Gumenyuk et al., 2001). For example, Wetzel et al. (2006) used a sound duration discrimination task, manipulating the frequency of the irrelevant stimulus in children (aged 6–8 and 10–12) and in young adults. The results showed behavioural distraction in all age groups, but more so in children (aged 6–8) compared to older children (10-12) and young adults, who did not differ from each other. In a study on deviance distraction and cognitive control, Wetzel and Schröger (2007) compared a group of children (aged 6–8, 10–12) and adolescents (aged 17–18) in a sound duration discrimination task with two conditions: unpredictable and predictable. In the predictable condition, a cue gave information about the time of occurrence and the type of sound (standard or deviant). In the unpredictable condition, a cue announced the time of occurrence of the next sound but not the type of sound. Participants were instructed to make use of the cue in order to avoid distraction. The results revealed behavioural distraction in both conditions (predictable and unpredictable), although it was reduced in the predictable condition compared to the unpredictable condition (in all age groups). Overall distraction decreased as age increased. The authors suggested that young children exhibit greater deviance distraction than older children and adolescents but benefit equally from cues to reduce distraction through cognitive control. On the other hand, other studies reported no age-related effects on distraction across childhood (auditory: Wetzel et al., 2009; auditory-visual: Ruhnau et al., 2013; see Wetzel & Schröger, 2014 for a review). For example, Ruhnau et al. (2013) used a cross-modal task and observed an absence of age-related effects on behavioural distraction comparing children (9–10 years) and adults.

Overall, the pattern of the results from developmental studies on deviance distraction is mixed and highlights the need of further research to shed light on the underlying processes of distraction and their maturation across development.

1.1.2.2.1.2. Ageing

Research on ageing indicates that old age is often accompanied by a decrease in some cognitive functions or abilities such as WM, long-term memory, reasoning or inhibition and that cognitive functions are slower in older adults (e.g., Craik, & Salthouse, 2000; Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988; May, Hasher, & Kane, 1999; Park, & Schwarz, 2000; Salthouse, 2000; Shimamura, 1990; 1994; West, 1999). A decrease in inhibition control or increase in distractibility in ageing (e.g., Alain, Ogawa, & Woods, 1996; Alain, & Woods, 1999; Biss, Campbell, & Hasher, 2013; Campbell, Hasher, & Thomas, 2010; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Lustig, Hasher, & Zacks, 2007; Rabitt, 1965; West & Alain, 2000) has been observed in several tasks (e.g., Simon: Bialystok, Craik, & Luk 2008; Pick & Proctor, 1999; stroop: West & Alain, 2000; flanker: Zeef, Sonke, Kok, Buiten, & Kenemans, 1996; oddball: Parmentier & Andrés, 2010).

In order to explain the age-related differences in cognition, different hypothesis have been proposed. For example, the general cognitive slowing view postulates that the speed with which cognitive processes are carried out is mainly responsible, although not exclusively, for age-relate differences in cognitive performance (Cerella, 1985; Earles, & Salthouse, 1995; Myerson, Ferraro, Hale, Lima, 1992; Salthouse, 1996a; Salthouse 1996b; Salthouse, 2000). Some studies have shown that some age-related differences, for example in WM, are reduced when controlling for the speed of processing (Salthouse 1991; 1992; Salthouse & Meinz, 1995). Other studies have highlighted that the decline in cognitive processes supported by the prefrontal cortex in older adults is greater than in other processes supported by non-frontal regions (West, 2000). However, the most widely accepted view is the inhibition hypothesis that claims that ageing reduces the efficacy of inhibition mechanisms (e.g., Hasher et al., 2007; Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999; Healey, Ngo, & Hasher, 2014).

The inefficient and/or slower inhibition of irrelevant stimuli disrupts the selection of target stimuli, as competition for selection and action between irrelevant and target stimulus lingers on.

In general, older adults seem to be more vulnerable to irrelevant stimuli (e.g., Andrés, Guerrini, Phillips, & Perfect 2008; Hasher & Zacks 1988; Lustig et al., 2007) independently of the sensory modality. However, this contention needs further qualification as this effect appears to be mitigated by sensory constraints. In a recent review, Guerreiro, Murphy, and Van Gerven (2010) reported extensive evidence of the modulating effect of sensory modalities in age-related distraction in different paradigms. The authors argued that ageing results in greater distraction in same-modality tasks (especially visual ones but also in auditory ones), but not in cross-modal tasks. For example, older adults exhibit greater distraction in uni-modal tasks such as in Stroop tasks (e.g., visual: Andrés et al., 2008; Belleville, Rouleau, & Van der Linden, 2006; Borella, Delaloye, Lecerf, Renaud, & De Ribaupierre, 2009; Kray, Eppinger, & Mecklinger, 2005; Salthouse, Atkinson, & Berish, 2003; auditory: Sommers & Danielson, 1999; Sommers & Huff, 2003), Simon tasks (visual: Bialystock, Craik, Klein, & Viswanathan, 2004; Pick & Proctor, 1999; Van der Lubbe, & Verleger, 2002; Vu & Proctor, 2008; auditory: Pick & Proctor, 1999), or reading with distraction tasks (Connelly, Hasher, & Zacks, 1991; Kim, Hasher, & Zacks, 2007; Li, Hasher, Jonas, Rahhal, & May, 1998). In contrast, older adults do not exhibit greater distraction in cross-modal tasks, especially when irrelevant stimuli are auditory and targets are visual (e.g., visual-auditory word pair memory task: Einstein, Earles, & Collins, 2002; auditory-visual Simon tasks: Proctor, Pick, Vu, & Anderson, 2005; Simon & Pouraghabagher, 1978) with the exception of the oddball paradigm (auditory-visual: Andrés et al., 2006; Parmentier & Andrés, 2010).

In contrast to Guerreiro et al. (2010), oddball studies show a different pattern in the age-related effect on deviance distraction across sensory modalities. Out of four studies examining the effect of old age on deviance distraction using a same-modality duration discrimination task in which participants categorized sounds as short or long while ignoring rare and unpredictable changes in pitch, three found identical degrees of deviance distraction in young and older adults (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005). Only one reported a sizable increase in distraction in older compared to young adults (Berti, Grunwald, & Schröger, 2013). However, it is worth pointing out that the above studies reached diverging results with respect to the effect of ageing on the electrophysiological indexes of deviance distraction. For example, while three studies found no effect of ageing on the MMN response (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005), Berti et al. (2013) reported weaker MMN amplitude in older adults. In contrast, Berti et al. (2013) found no effect of age on P3a and RON while other studies reported delayed or reduced P3a and RON (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005). Findings from studies using cross-modal oddball tasks produced consistent results reporting a marked increase in behavioural deviance distraction in older compared to young adults (Andrés et al., 2006; Parmentier & Andrés, 2010).

Overall, evidence for age-related effect in distraction is mixed. Some argue that ageing increases same-modality distraction but not cross-modal distraction (Guerreiro et al. 2010; for age-equivalent top-down modulation in cross-modal processing see also Guerreiro, Adam, & Van Gerven, 2014; Guerreiro, Anguera, Mishra, Van Gerven, &

Gazzaley, 2014; Guerreiro, Eck, Moerel, Evers, & Van Gerven, 2015), a hypothesis contradicted by uni-modal and cross-modal oddball studies (Andrés et al. 2006; Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005; Parmentier & Andrés 2010). However these contradictory results could be understood if one considers that they relate to distinct definitions of the concept of distraction. In the first group of studies, distraction is defined as crosstalk interference, which relates to the competition for selection and action between two stimuli activating the same task-set. Because selecting a stimulus against the competing irrelevant stimulus (and the response afforded by the first against that afforded by the second) can be expected to require more inhibitory control when the two stimuli share the same modality (since sensory information cannot be used as a selection criterion), ageing can be expected to enhance such distraction. In contrast, deviance distraction relates to the cost of reorienting attention to a target following the capture of attention by an unexpected irrelevant stimulus (e.g., Parmentier et al., 2008) and is therefore fundamentally distinct from crosstalk interference. When deviant and target stimuli are presented in distinct sensory modalities, attention is involuntarily directed to the deviant stimulus' irrelevant modality and control is required to reorient it toward the relevant one. Past studies of deviance distraction and ageing typically lacked adequate statistical power and did not compare uni-modal and cross-modal within-participant, however. Hence, in *Publication 2* we compare the effect of ageing on deviance distraction in uni-modal and cross-modal tasks using a within-participant design. In *Publication 3*, we extend research on the effect of ageing in uni-modal oddball tasks by comparing distraction in auditory and visual tasks in a large sample in order to ensure adequate statistical power.

1.1.2.2.2. Emotions

Recent studies have reported that deviance distraction can be modulated by one's emotional state (e.g., Pacheco-Unguetti & Parmentier, 2014; 2015). Pacheco-Unguetti and Parmentier (2014) studied the impact of the participant's emotional state on deviance distraction inducing a specific emotional state (sadness) in participants prior to inviting them to take part in a cross-modal oddball task involving emotionally neutral stimuli. Two induction conditions were compared: sad and neutral. The induction consisted in the retrieval of autobiographical memories (the saddest event in their lives in the sadness condition, or the last time they did their shopping, in the neutral condition) while listening to sad or neutral music respectively. Questionnaire measures collected before and after induction confirmed the efficacy of the induction. The results from the oddball task showed greater deviance distraction in sad participants compared to the neutral group. The authors suggested two possible explanations for their results: (1) sadness might modulate the state of attentional filters, relaxing them to allow unexpected stimuli to enter our focus of attention more easily; and/or (2) sadness might consume central attentional resources and thereby affect the reorientation of attention from the deviant stimuli to the target. While these two options have not been empirically tested yet, Pacheco-Unguetti and Parmentier (2015) showed that the results of Pacheco-Unguetti and Parmentier (2014) are not specific to sadness but also apply to a positive emotion: happiness. Apart from sadness and happiness, other studies examined the role of state and trait anxiety on distraction and found no impact of these factors on distraction (e.g., Hoskin, Hunter, & Woodruff, 2015; Osinsky, Gebhardt, Alexander, & Hennig, 2012). However, anxiety disorders appear to increase the probability of cognitive freezing by deviant sounds (Pacheco-Unguetti, Gelabert, & Parmentier, 2015). This result suggests that while sub-clinical levels of anxiety do not appear to modulate deviance distraction, pathological anxiety (which is often accompanied by additional disorders) appears to interfere with attentional mechanisms.

1.1.2.2.3. Working memory

Independently of the determinant of one's working memory capacity (WMC), (e.g., focus of attention view: Heitz & Engle, 2007; inhibition view: Lustig et al., 2007; primary and secondary memory view: Unsworth & Engle, 2007), a high WMC seems to shield better against distraction (e.g., Conway & Engle, 1994; Kane & Engle, 2000).

Some authors have suggested that WM, because it has been argued to play a role in the filtering of irrelevant information, may partly determine the degree of distraction induced by deviant sounds (although interestingly, it does not appear to affect other types of auditory distraction such as the irrelevant sound effect; e.g., Beaman, 2004). Using a serial recall task, Sörqvist (2010) embedded deviant sounds among streams of irrelevant speech presented concurrently with the encoding of to-be-remembered verbal sequences. Independently, the author measured the participants' WMC using the operation span task (OSPAN). This task consists of the alternate presentation of mathematical operations with words. Participants had to respond the mathematical problems as accurately and quickly as possible and recall as many of the words as they could remember, in the order of presentation. Sörqvist found that high WMC attenuates the impact of deviant sounds in a serial recall task. Using a cross-modal oddball task and the OSPAN task, Sörqvist, Nöstl, and Halin (2012) compared distraction in high- and low-WMC participants. High and low-WMC participants exhibited similar levels of deviance distraction. However, the level of distraction decreased across blocks in high-WMC participants but remained constant in low-WMC participants. The authors suggested that a higher WMC attenuates deviance distraction. In a recent review, Sörqvist and Rönnberg, (2014) argued that changes in WMC across the life span might potentially explain part of the variation of deviance distraction observed with age. Past research indicates that while performance in WM tasks improves with brain development from childhood to early adulthood, it declines in older adults (e.g., Fry & Hale, 1996; Gathercole, Pickering, Ambridge, & Wearing, 2004; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Hale, Bronik, & Fry, 1997; Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Roncadin, Pascual-Leone, Rich, & Dennis, 2007), as does the ability to ignore irrelevant information (Andrés et al., 2006; Lustig et al., 2007; Parmentier & Andrés, 2010). For example, Gathercole et al. (2004) studied the role of WM during childhood by examining three components proposed by Baddeley and Hitch (1974; central executive, the phonological loop, and the visuospatial sketchpad). The authors suggested that the capacity of the three components develops from age four until early adolescence, the phonological loop and the visuospatial sketchpad being two independent components coordinated by the central executive. Gazzaley et al. (2005) reported that older adults had difficulties suppressing irrelevant information as well as impaired WM performance, highlighting a top-down modulation deficit in older adults (see also Gazzaley et al., 2008) The developmental differences in terms of WM could reflect, in part, the maturation and developmental changes in the frontal cortex during childhood (Dempster, 1992; Goldman-Rakic, 1987) and the frontal cortex deterioration in ageing (Raz, 2000; West, 1996).

In *Publication 5*, we explore, among other aspects, whether the effect of age on deviance distraction may be explained, at least in part, by variations in WMC.

1.1.2.2.4. Response inhibition

An efficient cognitive functioning sometimes requires the inhibition of an ongoing behaviour or response in order to replace it by a different action. The ability to replace or cancel a prepotent response has been studied in the laboratory, mostly using the stop-signal paradigm (e.g., Logan, 1994; Logan & Cowan, 1984; Verbruggen & Logan, 2008). Inhibition, in this paradigm, represents “an entire process, extending from stimulus (stop signal) to response (internal inhibitory)” (Logan, 1994, p. 192). In the stop-signal task, participants perform a reaction time task (e.g., to discriminate between an X and O) and they are instructed to withhold a response if a stop signal (e.g., a tone) is presented (usually in 25% of trials). The stop-signal task can be understood by analogy with the horse race model. According to this model, in a situation where a stimulus triggers a response that must then be inhibited upon the presentation of the stop signal, the outcome depends on the competition between two independent processes—go and stop processes. If the go process finishes before the stop process, the response is not inhibited. In contrast, if the stop process finishes before the go process, the response is successfully inhibited. The stop-signal task allows the estimation of the covert reaction time of the stop process (stop-signal reaction time, SSRT), that is, the time that a person needs to inhibit a response that has already been initiated. In order to manipulate the probability of successful response inhibition, the gap between the presentation of the go stimulus and the stop signal is varied in the task following some adaptive algorithm (stop signal delay, SSD). The probability of inhibition is higher when the SSD is short and lower when the SSD increases (Logan & Cowan, 1984). Different adjustments can be used to bias this race as reactive and proactive response strategy adjustments. After a stop-signal trial, participants appear to change their response strategies (reactive response strategy); delaying their responses to increase the probability to inhibit a response in the next trial (e.g., Schachar, Chen, Logan, Ornstein, Crosbie, Ickowicz & Pakulak, 2004; van Boxtel, van der Molen, & Jennings, 2005; Verbruggen & Logan, 2008). Regarding proactive changes, reaction times in go trials increase when the probability of stop-signal trials increase as in blocks where stop-signal trials are expected compared to blocks where they are not expected (e.g., Logan & Burkell, 1986; Verbruggen, Liefoghe, Notebaert, & Vandierendock, 2005). Participants adjust their responses proactively at the beginning of the block and trial by trial, increasing the response times to the go trials in order to successfully inhibit a response (e.g., Verbruggen & Logan, 2009).

In general, attentional reorienting and response inhibition are usually studied in different paradigms. However, recent behavioural and neuroscientific work indicates that both might rely on similar cognitive and neural mechanisms. On the one hand, evidence from the “circuit breaker” account shows that a ventral attention network supports both reorienting and response inhibition (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002; Wiecki & Frank, 2013). According to this account, the reorienting response towards unexpected but potentially behavioural relevant stimuli is based on a ventral frontoparietal network that interrupts and resets ongoing actions as well as on a dorsal frontoparietal network that selects and links stimuli and responses. When a potentially relevant stimulus captures our attention, the ventral network interrupts the ongoing stimulus selection process in the dorsal network, allowing the selection of alternative information. The network activated in the stop-signal task (or go-no go) overlaps with the reorienting network and some researchers propose that both rely in the same inhibitory mechanisms (e.g., Aron, 2011; Chambers, Garavan, &

Bellgrove, 2009). For example, Wiecki and Frank (2013) present a model where structures associated with response inhibition (the right ventrolateral prefrontal cortex) are responsible for the detection of potentially relevant stimuli. Based on this idea, Wessel and Aron (2013) examined the role of motor slowing after novel events using a reaction time task and a stop-signal task. The results showed that novel events slow latencies in an unrelated task (see also Escera et al., 1998; Parmentier, 2008; Parmentier et al., 2008; Parmentier, Elsley et al., 2011; Vachon et al., 2012). The presentation of unexpected events recruited a neural network that was also activated on stop trials in the stop-signal task, where participants had to withhold a response. Additionally, corticospinal excitability was reduced when an unexpected stimulus occurred. The authors concluded that unexpected events cause distraction via global suppression of motor output (see also Aron, Robbins, & Poldrack, 2014). On the other hand, behavioural distraction caused by unexpected events has also been argued to reflect a time penalty associated with the orientation to and away from the unexpected novel stimulus (e.g., Parmentier, 2008; Parmentier, 2014; Parmentier et al., 2008). The presentation of infrequent stimuli (in attentional reorienting paradigms) and stop signals or no-go (in response-inhibition paradigms) activate a similar neural network because both might require the reorientation of attention and detection of novel and infrequent stimuli (e.g., Hampshire, 2015; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Parmentier, 2014; Parmentier et al., 2008, 2011; Schröger, 1996). Moreover, some studies suggest that response inhibition depends on the detection of the unexpected event (e.g., Boucher, Palmeri, Logan, & Schall, 2007; Salinas & Stanford, 2013; Verbruggen, Stevens, & Chambers, 2014).

How attentional reorienting and response inhibition are linked remains unclear and calls for further research. In *Publication 4* we study this link to shed light on this question.

It is worth pointing out that along with the ability to ignore an irrelevant stimulus, the ability to inhibit a response seems to improve through childhood (e.g., Bedard, Nichols, Barbosa, Schachar, Logan, & Tannock, 2002; Carver, Livesey, & Charles, 2001; Riderinkhof, Band, & Logan, 1999; Tillman, Thorell, Brocki, & Bohlin, 2008; van den Wildenberg, & van der Molen, 2004; Williams, Ponesse, Schachar, Logan, & Rosemary, 1999; but see Jennings, van der Molen, Pelham, Brock, & Hoza, 1997; Johnstone et al., 2007; Oosterlaan, & Sergeant, 1998; Schachar & Logan, 1990). This reveals the importance of the maturation of the prefrontal cortex during childhood (e.g., Aron, 2007) as well as other developmental changes such as the increase in effective connectivity in top-down cognitive control (e.g., frontal, subcortical, and oculomotor connectivity: Hwang, Velanova, & Luna, 2010). Urben, Van der Linden, and Barisnikov (2011) showed that this developmental trend was independent of processing speed and WM. The authors used the stop-signal paradigm, N-back task, and a simple reaction task to assess the developmental trend in response inhibition and to control for possible influences of WM or processing speed. Their results showed an improvement in response inhibition during childhood (assessed by the speeding of SSRT), as well as an improvement in the execution of responses (assessed by a decrease in reaction time in go trials up to age 10), in WM (up to ages 9–10), and in processing speed (up to 9–10). When controlling by WM and processing speed, the improvement on response inhibition remained significant. The developmental trend in response inhibition was independent of the other two processes (WM and processing speed), reflecting the importance of considering these processes as distinct.

The use of proactive response–strategy adjustments also improves during childhood (e.g., Blackwell & Munakata, 2014; Munakata, Snyder, & Chatham, 2012; Urben, Barisnikov, & Van der Linden, 2014). For example, Urben et al. (2014) used a stop-signal task to examine the control of response inhibition (6–12 years) and the use of response–strategy adjustments (proactive and reactive) during childhood. In line with previous studies, both response inhibition improved during childhood (decreasing SSRTs) and proactive adjustments (trading speed in the go trials to increase the success in inhibiting the response in the stop trials) improved. Children used the reactive adjustments efficiently (slowing of the response latencies after an unsuccessfully inhibited trial versus a successfully inhibited one); however, the reactive adjustments did not improve during childhood (e.g., Wiersema, van der Meere, & Roeyers, 2007). Munakata et al. (2012) highlighted three transitions during the development to exert a more flexible behaviour. The first developmental transition proposed by the authors is the transition of perseverations and habits to a more flexible behaviour as a response to an environmental signal, maintaining information and goals representations in WM, supported by top-down mechanisms that allow children to provide a flexible behaviour to changes. The second key point is the transition from reactive to proactive control. Children aged eight seem to use proactive control compared to children aged three in an AX continuous performance task [where the participants' task was to provide a response (e.g., using the right hand) to a pair of stimuli, an A followed by an X, and other response (e.g., using the left hand) to a different pair]. The third key point is the transition from externally driven to self-directed control, going from an exogenous control to an endogenous control, which is highly related to the activation of abstract representations. It is worth mentioning that these transitions occur at different ages depending on the task.

Research on response inhibition reported age-related slowing during adulthood [traditionally associated with frontal cortex deterioration (Raz, 2000; West, 1996)], reflecting a decrement in the ability to inhibit a behaviour (e.g., Andrés et al., 2008; Bedard et al., 2002; Kramer et al., 1994; May and Hasher, 1998), though some found only limited evidence for this (e.g., Williams et al., 1999). For example, Kramer et al. (1994) observed more difficulties to stop a response as age increases. Williams et al. (1999) studied response inhibition control across the lifespan. The authors used the stop-signal task in a group of participants aged between six and 81. The results showed faster responses on go-signal reaction time across childhood and a slowing across adulthood. Moreover, the ability to inhibit a response was faster with increasing age during childhood, but the evidence of a slowing during adulthood was limited (reported inhibition deficits to affect the very old participants). The authors suggested that the development of the inhibition and response execution processes could reflect different developmental time courses.

As explained above, the ability to inhibit a response seems to improve through childhood and declines in older adults, as does the ability to ignore irrelevant information. A reduction in inhibitory control in old age may partly account for the age-related changes in deviance distraction. In *Publication 5*, we aimed to examine the role of different processes (WM, response inhibition) on deviance distraction and whether age-related changes in deviance distraction are due to changes in response inhibition.

1.1.3. Differentiation of distraction by unexpected sounds from other auditory distraction effects

At this point, it is important to differentiate deviance distraction from others effects or types of distraction such as the attentional blink, the startle response, or the irrelevant speech effect.

The attentional blink (AB) is a well-known phenomenon that can be defined as "an effect that captures the temporal costs of allocating attention selectively" (MacLean, & Arnell, 2012, p. 1; see also Dux, & Marois, 2009; Martens & Wyble, 2010; Shapiro, Arnell & Raymon, 1997). AB is usually reported in a rapid serial visual presentation (RSVP) where two letters (Target 1 or T1 and Target 2 or T2) are presented in a sequence of irrelevant stimuli (e.g., digits), at a fast pace of presentation of several stimuli per second. The participants' task is to identify the targets and report them once the complete stream of stimuli has been presented (hence there is no time pressure in this task). When the gap between T1 and T2 is between 200 and 500 ms, participants are impaired at detecting T2 given detection of T1. Importantly, if participants are expressly instructed to ignore T1, they report T2 independently of the gap (Raymond, Shapiro, & Arnell, 1992). AB has been reported in different sensory modalities (e.g., visual: Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Shapiro, Raymond, & Arnell, 1994; auditory: Arnell & Jolicœur, 1999; Duncan, Martens, & Ward, 1997; tactile: Hillstrom, Shapiro, & Spence, 2002; auditory-visual: Arnell & Jolicœur, 1999; Arnell & Larson, 2002; Dell'acqua, Jolicoeur, Pesciarelli, Job, & Palomba, 2003; Jolicœur, 1999; Jolicœur & Dell'Acqua, 1999; but see Duncan et al., 1997; Potter, Chun, Banks, & Muckenhoupt, 1998; Soto-Faraco & Spence, 2002; visual-tactile: Soto-Faraco et al., 2002), age groups (e.g., older adults: Lahar, Isaak, & McArthur, 2001), and using different kind of stimuli (e.g., words, pictures).

One may wonder whether deviant sounds might act as some sort of T1 stimulus in the oddball task, and thereby affect the processing of the visual target. Deviance distraction and the AB effect are however well differentiated at the theoretical as well as at the empirical level. From a theoretical perspective, their underlying mechanisms appear quite distinct. While AB is thought to be a result of the reduction in attentional resources available to process T2 when T1 is attended, deviance distraction reflects the delay of the onset target' processing due to the shifts of attention to and from the irrelevant stimulus (Parmentier, 2008; Parmentier, 2014; Parmentier et al., 2008). Furthermore, in the cross-modal oddball task, irrelevant sounds are to be ignored, not attended. Hence it is difficult to argue that a deviant sound could be conceptually similar to the T1 stimulus in the AB paradigm. The contrast between deviance distraction and the AB is also demonstrable empirically. Indeed, the AB account would posit that the deviant should make attention blind to any stimulus presented shortly after. Yet, Parmentier et al. (2008, Experiment 3) demonstrated that an attention-grabbing visual distractor presented between the deviant sound and the visual target does not go unnoticed. On the contrary, it recaptures attention from the auditory modality to the visual, thereby eliminating deviance distraction. Such finding does not sit well with an AB account of deviance distraction.

A second phenomenon that may at first sight appear to relate to deviance distraction is the startle reflex. The startle reflex is defined as "a ubiquitous, cross-species response to abrupt and intense stimulation. It consists of a rapid sequential muscle contraction with the likely purpose of facilitating the flight reaction and/or to protect the body from a sudden attack" (Grillon & Baas, 2003, p. 1). In other words, the startle response can be defined as an automatic protective response caused by a sudden, abrupt, most often intense, stimulus. This kind of response has been studied through the lifespan (e.g., Balaban, 1995; Grillon, Dierker, & Merikangas, 1997) and across different modalities (auditory, visual, tactile). The acoustic startle response (ASR) is by and large the most commonly studied instance of this phenomenon and is typically observed in response to brief sudden noises (e.g., 40 ms burst of white noise) presented at a high intensity (90–110 A-weighted decibels dBA), (e.g., Grillon, 2002; Grillon & Baas, 2003). One may wonder whether deviant sounds in oddball tasks may yield an ASR and entail distraction for that reason. There are however strong elements distinguishing deviance distraction and the ASR. First, deviant sounds used in oddball tasks are typically longer (e.g., 150 ms) and of lower intensity (e.g., 75 dB) than stimuli eliciting an ASR. Moreover, startling sounds have limited impact on the processing of stimuli in a different modality (Silverstein, Graham, & Bohlin, 1981). Additionally, deviant sounds typically delay participants' responses in the task at hand (e.g., Parmentier, 2008; Parmentier, 2014) while responses are speeded up (or remain unaffected but not delayed) when the ASR is elicited (e.g., Carlsen, Dakin, Chua, & Franks, 2007; Lang, Davis, & Öhman, 2000). Finally, the ASR is an automatic response whereas deviance distraction has been shown to be modulated by top-down mechanisms (e.g., Berti & Schröger, 2003; Sussman et al., 2003; Wetzel & Schröger, 2007).

Finally, deviance distraction should be distinguished from another type of auditory distraction observed in serial recall tasks: the irrelevant sound effect (ISE). The ISE can be described as the disruption of serial recall performance for visually presented stimuli by a stream of changing-state, task-irrelevant, sounds (Jones, Madden, & Miles 1992; Jones & Macken 1993, 1995). Ample evidence (e.g., Jones & Macken, 1993) indicates that the serial memory (that is, memory for the order of the presentation of to-be-remembered items) is disrupted by the presentation of changing irrelevant sounds (ABCABC…) but not by the repetition of a single irrelevant sound (AAAAA…), and that this effect occurs whether the changing-state irrelevant sound is presented during the encoding of the to-be-rememebered sequence or during a subsequent retention interval (Macken, Mosdell & Jones, 1999). The ISE is also specific to tasks involving the processing of order information in short-term memory (e.g., Beaman & Jones, 1997). Several findings allow us to distinguish between this type of distraction and deviance distraction. First the cognitive locus of the ISE lies in the conflict between the obligatory processing of the order of the task-irrelevant sounds and the voluntary rehearsal of the to-be-remembered sequence of visual stimuli (Jones, Alford, Bridges, Tremblay, & Macken 1999; Jones & Tremblay 2000). In other words, the ISE is a case of process interference. In contrast, deviance distraction has been argued to reflect the involuntary shift of attention to and away from a stimulus violating predictions (hence it can be described as a case of attentional distraction). Moreover, the two types of distraction can be distinguished empirically. For example, Hughes et al. (2007) reported additive effects of changing-state irrelevant sounds and embedded deviant sounds on serial recall performance, and observed deviance distraction but no ISE in a missing item task (a task requiring item memory, not order memory, in which participants must identify the item missing from a presented sequence). They also showed that, contrary to the ISE, deviance distraction is only observed if the deviant sound is presented during the encoding to the to-be-remembered stimuli (not during a subsequent retention interval). Finally, one other noticeable difference between both phenomena is their sensitivity to the effect of ageing: while several studies found that age increases deviance distraction in cross-modal oddball tasks (Andrés et al., 2006; Parmentier & Andrés 2010), the ISE exhibits no age-related variation (Beaman 2005; Bell & Buchner 2007; Rouleau & Belleville 1996; Van Gerven, Meijer, Vermeeren, Vuurman, & Jolles 2007; Van Gerven & Murphy 2010).

Taken together, the evidence briefly described above clearly indicates that deviance distraction is distinct from the attentional blink effect, the startling effect and the irrelevant sound effect.

1.2. Publications included in this dissertation

Previous research reported behavioural distraction in the oddball paradigm varying with respect to the modality of relevant and irrelevant stimuli (e.g., Berti, 2008; Berti & Schröger, 2001, 2003, 2004, 2006; Parmentier, 2008; Parmentier et al., 2008). In all cases, deviant stimuli yielded significant distraction. This suggests that deviance distraction may reflect a general, modality-unspecific effect whereby unexpected stimuli capture attention irrespective of their sensory modality or that of the to-be-attended stimuli. However, recent evidence questions such contention (Ljungberg & Parmentier, 2012) by showing that the functional similarities between modalities do not necessarily imply an underpinning common mechanism. While past studies used stimuli in various sensory modalities, there has been no systematic attempt to orthogonally contrast the modalities of the irrelevant and relevant stimuli in oddball tasks. This was done across the visual and auditory modalities by Leiva, Parmentier, and Andrés (2015a; see *Publication 1*). Our results revealed deviance distraction for auditory deviants irrespective of the targets' modality. Visual deviants, in contrast, produced no deviance distraction (for visual or for auditory target stimuli), except in the specific situation in which participants were forced to attend to the irrelevant stimuli and under specific conditions related to the spatial properties of the stimuli. This study provides original evidence questioning the hypothesis of deviance distraction as a modality-independent mechanism.

Having established that deviance distraction is especially salient for auditory deviant stimuli (both when targets are auditory and when they are visual), we focused on this modality to study the effect of ageing on deviance distraction (Leiva, Parmentier, & Andrés, 2015b; see *Publication 2*). Ageing is typically associated with a reduction of the ability to ignore distraction. We aimed to examine whether this might be modulated by the sensory modality of the target stimuli. Our study was the first to measure the effect of ageing on deviance distraction in cross-modal (auditory-visual) and uni-modal (auditory–auditory) oddball tasks. The results showed an effect of age on distraction in the cross-modal task but not in the uni-modal task. We argued that ageing might affect processes involved in the switching of attention across modalities.

In our *Publication 2*, we did not find an age-related effect on deviance distraction in the uni-modal task, but it is worth noting that in this task targets and irrelevant stimuli were temporally and perceptually decoupled (i.e., irrelevant and relevant stimuli were presented as distinct perceptual objects and at distinct points in time). One may argue that distinguishing between targets and irrelevant stimuli and inhibiting the latter may be less demanding in such circumstances. If so, the strongest test of the effect of ageing on uni-modal tasks would be provided by tasks in which targets and irrelevant stimuli form part of the same perceptual stimulus. Therefore, in Leiva, Andrés, and Parmentier (2015; see *Publication 3*), we examined the effect of age on deviance distraction using uni-modal oddball tasks in both the auditory and the visual modalities, using a duration discrimination task in which relevant and irrelevant information formed part of the same perceptual object. Our results showed deviance distraction in the auditory and visual modalities, but the amount of distraction did not vary with age. Hence, together, *Publications 2* and *3* provide strong evidence that the effect of ageing on deviance distraction is specific to the cross-modal oddball task and that deviance distraction in purely auditory or visual oddball tasks does not increase in old age.

In Leiva, Parmentier, Elchlepp, and Verbruggen (2015; see *Publication 4*), we studied the hypothetical link between attentional reorienting and response inhibition. As discussed in section *1.1.2.2.4.*, recent research proposed that both processes might rely on similar cognitive and neural mechanisms. In two experiments, we contrasted the “circuit breaker” account (which assumes that unexpected events produce global suppression of motor output) and the “stimulus detection” account (which assumes that attention is reoriented to unexpected events). Our results supported the “stimulus detection” account (not the “circuit breaker” account), highlighting the importance of reorienting our attention in order to detect the unexpected signals and consequently cancel or update our actions.

Finally, in the last empirical chapter of this thesis (Leiva, Andrés, Servera, Verbruggen, & Parmentier, in press; see *Publication 5*), we adopted a more global perspective, integrating several of the factors manipulated in our earlier studies or discussed in the *Introduction* section, and explored deviance distraction across the lifespan (comparing children, young and older adults) and in relation to WM and response inhibition (both of which have recently been assumed to play a potential role in deviance distraction). The results revealed deviance distraction in all age groups, but more so in older adults compared to young adults and children (who did not differ from each other). Response inhibition did not account for deviance distraction in any of the age groups while WMC correlated positively with deviance distraction in children, negatively in older adults, and not at all in young adults.

2. OBJECTIVES

As referred in the initial pages of this dissertation, our general main aim was to explore the cognitive mechanisms underpinning distraction by unexpected stimuli as well as some important factors that may exert a modulatory effect on distraction. More specific objectives examined in this dissertation are briefly summarized in this section and detailed further in the *Publications* section.

Objective 1: Explore the role of sensory modalities by contrasting orthogonally and within-participant the modality (visual vs. auditory) of relevant and irrelevant stimuli in an oddball task.

Objective 2: Examine the effects of ageing on auditory deviance distraction when relevant stimuli are presented auditorily or visually.

Objective 3: Test the hypothesis that age does not increase deviance distraction in same-modality oddball tasks by (a) using the largest sample size to date (42 young and 42 older adults) to ensure adequate statistical power and (b) by extending the study of same-modality deviance distraction (so far limited to the auditory modality) to the visual modality.

Objective 4: Explore the link between attentional reorienting and response inhibition in a go/no-go task.

Objective 5: Study the variation of deviance distraction across the lifespan.

Objective 6: Examine the role of WMC and response inhibition on deviance distraction across the lifespan.

3. PUBLICATIONS

Publication 1

Distraction by deviance: Comparing the effects of auditory and visual deviant stimuli on auditory and visual target processing

Reference

Leiva, A., Parmentier, F. B. R., & Andrés, P. (2015a). Distraction by deviance: Comparing the effects of auditory and visual deviant stimuli on auditory and visual target processing. *Experimental Psychology*, *62*(1), 54-65. doi: 10.1027/1618-3169/a000273.

Motivation

Past research indicates that distraction by deviant stimuli may constitute a general phenomenon transcending sensory boundaries but one should be cautious before concluding that deviance distraction involves central a-modal mechanisms. The aim of this study was to examine whether deviance distraction was observed irrespective of modality boundaries by reporting the first study to manipulate orthogonally the modality (visual or auditory) of the relevant and irrelevant stimuli in an oddball paradigm.

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Research Article

Distraction by Deviance

Comparing the Effects of Auditory and Visual Deviant Stimuli on Auditory and Visual Target Processing

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Abstract. We report the results of oddball experiments in which an irrelevant stimulus (standard, deviant) was presented before a target stimulus and the modality of these stimuli was manipulated orthogonally (visual/auditory). Experiment 1 showed that auditory deviants yielded distraction irrespective of the target's modality while visual deviants did not impact on performance. When participants were forced to attend the distractors in order to detect a rare target ("target-distractor"), auditory deviants yielded distraction irrespective of the target's modality and visual deviants yielded a small distraction effect when targets were auditory (Experiments 2 & 3). Visual deviants only produced distraction for visual targets when deviant stimuli were not visually distinct from the other distractors (Experiment 4). Our results indicate that while auditory deviants yield distraction irrespective of the targets' modality, visual deviants only do so when attended and under selective conditions, at least when irrelevant and target stimuli are temporally and perceptually decoupled.

Keywords: attention, selective attention, visual attention, auditory attention

Several studies have established that attention can be involuntarily captured by sudden changes (oddball, novel, or deviant stimulus) in a sequence of otherwise repeated (standard) sounds. This type of attention capture has been studied from an electrophysiological perspective and is characterized by a pattern of three specific brain responses (e.g., Berti, 2008; Berti, Roeber, & Schröger, 2004; Schröger, 1996, 1997, 2005; Schröger & Wolff, 1998): Mismatch negativity (MMN) marking the detection of change (e.g., Näätänen, Paavilainen, Rinne, & Alho, 2007) or the mismatch between an incoming sound and the prediction of the cognitive system based on a rule abstracted from past events (e.g., Schröger, Bendixen, Trujillo-Barreto, & Roeber, 2007); P3a, assumed to indicate the involuntary orienting of attention toward a perturbing event (e.g., Escera, Alho, Schröger, & Winkler, 2000; Friedman, Cycowic, & Gaeta, 2001); and reorientation negativity (RON) reflecting the reorientation of attention toward relevant information or the task at hand (e.g., Berti & Schröger, 2003).

Behaviorally, responses in a primary task are delayed following the presentation of task-irrelevant novel or deviant auditory stimuli (Parmentier, 2014). This is the case regardless of whether distractor and target information are presented within the same or in different modalities. For example, in the so-called one-channel paradigm, targets and deviants are typically presented auditorily, usually as distinct features of the same auditory object and participants are asked, for example, to discriminate between long and short sounds irrespective of rare changes in their frequency (e.g., Berti & Schröger, 2003; Roeber, Berti, & Schröger, 2003). Even though frequency is irrelevant to the task and is to be ignored, response latencies in the primary task are significantly longer for frequency deviants relative to standards.

In the cross-modal oddball paradigm, in contrast, distractor and target are presented in distinct modalities and at different times. For example, in the auditory-visual oddball task, participants categorize visual stimuli (e.g., digits to be categorized as odd or even) while ignoring auditory distractors presented shortly before each visual stimulus (e.g., Andrés, Parmentier, & Escera, 2006; Escera, Alho, Winkler, & Näätänen, 1998).

The observation of behavioral distraction in both one-channel (e.g., Berti, 2008; Berti & Schröger, 2001, 2003, 2004, 2006; Leiva, Parmentier, & Andrés, 2014; Roeber, Widmann, & Schröger, 2003; Schröger & Wolff, 1998) and cross-modal tasks (auditory-visual: e.g., Escera et al., 1998, 2002; Ljungberg, Parmentier, Leiva, & Vega, 2012; Parmentier, 2008; Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008; Parmentier, Elsley, Andrés, & Barceló, 2011; Parmentier, Elsley, & Ljungberg, 2010; Parmentier,

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Maybery, & Elsley, 2010; tactile-visual: e.g., Ljungberg & Parmentier, 2012; Parmentier, Ljungberg, Elsley, & Lindkvist, 2011) suggests that distraction by deviant stimuli may constitute a general phenomenon transcending sensory boundaries (a contention bolstered by the finding of similar electrophysiological responses to deviant stimuli of various sensory modalities; e.g., Berti & Schröger, 2004; Escera et al., 1998; Knight, 1996). Such observation fits well with the theoretical framework proposed by Parmentier et al. (2008) in the context of the cross-modal oddball task. According to these authors, behavioral distraction does not stem from a slower processing of the visual targets or the planning and execution of responses per se, but from a time penalty associated with the involuntary shift of attention to and from a novel or deviant sound. Such principle, because not relying on sensory modality as a key factor, predicts distraction irrespective of the modality in which distractor and target stimuli are presented.

One should however be cautious before concluding that deviance distraction involves central a-modal mechanisms for two reasons: one empirical and the other methodological. Empirically, recent findings from Ljungberg and Parmentier (2012) suggest that functional similarities between auditory-visual and tactile-visual oddball tasks do not constitute evidence of the existence of shared cognitive mechanisms. The authors reported that while both versions of the task yield deviance distraction, post-deviance distraction (i.e., small amount of distraction observed on the first standard trial following a deviant one), and a similar proportional reduction of these effects with practice, no correlations were found across the two tasks for distraction or post-deviance distraction. Such results contradict the notion of a hypothetical a-modal mechanism as the source of behavioral distraction. Secondly, as pointed out earlier, one-channel and cross-modal oddball tasks vary in several respects. In addition to whether targets and distractors are presented in the same modality or not, they differ with respect to whether these stimuli form part of the same object or not. This is potentially important because of its implications for the deployment of voluntary attention. Indeed, in one-channel tasks, participants must attend a stimulus that carries both target and distractor information, such that by attending one they also attend the other (e.g., participants actively attending a tone to judge its duration cannot do so without also attending other aspects of that stimulus, such as its pitch).

The objective of our study was to examine whether deviance distraction is observed for targets and distractors presented within or between modalities (visual or auditory) while controlling for the perceptual and temporal decoupling of distractor and target information. To do so, we adapted the general structure of the cross-modal oddball task in which a distractor is presented first, followed by the target, and we manipulated the modality of these orthogonally. Under the a-modal hypothesis of deviance distraction, we predicted that deviant stimuli should delay responses to target irrespective of their sensory modality. The absence of distraction in any of our conditions would, in contrast, invalidate this hypothesis.

Experiment 1

Method

Participants

Fifty eight (40 females) undergraduate students from the University of the Balearic Islands, aged 18–37 ($M = 21.508$, $SD = 3.737$), participated in this study in exchange for course credit or a small honorarium. All reported normal hearing, and normal or corrected-to-normal vision.

Material and Stimuli

The task involved the presentation of auditory and visual stimuli. The auditory stimuli included the digits 1–6 spoken in a female voice. The duration of each digit was 400 ms. Two additional sounds were used, one consisting of a 150 ms sine-wave tone of a frequency of 600 Hz, the other of a 150 ms burst of white noise. All sounds were normalized and presented binaurally via headphones with an intensity of approximately 75 dB.

The visual stimuli consisted of the digits 1–6. The duration of each digit was 400 ms. Two additional visual stimuli were used, one consisting of a 150 ms blue circle (RGB values: 2, 98, 230), the other was a 150 ms green star (RGB values: 16, 134, 0). All visual stimuli sustained a visual angle of approximately 4.4°, with participants seated approximately 50 cm away from the screen. The RGB values were selected to produce equivalent levels of luminance (84 cd/m^2). All visual stimuli (digits and shapes) were presented in the center of the screen against a black background.

Design and Procedure

In every trial, the participant's task was to categorize a digit as odd or even while ignoring distractors presented shortly before each digit. Across the experiment, four conditions, stemming from the orthogonal crossing of the sensory modality in which distractor and target stimuli were presented (auditory or visual), were administered to all participants. The order of the four conditions was counterbalanced, within-participant, according to a Latin square design. Each condition involved two consecutive blocks of 192 test trials each.

A fixation cross was displayed at the center of the screen for the duration of each trial except during the presentation of a visual stimuli. Each trial started with the presentation of a 500 ms fixation cross followed by a 150 ms distractor. One hundred and fifty milliseconds after the distractor's offset, a digit was presented for 400 ms. The digits 1–6 were presented in a different random order for every participant but with equal probabilities across each block of trials and type of trial (standard or deviant, as described below). Following the digit, the fixation cross reappeared

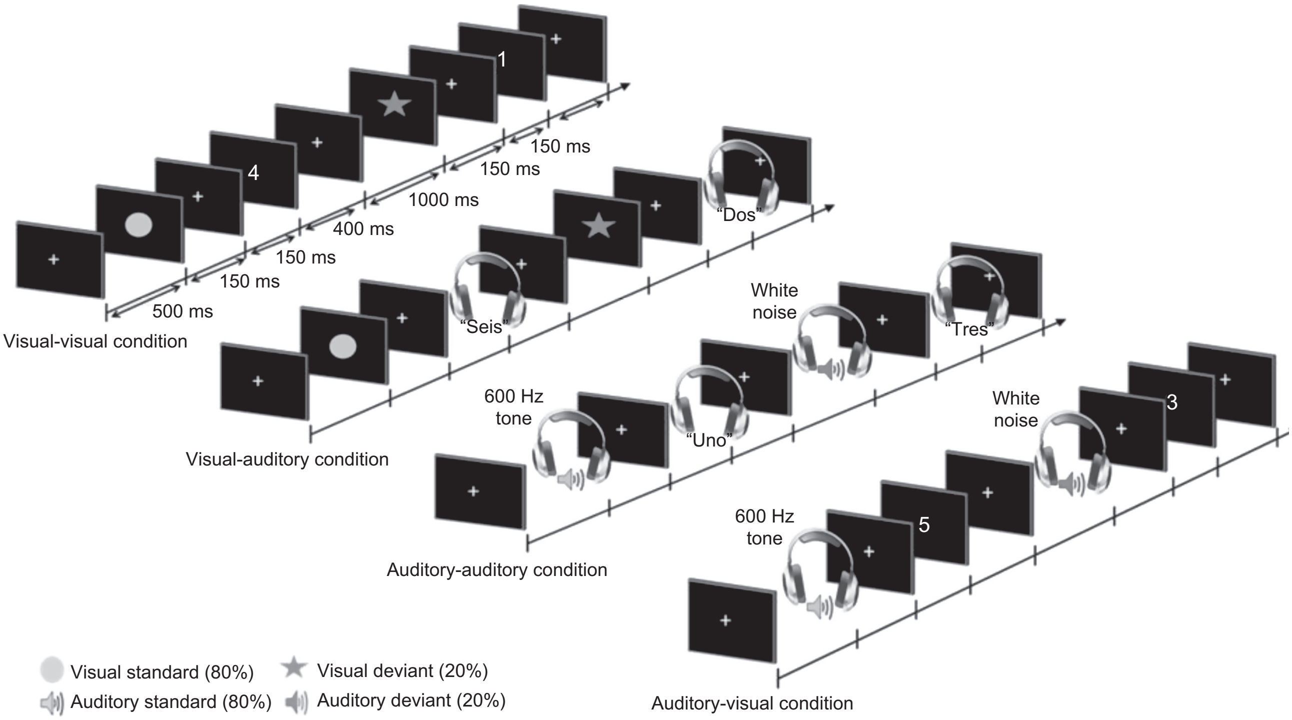

Figure 1. Schematic illustration of the experimental conditions of Experiment 1. In every trial, the participant's task was to categorize a digit as odd or even while ignoring distractors presented shortly before each digit (two trials of every condition are illustrated). Four conditions are illustrated. In the *visual-visual condition*, visual distractors took the form of a blue circle, light grey in the illustration, (standard distractor) or of a green star, dark grey in the illustration, (deviant distractor). In the *auditory-auditory condition*, distractors consisted of the 600 Hz sine-wave tone (standard distractor) and of a burst of white noise (deviant distractor). In the *visual-auditory condition*, distractors were visual as in the visual-visual condition, while targets were presented auditorily as in the auditory-auditory condition. In the *auditory-visual condition*, distractors were presented auditorily while targets were presented visually.

and remained visible for 1,000 ms, after which the next trial was automatically initiated. From the target's onset to the end of the response window, participants had 1,400 ms to categorize the target digit by pressing the keys X or Z on the computer keyboard using two fingers from their dominant hand. The mapping of keys to responses (odd, even) counterbalanced across participants. The total duration of the experiment session was approximately 45–50 min.

Four conditions, illustrated in Figure 1, were compared (visual-visual, auditory-auditory, visual-auditory, auditory-visual). In the *visual-visual condition*, targets and distractors were presented visually. Visual distractors took the form of a blue circle in 80% of trials (standard distractor) or of a green star in the remaining 20% of trials (deviant distractor). In the *auditory-auditory condition*, targets and distractors were presented auditorily. Distractors consisted of the 600 Hz sine-wave tone in 80% of trials (standard distractor) and of a burst of white noise in the remaining 20% of trials (deviant distractor). In the *visual-auditory condition*, distractors were visual as in the visual-visual condition, while targets were presented auditorily as in the auditory-auditory condition. In the *auditory-visual condition*, distractors were presented auditorily while targets were presented visually. In each condition, standard and deviant trials were ordered quasi-randomly in a different order for every condition and participant, with the constraint that deviant trials were never presented on consecutive trials.

Participants were instructed to ignore the distractors to concentrate on the categorization task, and to respond as quickly but as accurately as possible.

Results

Participants' responses were recorded and accuracy and response times (for correct responses) analyzed using 2 (Distractor Modality: auditory vs. visual) × 2 (Target Modality: auditory vs. visual) × 2 (Distractor Type: standard vs. deviant) ANOVAs for repeated measures. Significant interactions were analyzed using Tukey HSD tests. The same techniques were applied to all analyzes in this study.

Response accuracy was overall high (M = .911, SD = .083), as visible from Table 1. No significant main effects of distractor modality, $F(1, 57) < 1$, $\eta_p^2 = .010$, target modality, $F(1, 57) = 2.31$, $MSE = .010$, $p = .134$, $\eta_p^2 = .039$, or distractor type, $F(1, 57) < 1$, $\eta_p^2 = .003$, were found. No significant two-way interactions were observed

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Table 1. Mean proportions of correct responses in Experiments 1–4 as a function of the type of distractor type (deviant vs. standard) and the modality of distractor and target in the four conditions: AA (auditory-auditory), AV (auditory-visual), VA (visual-auditory), and VV (visual-visual). Figures within parentheses represent the standard deviation

Auditory distractor				Visual distractor			
Auditory target		Visual target		Auditory target		Visual target	
Standard	Deviant	Standard	Deviant	Standard	Deviant	Standard	Deviant
Experiment 1							
.917 (.058)	.920 (.060)	.901 (.128)	.896 (.135)	.922 (.053)	.916 (.057)	.909 (.064)	.912 (.058)
Experiment 2							
.887 (.073)	.891 (.079)	.914 (.064)	.901 (.081)	.918 (.049)	.912 (.074)	.899 (.061)	.916 (.073)
Experiment 3							
				.892 (.069)	.894 (.083)	.870 (.075)	.875 (.071)
Experiment 4							
.857 (.104)	.797 (.136)	.878 (.089)	.821 (.115)	.892 (.067)	.899 (.070)	.883 (.077)	.882 (.091)

between target and distractor modality, $F(1, 57) < 1$, $\eta_p^2 = .009$, distractor modality and distractor type, $F(1, 57) < 1$, $\eta_p^2 < .001$, or target modality and distractor type, $F(1, 57) < 1$, $\eta_p^2 = .001$. However, significant triple interaction was observed, $F(1, 57) = 4.638$, $MSE = .0004$, $p = .036$, $\eta_p^2 = .075$. Further analysis revealed that this interaction reflected the fact that responses to visual targets were slightly less accurate than to auditory targets (greatest $p = .028$) except in the case of deviant trials when distractors were visual (in which case accuracy levels to visual and auditory targets were equivalent, $p = .981$).

The analysis of response times proved more revealing (see Figure 2, Panel A). The main effect of distractor modality was significant, with longer response times for auditory than visual distractors, $F(1, 57) = 8.727$, $MSE = 1701.054$, $p = .005$, $\eta_p^2 = .133$. Response times were significantly longer for auditory than visual targets, $F(1, 57) = 689.136$, $MSE = 4608.099$, $p < .001$, $\eta_p^2 = .924$, an effect that might reflect the fact that the identify of digits is available from the onset for visual stimuli but become clear later for auditory stimuli. The main effect of deviance was also significant, with longer response times for deviant than standard trials, $F(1, 57) = 47.016$, $MSE = 349.124$, $p < .001$, $\eta_p^2 = .452$. The Distractor × Target Modality interaction was not significant, $F(1, 57) = 3.338$, $MSE = 1595.848$, $p = .073$, $\eta_p^2 = .055$, and neither were the Target Modality × Distractor Type, $F(1, 57) < 1$, $\eta_p^2 = .009$, or three-way interactions, $F(1, 57) = 1.274$, $MSE = 446.361$, $p = .264$, $\eta_p^2 = .022$. Importantly, however, a significant Distractor Modality × Distractor Type interaction was observed, $F(1, 57) = 46.399$, $MSE = 253.289$, $p < .001$, $\eta_p^2 = .449$. This interaction reflected the presence of distraction when distractors were auditory ($M = 609.47$, $SD = 115.08$, and $M = 587.51$, $SD = 108.76$, for the deviant and standard conditions respectively), $p < .001$. In contrast, no distraction was observed when distractors were visual ($M = 588.09$, $SD = 105.60$, and $M = 586.26$, $SD = 105.96$, for deviant and standard conditions respectively), $p = .9256$.

Discussion

The results from Experiment 1 are unambiguous: using a task in which distractors and targets were perceptually and temporally decoupled, deviance distraction was observed for auditory distractors irrespective of the modality of the target stimuli. In contrast, visual distractors did not yield distraction, whether targets were visual or auditory.

These results suggest that auditory stimuli constitute potent distractors, affecting responses to visual as well as auditory targets. While distraction in the auditory-visual condition was expected on the basis of previous work (e.g., Escera et al., 1998; Parmentier et al., 2008), the results from the auditory-auditory condition show that distractor and target presented in the auditory modality exhibit distraction when perceptually and temporally decoupled just as when presented as fused into a single stimulus in past studies using the one-channel paradigm (e.g., Berti & Schröger, 2003; Roeber et al., 2003; Schröger & Wolff, 1998; Wetzel & Schröger, 2007a, 2007b).

If the absence of distraction in the visual-auditory task questions the notion of deviance distraction as the manifestation of an hypothetical a-modal set of mechanisms, the results from the visual-visual condition pose the additional challenge of clashing with previous reports of distraction in one-channel visual tasks (e.g., Berti & Schröger, 2004, 2006). One possible explanation for this discrepancy stems from methodological differences between our experiment and past visual oddball studies. For example, in the task used by Berti & Schröger (2004), participants judged the duration of a small gray triangle embedded in a green square in the face of rare and unexpected changes in the spatial relationship between these stimuli. It is possible that

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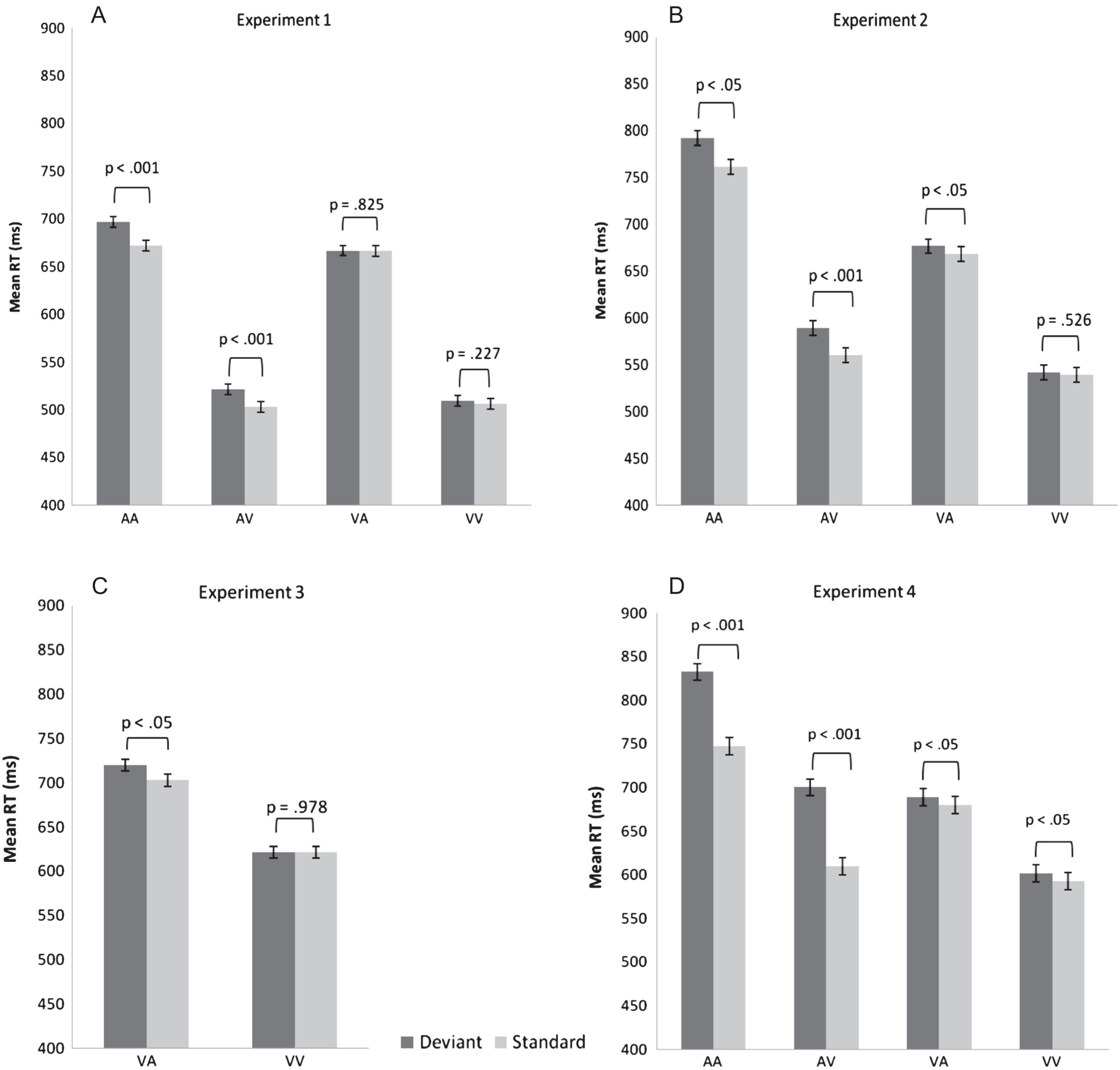

Figure 2. Mean response times in Experiments 1–4 (Panels A, B, C & D, respectively) as a function of the type of distractor (deviant vs. standard) and the modality of distractor and target: auditory-auditory (AA), auditory-visual (AV), visual-auditory (VA), visual-visual (VV). The error bars represent 95% confidence interval (calculated based on the three-way interaction, following Jarmasz & Hollands, 2009; Hollands & Jarmasz, 2010). *P*-values refer to *T*-test assessing the presence of deviance distraction. Participants in Experiment 1 were instructed to ignore distractors. Participants in Experiments 2, 3, and 4 were forced to attend to them (see Method section for details).

participants were successful in inhibiting visual distractors in our visual-visual condition because distractors and targets were perceptually and temporally separated. In other words, it may be that the distraction effect reported in past visual oddball tasks (e.g., Berti & Schröger, 2001, 2004, 2006) came about because such studies incited participants to direct attention to the distractor as well as to the target. If so, a new prediction can be put forward, namely that distraction might emerge in our task if participants are forced to attend to the distractors. This prediction was tested in Experiment 2 in which we modified the task from Experiment 1 to include, apart from the standard and deviant distractors, a third class of distractors to which participants were instructed to respond. The function of these catch trials was to incite participants to direct attention to distractors as well as to targets. If visual deviants require

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to be attended to in order to induce distraction, significant distraction should now be observed in the visual-visual and visual-auditory conditions.

Experiment 2

Method

Participants

Fifty-two (26 females) undergraduate students from the University of the Balearic Islands, aged 18–31 ($M = 21.85$, $SD = 3.22$), participated in this study in exchange for course credit or a small honorarium. All reported normal hearing, and normal or corrected-to-normal vision.

Material and Stimuli

Three sounds were used: a 150 ms sine-wave tone of a frequency of 600 Hz, a 150 ms sine-wave tone of a frequency of 710 Hz, and a 150 ms burst of white noise. Three visual stimuli were used: a 150 ms blue circle (RGB values: 2, 98, 230), a 150 ms green star (RGB values: 16, 134, 0), and a 150 ms blue square (RGB values: 2, 98, 230). The RGB values were selected to result in the same level of luminance (84 cd/m^2). All visual stimuli were presented at the center of the screen against a black background and sustained a viewing angle of approximately 4.4°.

Design and Procedure

As in Experiment 1, the participants' primary task was to categorize the parity of visual or auditory digits. However, their task differed from it in one important respect: apart from the standard and deviant distractors, which participants did not respond to, a third type was included to which participants had to respond by pressing the space bar. This manipulation aimed to force participants to voluntary attend to the distractors.

The design and procedure of Experiment 2 was similar to that of Experiment 1 in all aspects except for the following. For each combination of distractor and target modalities (auditory-auditory, auditory-visual, visual-visual, visual-auditory), standard distractors were presented in 60% of trials and deviant distractors in 10% (Figure 3). In the remaining 30% of trials, a "target-distractor" was used, corresponding to a blue square (in the visual distractor conditions) or a 710 Hz sine-wave tone (in the auditory distractor conditions). Participants were instructed to categorize the target digits as odd or even using the left and right buttons of the computer mouse (mapping of keys to responses counterbalanced across participants) using their dominant hand. They were also instructed to press the space bar, using their other hand, whenever a target-distractor was presented. In such trials, they were asked to press the space bar first and categorize the digit next. Instructions emphasized the need to perform both digit categorization and target-distractor detection as fast and accurately as possible. In order to make this secondary task relatively demanding, target-distractors were perceptually similar to the standard distractors (sharing their color in the case of visual distractors, or consisting of a sine-wave tone in the case of auditory distractors). Given the greater complexity of the participants' task in Experiment 2, the response window was extended from 1,400 ms (Experiment 1) to 1,800 ms. Before the experiment began, participants were presented with all types of distractors one at a time and were allowed to see or listen to them as many times as they wished in order to remember which of the distractors required a response.

Results

In this experiment and the next two, we analyzed performance from the standard and deviant conditions, not from the target-distractor condition.

Participants performed the digit categorization task with high accuracy overall ($M = .904$, $SD = 0.07$, see Table 1). The analysis of the proportion of correct responses showed no significant main effect of distractor modality, $F(1, 51) = 3.377$, $MSE = .005$, $p = .072$, $\eta_p^2 = .062$, target modality, $F(1, 51) < 1$, $\eta_p^2 = .010$, or distractor type, $F(1, 51) < 1$, $\eta_p^2 < .001$. No significant two-way interactions were observed: Distractor Modality × Distractor Type, $F(1, 51) = 2.743$, $MSE = .001$, $p = .104$, $\eta_p^2 = .051$, or Target Modality × Distractor Type, $F(1, 51) = 1.60$, $MSE = .001$, $p = .691$, $\eta_p^2 = .003$, but a two-way interaction was observed: Target Modality × Distractor Modality, $F(1, 51) = 4.943$, $MSE = .004$, $p = .031$, $\eta_p^2 = .088$, reflecting a slightly larger advantage of auditory targets over visual ones when the distractor was auditory rather than visual. The triple interaction was significant, $F(1, 51) = 6.409$, $MSE = .002$, $p = .014$, $\eta_p^2 = .112$. This interaction reflected a slightly lower level of accuracy for auditory targets compared to visual targets in the standard condition when the distractor was auditory ($p = .013$), while accuracy levels were equivalent in all other cases (smallest $p = .239$).

The analysis of response times for correct responses (see Figure 2, Panel B) revealed a significant main effect of distractor modality, $F(1, 51) = 84.236$, $MSE = 5941.187$, $p < .001$, $\eta_p^2 = .623$, with slower responses in the presence of auditory than visual distractors. Response times were also slower for auditory targets compared to visual ones, $F(1, 51) = 445.653$, $MSE = 6512.876$, $p < .001$, $\eta_p^2 = .897$, and for deviant distractors compared to standard ones, $F(1, 51) = 39.385$, $MSE = 825.690$, $p < .001$, $\eta_p^2 = .436$. A significant Distractor Modality × Target Modality interaction was observed, $F(1, 51) = 31.122$, $MSE = 4134.212$, $p < .001$, $\eta_p^2 = .379$. This interaction reflected longer response times in the auditory-auditory ($M = 776.99$, $SD = 115.52$) than in the auditory-visual ($M = 574.77$, $SD = 98.77$) condition ($p < .001$), as well as longer response times in the visual-auditory ($M = 672.46$,

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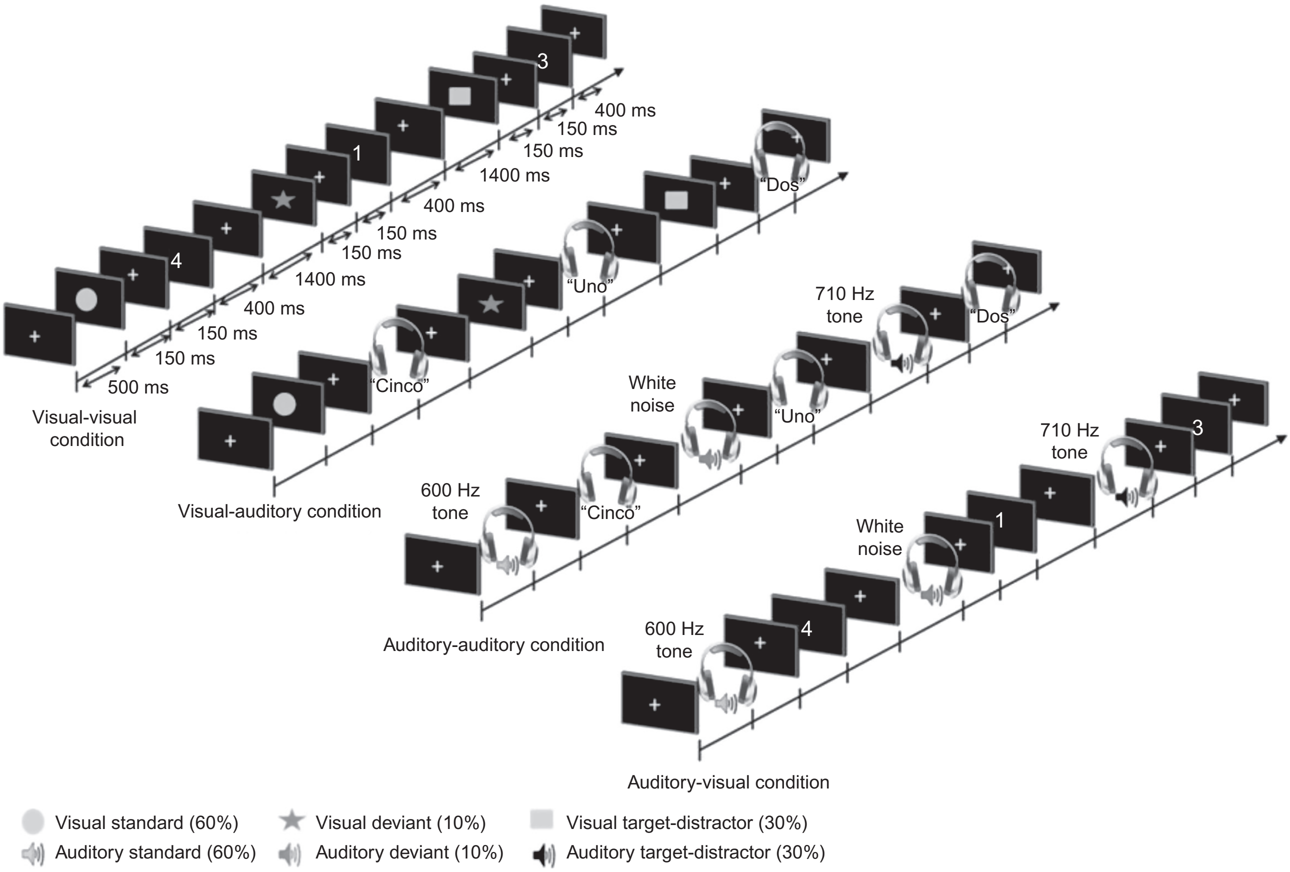

Figure 3. Schematic illustration of the experimental conditions of Experiment 2. Participants' primary task was to categorize the parity of visual or auditory digits (three trials of every condition are illustrated). Three types of distractors are included, standard and deviant distractors, which participants did not respond to, and a third type (target-distractor) which participants had to respond by pressing the space bar. Four conditions are illustrated. In the *visual-visual condition*, visual distractors took the form of a blue circle, light grey in the illustration, (standard distractor), a green star, dark grey in the illustration, (deviant distractor) or a blue square, light grey in the illustration, (target-distractor). In the *auditory-auditory condition*, distractors consisted of the 600 Hz sine-wave tone (standard distractor), a burst of white noise (deviant distractor) or 710 Hz sine-wave tone (target-distractor). In the *visual-auditory condition*, distractors were visual as in the visual-visual condition, while targets were presented auditorily as in the auditory-auditory condition. In the *auditory-visual condition*, distractors were presented auditorily while targets were presented visually.

SD = 99.04) than in the visual-visual (M = 540.57, SD = 84.30) condition (p < .001). The Target Modality × Distractor Type was not significant, $F(1, 51) < 1$, η_p^2 = .014. The Distractor Modality × Distractor Type interaction was significant, $F(1, 51) = 19.613$, MSE = 765.065, p < .001, η_p^2 = .278, reflecting overall greater distraction (deviant minus standard) for auditory distractors (p < .001) compared to visual ones (p = .726). Importantly however, the three-way interaction was not significant, $F(1, 51) < 1$, η_p^2 = .003.

Discussion

Experiment 2 introduced a manipulation aiming to force participants to attend to the distractors in order to establish whether visual deviants would then yield distraction as they do in one-channel tasks (e.g., Berti & Schröger, 2001, 2004, 2006). The results were mixed. As in Experiment 1, deviance distraction was observed for auditory distractors regardless of the modality of the target. Visual distractors, on the other hand, only yielded distraction when targets were auditory but not when they were visual. Directing attention to visual distractors was therefore partly successful in eliciting distraction, but not completely. Most critically, it was not in the very condition where past work (e.g., Berti & Schröger, 2001, 2004, 2006) predicted distraction: the visual-visual condition. These findings suggest that the distraction measured by others in tasks where distractor and target formed part of the same perceptual object (Berti & Schröger, 2004, etc.) is unlikely to be due to the voluntary attending of the distractors.

However, before ruling out a possible role for the voluntary attending of the distractor in visually induced deviance

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distraction, it is worth considering whether some extraneous factors might have masked or prevented distraction from being observed in our visual-visual condition. More specifically, it may be useful to rule out the possibility that visual deviants may have, by virtue of capturing attention, yielded spatial cueing or the stronger focusing of attention to their spatial location. This may in turn have benefited the processing of a subsequent stimulus (the target) in that location. It is well established that the processing of a visual stimulus can be enhanced when attention is exogenously captured to its location by a prior cue (visual modality: e.g., Jonides, 1981; Yantis & Jonides, 1984; tactile: e.g., Posner, 1978; Spence & McGlone, 2001; auditory: e.g., Spence & Driver, 1994). Furthermore, there is also evidence that the capture of attention by deviant stimuli can trigger opposite and simultaneous effects on responses to a visual target. For example, Ljungberg and Parmentier (2012) found that urgently spoken deviant words speed up responses relative to a calmly spoken version of the same words, thereby mitigating deviance distraction. Also, Parmentier, Turner, and Perez (2014) found that a spoken deviant word (e.g., "left") semantically congruent with an upcoming visual target (left arrow) facilitated target processing to the point of compensating for distraction. In order to establish whether some processing facilitation may have masked deviance distraction in our visual-visual condition, Experiment 3 used the visual-visual and visual-auditory conditions of Experiment 2 with the difference that targets randomly appeared above or below the central location. Experiment 3 also differed from Experiment 2 insofar as no temporal gap separated the distractor's offset from the target's onset. This was implemented in view of the fact that performance was overall faster for visual targets compared to auditory ones in Experiments 1 and 2, suggesting that visual processing is faster than auditory processing. We reasoned that reducing the gap between distractor and target may increase the impact of deviance distraction and render our task more sensitive. The critical prediction for Experiment 3 was that if deviance distraction was cancelled out by target processing facilitation in the visual-visual condition of Experiment 2, deviance distraction should be found in Experiment 3 for that condition. The absence of distraction would, on the other hand, support the view that visual distractors, even when voluntarily attended to, do not yield deviance distraction when perceptually and temporally decoupled.

Experiment 3

Method

Participants

Forty-six (32 females) undergraduate students from the University of the Balearic Islands, aged 18–30 (M = 20.32, SD = 2.11), participated in this study in exchange for course credit or a small honorarium. All reported normal hearing, and normal corrected-to-normal vision.

Material and Stimuli

Materials and stimuli were as in the visual-visual and visual-auditory conditions of Experiment 2.

Design and Procedure

The task used in Experiment 3 was similar to that reported in Experiment 2 except for some important differences described below. First and foremost, only conditions with visual distractors were presented (visual-visual and visual-auditory condition). In addition, the temporal gap between distractor and target was reduced from 150 ms (Experiments 1 & 2) to 0 ms (offset to onset). Finally, visual digits appeared above or below the central fixation cross (at a visual angle of approximately 7.4°), at random but with equal probabilities across all combinations of digits (1–6) and types of distractor (standard, deviant).

Participants performed 4 blocks of 252 trials each (12 serving as practice trials and only including standard distractors). Tasks instructions and response keys were as in Experiment 2.

Results

Accuracy was overall high (M = .883, SD = 0.08, see Table 1). Higher accuracy was observed for auditory than visual targets, $F(1, 45) = 7.851$, MSE = .003, p = .007, $\eta_p^2 = .149$. The main effect of distractor type was not significant, $F(1, 45) < 1$, $\eta_p^2 = .006$, and neither was the Target Modality × Distractor Type interaction, $F(1, 45) < 1$, $\eta_p^2 = .002$.

The analysis of response times for correct responses (see Figure 2, Panel C) showed slower responses for auditory targets than for visual ones, $F(1, 45) = 125.941$, MSE = 2946.766, $p < .001$, $\eta_p^2 = .737$, and for deviant distractors than for standards ones, $F(1, 45) = 5.810$, MSE = 579.428, p = .020, $\eta_p^2 = .114$. A significant Target Modality × Distractor Type interaction was observed, $F(1, 45) = 6.620$, MSE = 495.274, p = .013, $\eta_p^2 = .128$, reflecting the presence of deviance distraction for auditory targets (p = .004) but its absence for visual distractors (p = .999).

Discussion

Experiment 3 replicated the results of Experiment 2: Deviance distraction was observed for visual irrelevant stimuli when the target stimuli were auditory but not when they were visual. The latter was found even though irrelevant and target stimuli were presented in distinct spatial locations, thereby ruling out the possibility that the absence of distraction observed in Experiment 2 was due to visual deviants facilitating the processing of the following target through spatial cueing.

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Before concluding that irrelevant visual deviants do not yield distraction when targets are visual, it is worth pointing a methodological aspect of Experiments 2 and 3 that may have hampered deviance distraction. Namely, the standard irrelevant visual stimuli and the visual target-distractors shared the same color (blue square and blue circle respectively). This made the deviant visual stimulus (green star) relatively distinct and potentially easier to ignore. To avoid this limitation, Experiment 4 used a target-distractor that no longer shared the color of any of the irrelevant visual stimuli. Furthermore, we counterbalanced the standard and deviant stimuli across participants in the visual but also the auditory irrelevant stimulus conditions. In addition, we also replaced the fixation cross by a frame to avoid a visual overlap with visual irrelevant and target stimuli[1].

Experiment 4

Method

Participants

Fifty-eight (44 females) undergraduate students from the University of the Balearic Islands, aged 18–24 ($M = 19.40$, $SD = 1.39$), participated in this study in exchange for course credit or a small honorarium. All reported normal hearing, and normal corrected-to-normal vision.

Material and Stimuli

Materials and stimuli were as in the conditions of Experiment 3, but the 150 ms blue square (RGB values: 2, 98, 230) was replaced by a 150 ms orange square (RGB values: 200, 80, 0).

Design and Procedure

The task used in Experiment 4 was similar to that reported in Experiment 3 except for some important differences described below. First, the central fixation cross was replaced by a frame for the duration of the whole experiment. In addition, the spatial distance between the visual distractors and the visual digits was increased (a visual angle of approximately 8.4°) to reduce further the chances that visual deviant stimuli might cue spatial attention to the location of the target and thereby facilitate its processing (which might mask deviance distraction). Finally, a counterbalanced design was presented with 50% of the participants performing the task with the burst of white noise as the standard auditory distractor and the 600 Hz tone as a deviant (and vice versa for the remaining participants). Similarly, in the visual conditions, 50% of the participants performed the task with the blue circle as the deviant visual distractor and the green star as the standard (and vice versa for the remaining participants; the target distractor was an orange square).

Participants performed 8 blocks (2 counterbalanced blocks of each condition, as in Experiment 2) of 252 trials each (12 trials serving as practice trials and only including standard distractors). Tasks instructions and response keys were as in Experiment 2.

Results

Participants performed the digit categorization task with high accuracy overall ($M = .864$, $SD = 0.10$, see Table 1). The analysis of the proportion of correct responses showed a significant main effect of distractor modality, $F(1, 57) = 30.725$, $MSE = .010$, $p < .001$, $\eta_p^2 = .350$, with higher accuracy for visual than auditory distractors. Accuracy was also higher for standard than deviant distractors, $F(1, 57) = 23.764$, $MSE = .004$, $p < .001$, $\eta_p^2 = .294$. The main effect of target modality was not significant, $F(1, 57) < 1$, $\eta_p^2 = .004$. Significant two-way interactions were observed: Distractor Modality × Distractor Type, $F(1, 57) = 53.163$, $MSE = .002$, $p < .001$, $\eta_p^2 = .483$, reflecting overall greater accuracy for visual distractors compared to auditory ones for deviant stimuli ($p < .001$) compared to standard ones ($p = .106$); or Distractor Modality × Target Modality, $F(1, 57) = 4.954$, $MSE = .007$, $p = .030$, $\eta_p^2 = .080$, this interaction reflected greater accuracy for visual distractors compared to auditory ones when the target was auditory ($p < .001$), while accuracy levels were equivalent in all other cases (smallest $p = .162$). The Target × Distractor Type interaction was not significant, $F(1, 57) < 1$, $\eta_p^2 = .002$. The triple interaction was not significant, $F(1, 57) < 1$, $\eta_p^2 = .013$.

The analysis of response times for correct responses (see Figure 2, Panel D) revealed a significant main effect of distractor modality, $F(1, 57) = 213.032$, $MSE = 3636.163$, $p < .001$, $\eta_p^2 = .789$, with slower responses in the presence of auditory than visual distractors. Response times were also slower for auditory targets compared to visual ones, $F(1, 57) = 326.114$, $MSE = 4374.552$, $p < .001$, ${\eta_p}^2 = .851$, and for following deviant distractors compared to standard ones, $F(1, 57) = 151.916$, $MSE = 1776.788$, $p < .001$, $\eta_p^2 = .727$. A significant Distractor Modality × Target Modality interaction was observed, $F(1, 57) = 33.673$, $MSE = 1964.982$, $p < .001$, $\eta_p^2 = .371$. This interaction reflected longer response times in the auditory-auditory ($M = 790.00$, $SD = 108.70$) than in the auditory-visual ($M = 655.22$, $SD = 120.49$) condition ($p < .001$), as well as longer response times in the visual-auditory ($M = 684.40$, $SD = 97.67$) than in the visual-visual condition ($M = 597.39$, $SD = 98.26$), $p < .001$. The interaction between target modality and distractor type was not significant, $F(1, 57) < 1$, $\eta_p^2 = .003$. The Distractor Modality × Distractor Type interaction was significant, $F(1, 57) = 102.096$,

[1] We thank the anonymous reviewers for suggesting these methodological modifications.

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MSE = 1765.390, $p < .001$, $\eta_p^2 = .642$, reflecting overall greater distraction for auditory distractors ($p < .001$) compared to visual ones ($p < .01$). Importantly however, the three-way interaction was not significant, $F(1, 57) < 1$, $\eta_p^2 = .003$. Deviance distraction was present in all Distractor Modality × Target Modality combinations (greatest $p = .03$).

Discussion

The results of Experiment 4 revealed deviance distraction in all conditions, although it was stronger when the irrelevant stimuli were auditory than when they were visual. The novel aspect of the results is the emergence of a clearer deviance distraction in conditions involving visual irrelevant stimuli. This finding suggests that the methodological modifications brought to Experiment 4 helped reveal the effect. In particular, we think that the removal of the color overlap between target-distractor and the standard irrelevant visual stimulus forced participants to assess each visual stimulus and eliminated the possibility that the visual deviant stimulus would be more easily inhibited because of its relatively distinct color.

The results from the auditory condition command an observation, namely that the effects of auditory distraction observed in Experiment 4 are visibly larger than those observed in the conditions using visual irrelevant stimuli (*M* = 85.09 ms, *SD* = 18.21; *M* = 90.22, *SD* = 35.22; in the auditory-visual and auditory-auditory conditions, compared to *M* = 9.15 ms, *SD* = 31.23 and *M* = 8.49 ms, *SD* = 24.71 in the visual-auditory and visual-visual conditions respectively) but also larger than those observed in the auditory distractor conditions of our earlier experiments. We think that the largest distraction effect observed in the auditory-auditory and auditory-visual conditions is driven by the participants who were presented with white noise as the standard stimulus and the 600 Hz tone as the deviant stimulus. Indeed for these participants the discrimination between the deviant and the target-distractor would have been harder (having to differentiate between 600 Hz and 710 Hz tones) than for participants who were presented with the white noise as deviant. The data appear to support this hypothesis, as deviance distraction was indeed greater when the standard consisted of white noise (*M* = 111.13 ms, *SD* = 11.79, and *M* = 128.09 ms, *SD* = 26.71, in the auditory-auditory and auditory-visual conditions respectively) than when white noise was used as deviant stimulus (*M* = 60.59 ms, *SD* = 13.32, and *M* = 49.66 ms, *SD* = 26.14, in the auditory-auditory and auditory-visual conditions respectively).

General Discussion

The aim of the present study was to measure deviance distraction in a paradigm in which distractors and targets were presented visually or auditorily in an orthogonal fashion, temporally and perceptually decoupled. The general question at stake in our study was whether deviance distraction was observed irrespective of modality boundaries. Overall, our results suggest that this is not the case and that it is more solid and prominent when standard and deviant stimuli are auditory than when they are visual. Indeed, while auditory deviance distraction was systematically found in our experiments, a visual deviance distraction effect was only observed in the cross-modal condition when participants were forced to attend to the irrelevant visual stimuli. In the visual-visual condition a relatively small effect of deviance distraction was only observed when potential attenuations by factors such as visual masking, spatial cueing of the target stimuli, or the visual distinctiveness of the deviant stimulus were controlled for.

The findings from the auditory-visual condition of Experiment 1 replicate previous work using the same task (e.g., Escera et al.,1998, 2002; Mayas, Parmentier, Andrés, & Ballesteros, 2014; Parmentier, 2014; Parmentier et al., 2008; Parmentier, Elsley, et al., 2010). More interestingly, the results from the auditory-auditory condition indicate that distraction is observed when target and irrelevant auditory stimuli are temporally and perceptually decoupled, just as it is observed in pure auditory oddball tasks in which these stimuli are presented within the same perceptual object (e.g., Berti & Schröger, 2003; Roeber et al., 2003). Most notably, however, the absence of distraction in conditions where the distractor was visual questions the hypothesis that deviance distraction is insensitive to modality influences, at least when irrelevant and target stimuli are presented separately. This latter consideration may be important as a reliable effect of deviance distraction has been reported in studies in which irrelevant and target visual features are simultaneously and as part of the same visual object (e.g., Berti & Schröger, 2001, 2004, 2006). In other words, it may be that visual deviance is best observed when irrelevant and target features are perceptually bound. Experiment 2 sought to establish whether this discrepancy might be eliminated when participants are forced to attend to the irrelevant stimuli (in an attempt to emulate what we think happens when irrelevant and target are presented within the same visual object). The results showed that forcing participants to attend to irrelevant stimuli in order to detect a rarely occurring target-distractor stimulus embedded among them resulted in a small degree of deviance distraction but only when targets were auditory, not when they were visual. This finding was replicated in Experiment 3 while reducing the risk that the presentation of the irrelevant deviant stimuli might have attracted attention to the spatial location of the upcoming target, thereby masking a potential deviance distraction effect. A small deviance distraction was only observed for visual irrelevant and target stimuli when the deviant stimulus did not stand out on the basis of its color, participants were forced to attend to the irrelevant stimuli, the target stimulus was presented immediately after the irrelevant stimulus, no fixation cross was used, and no spatial overlap was present between irrelevant and target stimuli. In other words, while visual deviants can yield distraction with visual targets, the effect is limited and clearly not as solid and as large as the distraction observed with auditory irrelevant stimuli (which

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is observed even when participants are instructed to ignore the irrelevant stimuli).

In sum, our results show that in a task in which distractor and target are temporally and perceptually decoupled, deviance distraction is observed for auditory distractors irrespective of the targets' modality or whether the task require participants to ignore or to attend to the distractor. For visual distractors, deviance distraction was only observed when participants voluntarily attended to the distractors and under certain methodological conditions. Past research indicates that deviant stimuli impact on behavioral performance in functionally similar ways across paradigms (one-channel or two-channel, e.g., Andrés et al. 2006; Berti & Schröger, 2001; Escera et al., 1998; Roeber et al., 2003) and modalities (visual, e.g., Berti & Schröger, 2001, 2004, 2006; auditory, e.g., Berti & Schröger, 2003; Roeber et al., 2003; auditory-visual, e.g., Escera et al., 1998, 2002; Ljungberg et al., 2012; Parmentier et al., 2008; Parmentier, Elsley, et al., 2010; tactile-visual, e.g., Ljungberg & Parmentier, 2012; Parmentier, Ljungberg, et al., 2011). While such evidence is compatible with the notion that deviance distraction, at least in its behavioral aspects, may stem from central mechanisms operating irrespective of modality boundaries, our findings are not.

In conclusion, our results (1) question the hypothesis that deviance distraction may be underpinned by a set of modality-independent mechanisms, and (2) demonstrate that while auditory deviants yield distraction irrespective of the targets' modality, visual deviants only do so when attended and, as described above, under very selective conditions.

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Publication 2

Aging increases distraction by auditory oddballs in visual, but not auditory tasks

Reference

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Motivation

As demonstrated in *Publication 1*, deviance distraction is especially salient for auditory deviant stimuli (both when targets are auditory and when they are visual). Hence we focused on the impact of auditory distractors on both visual and auditory target stimuli and examined the effect of ageing on deviance distraction. This study was the first to compare the performance of young and old adults in both auditory-auditory and auditory-visual oddball paradigms using a within-participant design.

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ORIGINAL ARTICLE

Aging increases distraction by auditory oddballs in visual, but not auditory tasks

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Abstract Aging is typically considered to bring a reduction of the ability to resist distraction by task-irrelevant stimuli. Yet recent work suggests that this conclusion must be qualified and that the effect of aging is mitigated by whether irrelevant and target stimuli emanate from the same modalities or from distinct ones. Some studies suggest that aging is especially sensitive to distraction within-modality while others suggest it is greater across modalities. Here we report the first study to measure the effect of aging on deviance distraction in cross-modal (auditory–visual) and uni-modal (auditory–auditory) oddball tasks. Young and older adults were asked to judge the parity of target digits (auditory or visual in distinct blocks of trials), each preceded by a task-irrelevant sound (the same tone on most trials—the standard sound—or, on rare and unpredictable trials, a burst of white noise—the deviant sound). Deviant sounds yielded distraction (longer response times relative to standard sounds) in both tasks and age groups. However, an age-related increase in distraction was observed in the cross-modal task and not in the uni-modal task. We argue that aging might affect processes involved in the switching of attention across modalities and speculate that this may due to the slowing of this type of attentional shift or a reduction in cognitive control required to re-orient attention toward the target's modality.

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Introduction

Efficient cognitive functioning often requires selective attention, that is, the ability to filter out task-irrelevant stimuli in order to concentrate on the task at hand. Counterbalancing our selective attention mechanisms, other mechanisms ensure that unexpected but potentially important stimuli can break through attention and capture it. While adaptive, this mechanism also presents one downside when the attention capturing stimuli are irrelevant: distraction. One class of stimuli that have repeatedly shown to capture attention are sudden changes (oddball, novel, or deviant stimuli) in a sequence of otherwise repeated or predictable (standard) sounds (e.g., Bendixen, Roeber, & Schröger, 2007). This type of attention capture has largely been studied from an electrophysiological perspective and is characterized by a triumvirate of specific brain responses (e.g., Schröger, 1996, 1997; Horváth, Winkler, & Bendixen, 2008; Berti et al., 2013): mismatch negativity (MMN) marking the detection of change (Näätänen et al., 2007) or the violation of expectations (e.g., Saarinen, Paavilainen, Schröger, Tervaniemi, & Näätänen, 1992; Paavilainen, Jaramillo, Näätänen, & Winkler, 1999; Paavilainen, Simola, Jaramillo, Näätänen, & Winkler, 2001; van Zuijen, Sussman, Winkler, Näätänen, & Tervaniemi, 2005; Bendixen, Roeber, & Schröger, 2007; Paavilainen, Arajärvi, & Takegata 2007; Winkler 2007), P3a assumed to indicate the involuntary orienting of attention towards a perturbing event (e.g., Grillon, Courchesne, Ameli, Geyer, & Braff, 1990; Woods, 1992; Escera et al., 2000; Friedman et al., 2001; Polich, 2007) and a reorientation negativity (RON) reflecting the reorientation of attention toward the task at hand and reactivation of the relevant task set in working memory (e.g., Berti & Schröger, 2003; Munka & Berti, 2006; Berti, 2008).

Interestingly, deviant sounds also produce clear behavioral distraction (see Parmentier, 2014, for a review) typically by delaying responses to target stimuli and, in some cases, by reducing response accuracy, as first reported by Schröger (1996) in a task in which participants discriminated the intensity of sounds presented to the right ear while ignoring distracter tones presented to the left ear. Such distraction is observed in same-modality (auditory or visual) tasks where participants categorize sounds while ignoring rare changes in a task-irrelevant feature (e.g., Schröger & Wolff, 1998; Berti & Schröger, 2001, 2003, 2004, 2006; Parmentier, Maybery, Elsley, 2010b; Roeber, Berti, & Schröger, 2003; Roeber, Widmann, & Schröger, 2003; Berti, 2008; Boll & Berti, 2009; Parmentier & Hebrero, 2013) or in cross-modal tasks where participants perform a primary visual task while ignoring the irrelevant stimulus (auditory or tactile) preceding each target stimulus (auditory–visual: e.g., Escera, Alho, Winkler, & Näätänen, 1998; Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008; Parmentier, Elsley, & Ljungberg, 2010a; Parmentier, Elsley, Andrés, & Barceló, 2011a; tactile-visual: e.g., Parmentier, Ljungberg, Elsley, & Lindkvist, 2011b). Deviance distraction has been argued to reflect, in part, the time penalty associated with the orientation of attention to and from the deviant stimulus (Parmentier et al., 2008), and can be exacerbated by a conflict between the involuntary processing of the deviant sounds' content and the voluntary processing of the target stimulus (Parmentier, 2008; Parmentier, Turner, & Elsley, 2011c; Parmentier, Turner, & Perez, 2014; see also Roye, Jacobsen, & Schröger, 2013, for evidence of this effect with deviant stimuli that acquire a personal meaning through training). The functional similarity of distraction across various combinations of sensory modalities highlighted above is further reinforced by the recent finding that distraction in auditory–visual and auditory oddball tasks obey similar functional constraints (Parmentier, Elsley, & Ljungberg, 2010a; Li, Parmentier, & Zhang, 2013).

The identical signature of deviance distraction (measured behaviorally or electro-physiologically) regardless of the sensory modality in which distracter and target stimuli are presented offers a unique opportunity to address an issue seldom investigated in this field but object of recent interest (Guerreiro et al., 2010): the effect of aging on the ability to ignore distracters as a function of whether distracters and targets are presented in the same or in different sensory modalities.

While it is widely accepted that with aging comes a reduction in the ability to inhibit distracters (e.g., Hasher & Zacks, 1988; Lustig, Hasher, & Zacks, 2007; Andrés, Guerrini, Phillips, & Perfect, 2008), this contention needs further qualification as this effect appears to be mitigated by sensory constraints. Indeed, in a recent review of some 150 studies on age-related distraction, Guerreiro et al. (2010) argued that aging results in greater distraction in same-modality tasks (especially visual ones but also in auditory ones), but not in cross-modal tasks (which have been relatively rare compared to same-modality tasks). For example, older adults exhibit greater distraction in visual and auditory Simon tasks (Pick & Proctor, 1999; Bialystok, Craik, & Luk, 2008) but not in a cross-modal version where distracters are auditory and targets are visual (Simon & Pouraghabagher, 1978).

In contrast to Guerreiro et al.'s (2010) claim that aging does not increase distraction in cross-modal tasks, (Andrés et al. 2006; see also Parmentier and Andrés, 2010) reported a two-fold increase of distraction in older adults compared to young in an auditory–visual oddball task (the study further demonstrated that this effect of aging was specific to deviance distraction and did not affect alertness). However, findings from the few studies examining the effect of aging on deviance distraction using purely auditory tasks (tasks in which the target and deviant features are embedded in the same stimulus) produced mixed results. Berti, Grunwald & Schröger (2013) reported greater behavioral distraction in older than in young adults in an experiment in which participants performed an auditory duration discrimination task while instructed to ignore rare changes in their pitch. Using a similar task in children, young and older adults, Horváth, Czigler, Birkás, Winkler and Gervai (2009) found no difference between young and older adults with respect to behavioral deviance distraction but reported a delay of the P3a and RON responses in the older participants. Finally, using the duration judgment task too, Getzmann, Gajewski and Falkenstein (2013b) compared low- and high-performing older adults to young adults. High performance older adults were participants who showed little difference in inverse efficiency (RTs divided by the rate of correct responses) between standard and deviant conditions (the high-performing older adults were comparable to the young adults in that respect). These authors found no effect of aging on behavioral deviance distraction when comparing young adults to high-performing older adults but a reduction of response accuracy in the low-performing older adults.

To sum up, while a large amount of work converges to conclude that aging increases distraction by irrelevant stimuli (e.g., uni-modal tasks, Connelly, Hasher, & Zacks, 1991; Pick & Proctor, 1999; West & Alain, 2000; Berti et al., 2013; e.g., cross-modal tasks, Alain & Woods, 1999;

Andrés, Parmentier, & Escera, 2006; Parmentier & Andrés, 2010), the existing literature lacks coherence with respect to the impact of the sensory modality of the irrelevant and target stimuli. Some argue that aging increases same-modality distraction but not cross-modal distraction (Guerreiro et al., 2010), a hypothesis contradicted by others (Guerreiro et al., 2013), especially cross-modal oddball studies (Andrés et al., 2006; Parmentier & Andrés, 2010). Interestingly, to our knowledge, the few studies contrasting same-modality and cross-modal tasks directly and within-participant consistently showed an age-related increase in cross-modal conditions but not in same-modality ones (Guerreiro & Van Gerven, 2011; Guerreiro et al., 2013). This kind of direct comparison has not been explored using an oddball task, however.

The objective of our study was to examine the effects of aging on auditory deviance distraction when targets are presented in the auditory modality too (uni-modal) and when they are presented visually (cross-modal). To do so, we adopted the general structure of the oddball task in which an irrelevant stimulus is presented immediately before a target (e.g., Andrés et al., 2006; Parmentier et al., 2008; Parmentier & Andrés, 2010). Under the hypothesis of a greater age-related vulnerability of same-modality distraction (e.g., Guerreiro et al., 2010), we predicted greater distraction in our auditory–auditory oddball task than in our auditory–visual oddball task. Under the hypothesis of greater age-related distraction in cross-modal tasks than same-modality ones (Alain & Woods, 1999; Andrés, Parmentier & Escera, 2006; Parmentier & Andrés, 2010), we predicted an age-related increase of distraction in the auditory–visual oddball task compared to the auditory–auditory oddball task.

Experiment

Method

Participants

Forty-four participants took part in this study: 22 young adults (19 females) aged 18–37 ($M = 21.6$, $SD = 4.6$), and 22 older adults (14 females) aged 54–74 ($M = 63.9$, $SD = 5.7$). The young adults were undergraduate students from the University of the Balearic Islands who participated in exchange for course credit or a small honorarium. The older participants were recruited through an advertisement in a local newspaper. The Mini-Mental State Examination (Lobo et al., 1979) was administered to older participants to exclude participants with potential cognitive impairment. Participants provided written consent by signing a consent form and performed the experiment in accordance with the ethical standards laid down in 1964 Declaration of Helsinki and its later amendments. The University of the Balearic Islands Institutional Review Board approved this procedure. All older participants exhibited performance within the healthy range ($M = 29.6$, $SD = .73$). The WAIS-III vocabulary test (Yela & Cordero, 2000) was administered as a measure of crystallized intelligence and, as expected, was significantly greater in older adults [$t(42) = 3.128$, $p < .05$; young: $M = 12.4$, $SD = 1.8$; older adults: $M = 14.4$, $SD = 2.3$). All participants reported normal hearing, and normal or corrected-to-normal vision.

Material and stimuli

The task involved the presentation of auditory and visual stimuli. The auditory stimuli included the digits 1–6 spoken in a female voice. The duration of each digit was 400 ms. Two additional sounds were used, one consisting of a 150 ms sine-wave tone of a frequency of 600 Hz, the other of a 150 ms burst of white noise (the latter used as a deviant sound; see Berti, 2012, for a comparison between novel and deviant sounds). All sounds were normalized in level and presented binaurally via headphones with an intensity of approximately 75 dB (SPL).

The visual stimuli consisted of the digits 1–6 presented at the center of a computer screen in white color against a black background. These stimuli sustained a visual angle of approximately 4.4°, with participants seated approximately 50 cm away from the screen.

Design and procedure

In every trial, the participant's task was to categorize a digit as odd or even while ignoring an irrelevant stimulus presented shortly before each digit. In each trial, a fixation cross was visible at the center of the screen for the duration of the whole trial except during the presentation of a visual stimulus. Each trial started with the presentation of a 150 ms task-irrelevant sound. This sound consisted of the 600 Hz sine-wave tone in 80 % of trials (standard sound) and the burst of white noise in the remaining 20 % of trials (deviant sound). Standard and deviant trials were ordered quasi-randomly in a different order for every condition and participant, with the constraint that deviant trials were never presented on consecutive trials. One hundred and fifty milliseconds after the distracter's offset, a digit was presented for 400 ms. In one block of trials, the digits were presented auditorily (*auditory–auditory condition*). In a separate block of trials, it was presented visually (*auditory–visual condition*). The order of the two conditions was counterbalanced across participants. The digits 1–6 were presented in a different random order for every participant

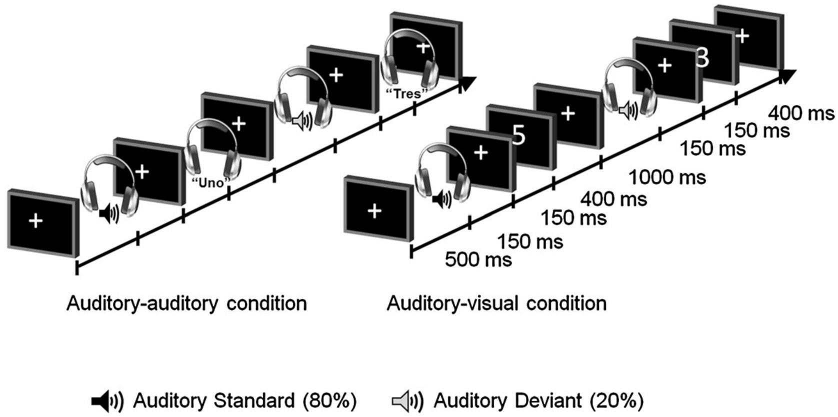

Fig. 1 *Illustration of the task procedure.* Schematic illustration of two trials in the auditory–auditory and auditory–visual oddball tasks. In every trial, the participant's task was to categorize a digit as odd or even while ignoring an irrelevant stimulus presented shortly before each digit. In the *auditory–auditory* task, irrelevant sounds consisted of a 600 Hz sine-wave tone (standard sound) and of a burst of white noise (deviant sound). In the *auditory–visual* task, the irrelevant sounds were as in the auditory–auditory task but targets were presented visually. (the digits "uno" and "tres" used as examples in this figure mean "one" and "three" in English)

and condition but with equal probabilities across each block of trials and trial type (standard or deviant, as described below). Following the digit, the fixation cross reappeared and remained visible for 1,000 ms, after which the next trial was automatically initiated. From the target's onset to the end of the response window, participants had 1,400 ms to categorize the target digit by pressing the keys X or Z on the computer keyboard using two fingers from their dominant hand (see Fig. 1). The mapping of keys to responses (odd, even) was counterbalanced across participants. The total duration of the experiment session was approximately 30 min. Participants were instructed to ignore the distracters to concentrate on the digit categorization task, and to respond as quickly but as accurately as possible.

Results

The proportion of correct responses and mean response time were analyzed using 2 (age: young vs older) × 2 (target modality: auditory vs visual) × 2 (type of irrelevant sound: standard vs deviant) mixed-model ANOVAs. Overall, accuracy was high ($M = 0.93$, $SD = 0.10$), and did not vary with age [$F(1,42) = 3.284$, $MSE = 0.024$, $p = .077$, $\eta_p^2 = .073$], target modality [$F(1,42) < 1$, $MSE = 0.019$, $p = .369$, $\eta_p^2 = 0.019$], or type of irrelevant sound [$F(1,42) < 1$, $MSE = 0.001$, $p = .694$, $\eta_p^2 = 0.004$]. No significant interaction was observed: target modality x age [$F(1,42) < 1$, $MSE = 0.019$, $p = .616$, $\eta_p^2 = 0.006$], type of irrelevant sound x age [$F(1,42) = 1.662$, $MSE = 0.001$, $p = .204$, $\eta_p^2 = 0.038$], target modality × type of irrelevant sound [$F(1,42) < 1$, $MSE = 0.001$, $p = .783$, $\eta_p^2 = 0.002$], or the triple interaction [$F(1,42) = 2.886$, $MSE = 0.001$, $p = .097$, $\eta_p^2 = 0.064$].

Response times (see Table 1) were slower in older adults than in the young [$F(1,42) = 25.607$, $MSE = 26{,}994.129$, $p < .001$, $\eta_p^2 = 0.379$], slower for auditory targets than for visual ones [$F(1,42) = 225.443$, $MSE = 4{,}916.501$, $p < .001$, $\eta_p^2 = 0.843$], and slower in the deviant condition relative to the standard [$F(1,42) = 71.929$, $MSE = 592.022$, $p < .001$, $\eta_p^2 = 0.631$]. The type of irrelevant sound x age interaction was not significant [$F(1,42) = 1.760$, $MSE = 592.022$, $p = .192$, $\eta_p^2 = 0.040$], but the target modality x type of irrelevant sound and triple interaction were [$F(1,42) = 4.460$, $MSE = 541.185$, $p = .041$, $\eta_p^2 = 0.096$, and $F(1,42) = 4.451$, $MSE = 541.185$, $p = .041$, $\eta_p^2 = 0.096$]. Distraction was significant for the auditory–auditory condition in both young and older participants [young: $t(21) = 6.013$, $p < .001$, $d = 0.649$; older: $t(21) = 3.876$, $p < .001$, $d = 0.900$], as it was for the auditory–visual condition in both age groups [young: $t(21) = 1.896$, $p < .05$, $d = 0.523$; older: $t(21) = 4.233$, $p < .001$, $d = 0.972$] (see Fig. 2, panel A). Further contrasts (planned comparison F tests) were carried out to assess the age × type of irrelevant sound interaction in each target modality condition, revealing that aging did not affect deviance distraction in the auditory–auditory condition [$F(1,42) < 1$, $MSE = 642.251$, $p = .220$, $\eta_p^2 = 0.005$] but did so significantly in the auditory–visual condition [$F(1,42) = 6.742$, $MSE = 490.956$, $p = .013$, $\eta_p^2 = 0.073$], as visible from Fig. 2, panel B.

Table 1 Mean accuracy rates and response times for young and older adults as a function of the type of irrelevant sound (deviant versus standard) and the target modality (auditory–auditory, auditory–visual)

	Auditory target			Visual target		
	Standard	Deviant	Distraction	Standard	Deviant	Distraction
Accuracy (proportion correct)						
Young	0.917 (0.054)	0.932 (0.062)	−0.014	0.898 (0.185)	0.893 (0.197)	0.005
Older	0.964 (0.034)	0.948 (0.058)	0.016	0.949 (0.052)	0.947 (0.047)	0.002
RTs (ms)						
Young	652.44 (79.05)	693.49 (86.03)	41.05**	503.17 (50.07)	514.61 (60.03)	11.44*
Older	774.93 (106.59)	810.92 (113.65)	35.99**	621.62 (102.53)	657.59 (107.41)	35.97**

Values within brackets represent the standard deviation

* $p < .05$, ** $p < .001$

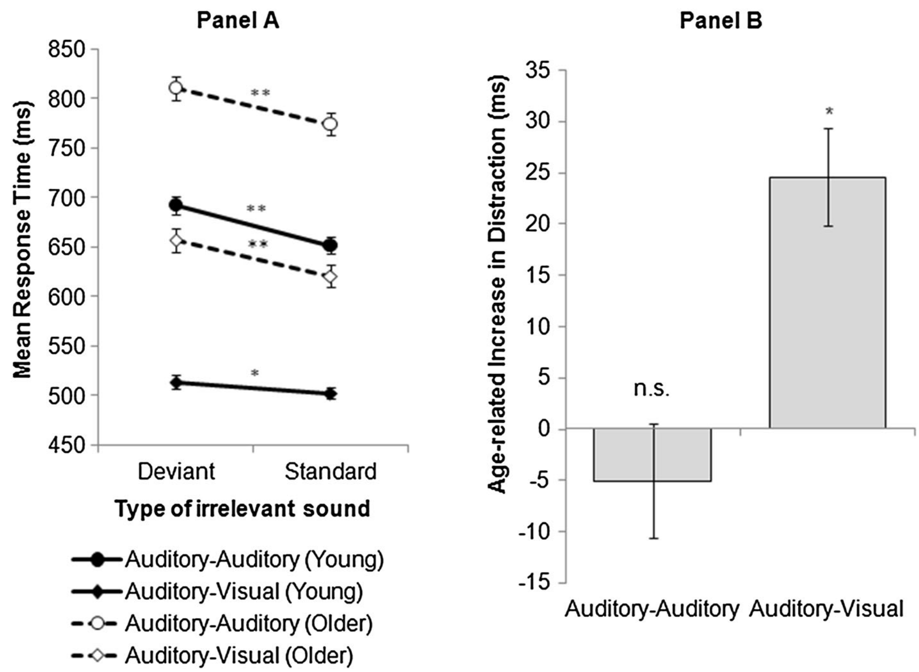

Fig. 2 *Response times and age-related effect. Panel A* mean response times as a function of the type of irrelevant sound (deviant versus standard) and the target modality (auditory–auditory, auditory–visual). *Panel B* age-related increase in distraction as a function of the target modality (auditory–auditory, auditory–visual). The age-related increase is calculated by subtracting the distraction effect (deviant minus standard response times) in the older adults from that in the young adults. A *positive value* indicates that aging increases distraction. *Error bars* represent one standard error of the mean. *$p < .05$, **$p < .001$

Discussion

The aim of the present study was to evaluate the effect of aging on distraction by deviant sounds in auditory (uni-modal) and visual (cross-modal) digit categorization tasks. Deviance distraction was observed in both age groups and both tasks. That is, the presentation of a deviant sound prior to the target stimulus yielded longer response times relative to the standard condition. Most importantly, however, aging increased this distraction effect in the cross-modal task but not in the uni-modal task.

The finding of a larger distraction in older adults in the auditory–visual cross-modal oddball task replicates the finding of Andrés, Parmentier & Escera (2006) and Parmentier & Andrés (2010). Our results are, on the other hand, not consistent with the hypothesis put forward by Guerreiro et al. (2010), namely that by and large aging appears to augment distraction when irrelevant and target stimuli are presented in the same modality. While this conclusion is based on the reviewing of a large number of studies, the vast majority of them used same-modality tasks and the number of cross-modal studies was, comparatively, small. Furthermore, the few exemplars of the latter varied greatly in terms of methodology (cross-modal oddball tasks: e.g., Alain & Woods, 1999; Andrés et al., 2006; irrelevant sound tasks,: e.g., Belleville, Rouleau, Van der Linden, & Collette, 2003; Enmarker, 2004; Beaman, 2005; Bell & Buchner, 2007; cross-modal Simon tasks: e.g., Simon & Pouraghabagher, 1978; Proctor, Pick, Vu, & Anderson, 2005; memory for unattended auditory information: e.g., Murphy, McDowd, & Wilcox, 1999; psychophysiological evidence: e.g., Townsend, Adamo, & Haist, 2006; Stevens, Hasher, Chiew,

& Grady, 2008; Hugenschmidt, Mozolic, Tan, Kraft, & Laurienti, 2009; performance on a primary auditory task: Einstein, Earles, & Collins, 2002; memory for unattended visual information: Murphy, Pelletier, Bailey, & Howell, 2004). Importantly, we note that in studies in which the two types of tasks (uni-modal and cross-modal) have been directly compared, the age-related increase in distraction has in fact been observed in the cross-modal and not the same-modality condition (Guerreiro et al., 2013).

We can offer two tentative explanations for the apparent discrepancy between results from aging studies using the cross-modal oddball task and the position of Guerreiro et al. (2010). First, in contrast to other distraction paradigms, irrelevant and target stimuli are temporally decoupled in our task. This may be an important characteristic because it grants the irrelevant stimulus the value of an unspecific warning cue. The relevance of this aspect is demonstrated by the finding that deviance distraction disappears when the irrelevant sounds no longer announce the target stimulus (Parmentier, Elsley, & Ljungberg, 2010a; Wetzel, Widmann, & Schröger, 2012; see Parmentier, 2014, for a discussion), even in purely auditory oddball tasks where target and irrelevant features form part of the same stimulus (Li et al., 2013). If the sounds convey useful information for goal-directed behavior, then they may be regarded as functionally distinct from the irrelevant stimuli or features used in other paradigms in which they must be suppressed in order to allow for the selection of the target stimulus (as, for example, in the Stroop task: West & Alain, 2000; Wurm et al., 2004; e.g., Simon task: Pick & Proctor, 1999; Van der Lubbe & Verleger, 2002; Proctor, Pick, Vu, & Anderson, 2005). This in fact leads us to the second possible explanation for the apparent contradiction between our results and Guerreiro et al.'s (2010) conclusion: the cognitive fallout of the distracter-target relationship. In the oddball task as we used it (that is, presenting the irrelevant sound prior to the target), distraction is thought to reflect the time penalty associated with the involuntary orientation of attention to and from the deviant distracter (Parmentier et al., 2008). Such mechanism does not require the selection of a target against a distracter. This is arguably quite distinct from the cases where target and distracter are presented simultaneously but as distinct objects competing for attention (e.g., Flanker task: Maylor & Lavie, 1998; Colcombe, Kramer, Erickson, & Scalf, 2005; Samanez-Larkin, Robertson, Mikels, Carstensen & Gotlib, 2009). In such cases, selective attention is required, and in fact obligatory, if the target is to be successfully selected and the irrelevant stimulus suppressed (even more so given that in most studies of this type distracter and target form part of the same task-set and so competition also exists at the level of response selection and production). Viewed this way, the apparent contradiction between past studies might perhaps be dissipated by making the reasonable (though speculative) proposition that aging affects the attentional mechanisms in charge of selective attention and that such selection is rendered more difficult when target and irrelevant stimuli share many features (which will invariably be the case when they are presented in the same modality). When presented in distinct modalities, selective attention may capitalize on a modality anchor to separate the two. Hence in the case of most distraction studies in which selective attention is required for efficient performance, same modality tasks would require greater attentional control and therefore be specifically sensitive to the impact of aging.

In the case of the oddball task, the impact of sensory modality is arguably quite distinct because the origin of distraction lies not at the level of attentional selection but in the shifts of attention to and from the deviant stimulus. Parmentier et al. (2008) suggested that such shift may operate at the level of the sensory modalities, namely that the deviant stimulus, by capturing attention, may trigger an orientation of attention toward the deviant's modality. Such shift could only occur when irrelevant and target stimuli belong to distinct modalities, however. Interestingly, it has been documented that shifts of attention between two stimuli comes with a time penalty when these stimuli are presented in distinct sensory modalities (Turatto et al., 2002; Shomstein & Yantis, 2004; Turatto et al., 2004; Rodway, 2005; Miles, Brown, & Poliakoff, 2011), and some evidence from young adults indicates that auditory deviants are especially disruptive when targets are visual compared to auditory (Bendixen, Grimm, Deouell, Wetzel, Mädebach, & Schröger, 2010). One may reasonably hypothesize that modality shifts affected by aging would at the minimum be so by virtue of mere cognitive slowing (e.g., Shimamura, 1994; Salthouse, 1996; Salthouse et al., 1998) and possibly a reduction in attentional control (Kray, Eppinger, & Mecklinger, 2005; Prakash, Erickson, Colcombe, Kim, Voss, & Kramer, 2009). If we assume that the shift between modalities is less efficient or slower in older adults, then our findings can be accounted for.

Further work is necessary to fully understand the conditions in which aging increases distraction in purely auditory tasks. Such studies (Berti et al., 2013; Horváth et al., 2009; Getzmann, Gajewski and Falkenstein et al., 2013b; the present study) yielded varying results, suggesting that small methodological or individual differences may play a role in ways that are yet to be determined. For example, Berti et al. (2013) used inter-trial intervals that were about twice as long as those used in other studies, perhaps encouraging participants to privilege response accuracy and thereby increasing the probability of distraction showing in response times. Other possible factors may include variations in the older adults' characteristics across studies with respect to variables such as their genetic profile (Getzmann, Gajewski, Hengstler, Falkenstein, & Beste, 2013c), their level of cardio-vascular fitness (Getzmann, Falkenstein, & Gajewski, 2013a), or the extent to which they practice cognitively taxing activities such as video games (Mayas, Parmentier, Andrés, & Ballesteros, 2014). Under what conditions aging increases deviance distraction when irrelevant and target stimuli are auditory and form part of the same perceptual object remains therefore unclear. What our study and some past work (Andrés et al., 2006; Parmentier & Andrés, 2010) does suggest, however, is that aging has a clear effect on deviance distraction in the cross-modal oddball task. We speculate that this stronger effect might relate to cognitive mechanisms involved in the shift of attention across sensory modalities. If so, it may for example be interesting in the future to examine whether or not forcing attention back to the visual modality prior to the presentation of the visual target stimulus would benefit older adults as it does young adults (Parmentier et al., 2008). Finally, it is worth mentioning that our results also participate to distinguish between two types of auditory distraction: deviance distraction and the irrelevant speech effect. The latter relates to the disruption that acoustically changing irrelevant speech exerts on serial memory for visually presented materials (Jones, Madden & Miles 1992; Jones & Macken, 1993, 1995). Much research suggests that the cognitive locus of this effect lies in the conflict between the obligatory processing of the order of the irrelevant changing auditory stimuli and the voluntary rehearsal of the to-be-remember sequence of stimuli (Jones, Alford, Bridges, Tremblay, & Macken, 1999; Jones & Tremblay, 2000). Interestingly, recent work indicates that deviance distraction can be empirically distinguished from the irrelevant speech effect (Hughes, Vachon, & Jones, 2005, 2007). Our data provide further support for this distinction, for the age-related increase we and others found (Andrés, Parmentier, & Escera, 2006; Parmentier & Andrés, 2010; Berti et al., 2013) contrasts with the absence of an age effect on the irrelevant speech effect (Rouleau & Belleville, 1996; Beaman, 2005; Bell & Buchner, 2007; Van Gerven, Meijer, Vermeeren, Vuurman, & Jolles, 2007; Van Gerven & Murphy, 2010). Taken together, these studies suggest that aging constitutes another factor dissociating between deviance distraction and the irrelevant speech effect. Viewed from another angle, these considerations imply that aging does not increase all types of auditory distraction indiscriminately: It does not affect the processing of order information in memory but it affects processes involved in the attentional orienting to and re-orientation from unexpected auditory change.

In conclusion, our results show that (1) deviant sounds impact on performance in an unrelated categorization task, whether visual or auditory and that (2) age increases auditory distraction when targets are visual (cross-modal) and not necessarily when they are auditory (same modality).

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Publication 3

When aging does not increase distraction: Evidence from pure auditory and visual oddball tasks

Reference

Leiva, A., Andrés, P., & Parmentier, F. B. R. (2015). When aging does not increase distraction: Evidence from pure auditory and visual oddball tasks. *Journal of Experimental Psychology: Human Perception and Performance*. *41*(6), 1612-1622. doi: 10.1037/xhp0000112.

Motivation

Publication 2 demonstrated that older adults exhibit greater deviance distraction than young adults in the cross-modal (auditory-visual) oddball task but not in the uni-modal task in which the irrelevant auditory stimulus is followed by an auditory target stimulus. Such results are at odds with the findings of Bert et al. (2013) in which greater behavioral deviance distraction was observed in older adults compared to young adults. The latter may reflect the fact that Berti et al. (2013) asked participants to judge the duration of tones while ignoring rare and unpredictable changes in pitch, hence forcing participants to attend to the stimuli containing the deviant feature. *Publication 3* used a similar method and also extended it to the visual modality, comparing young and older adults in auditory and visual duration discrimination tasks. Its aim was to test the hypothesis that age does not increase deviance distraction in same-modality oddball tasks (whether auditory or visual) by using a larger sample size (and more adequate statistical power) than in Berti et al.'s (2013) study.

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When Aging Does Not Increase Distraction: Evidence From Pure Auditory and Visual Oddball Tasks

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Past research indicates that age increases deviance distraction in cross-modal oddball tasks, but results are few and less conclusive in purely auditory oddball tasks, with 3 studies not reporting age-related increase in deviance distraction against 1 that did ($d = 1.04$). This study aimed to (a) examine the effect of age on deviance distraction using the largest sample size to date to ensure adequate statistical power and (b) extend the study of same-modality deviance distraction to the visual modality. We compared 42 young and 42 older adults in auditory and visual duration discrimination tasks in which stimuli were presented with rare and unexpected task-irrelevant changes in pitch (in the auditory task) or location (in the visual task). The statistical power of our experiment to detect an effect size (d) of 1.04 was .999. Our results showed deviance distraction (longer response times for deviant stimuli than for standard stimuli) in both modalities. Importantly, these effects did not vary with age. Strong support for the absence of age-related variation in deviance distraction was further demonstrated by Bayes factor analysis. We conclude that aging does not appear to increase behavioral distraction by deviant stimuli in same-modality oddball tasks.

Keywords: deviance distraction, auditory distraction, visual distraction, aging, attention capture

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Research indicates that old age is often accompanied by an increase in distractibility (e.g., Lustig, Hasher, & Zacks, 2007). By and large, this conclusion is based on tasks tapping selective attention and inhibitory mechanisms in which participants must select a target stimulus against distractors (most often presented simultaneously), yielding crosstalk interference. For example, older adults exhibit greater distractibility in Stroop tasks (e.g., Andrés, Guerrini, Phillips, & Perfect, 2008; West & Alain, 2000) and Simon tasks (e.g., Pick & Proctor, 1999). Overall, the consensus view is that aging reduces the efficacy of inhibition mechanisms (e.g., Hasher & Zacks, 1988): The inefficient and/or slower inhibition of distractors disrupts the selection of the target as competition for selection and action between distractor and target lingers on.

If generally accepted, the view that age increases distraction warrants some qualification. In an extensive review of the literature, Guerreiro, Murphy, and Van Gerven (2010) argued that the effect of age on distraction is mediated by the sensory modalities in which distractors and target stimuli are presented. More specifically, they argued that aging increases distraction in same-modality but not in cross-modal interference tasks. Although the same authors later reported the opposite pattern of data in a selective attention task (Guerreiro, Murphy, & Van Gerven, 2013), the conclusion has held true across a large range of studies (e.g., age-equivalent distraction in cross-modal Simon tasks [Proctor, Pick, Vu, & Anderson, 2005] and irrelevant speech studies [e.g., Beaman, 2005]), with one notable exception: studies measuring the so-called deviance distraction using oddball tasks (e.g., Andrés, Parmentier, & Escera, 2006; Parmentier & Andrés, 2010).

Deviance distraction is observed when participants must respond to target stimuli while ignoring rare and unexpected changes in a stream of otherwise repeated or predictable task-irrelevant stimuli that do not yield crosstalk interference but, instead, trigger involuntary shifts of attention detrimental to the primary task (e.g., Bendixen, Roeber, & Schröger, 2007; Parmentier, Elsley, Andrés, & Barceló, 2011; for a review, see Parmentier, 2014). Such distraction has been reported using two variations of the oddball paradigm: cross-modal and same-modality oddball tasks. In the

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cross-modal oddball task (e.g., Escera, Alho, Winkler, & Näätänen, 1998; Parmentier, Elsley, & Ljungberg, 2010), participants categorize visual target stimuli (e.g., digits as odd or even) immediately preceded by auditory (e.g., Munka & Berti, 2006; Parmentier, Maybery, & Elsley, 2010; SanMiguel, Linden, & Escera, 2010) or tactile (Parmentier, Ljungberg, Elsley, & Lindkvist, 2011) irrelevant stimuli. In the same-modality oddball task—auditory (Berti, 2008; Grimm et al., 2008; Schröger, 1996; Sussman, Winkler, & Schröger, 2003) or visual (Berti & Schröger, 2004; Boll & Berti, 2009; Grimm, Bendixen, Deouell, & Schröger, 2009)—participants typically categorize one feature of stimuli (e.g., their duration) while ignoring rare changes in a task-irrelevant feature (e.g., their pitch). In both versions of the task, the key manipulation consists in repeating the same irrelevant stimulus or irrelevant feature on the majority of trials (*standard* stimulus) and, on rare and unpredictable trials, replacing it with another (*deviant* stimulus) or by ever-changing ones (*novel* stimuli). In both tasks, deviant stimuli elicit distraction at the electrophysiological and behavioral levels. At the electrophysiological level, unexpected changes in a repetitive or otherwise structured auditory sequence typically yield three specific brain responses (e.g., Berti, 2008; Berti, Roeber, & Schröger, 2004; Schröger, 1996, 1997, 2005, 2007; Schröger & Wolff, 1998): mismatch negativity (MMN; e.g., Näätänen, 1990; Näätänen, Paavilainen, Rinne, & Alho, 2007), P3a (e.g., Escera et al., 1998), and reorientation negativity (RON; e.g., Berti & Schröger, 2001). The MMN response is considered to reflect the detection of a mismatch between an incoming sound and the neural trace of past sounds (e.g., Näätänen, 1990) or the detection of a violation of predictions (e.g., Schröger, Bendixen, Trujillo-Barreto, & Roeber, 2007; Winkler, 2007). The P3a and RON responses are, respectively, viewed as an index of the involuntary orientation of attention toward the deviant or novel stimulus and an index of the reorientation of attention toward the primary task, including the reactivation of relevant task sets in working memory. At the behavioral level, deviant stimuli typically delay responses to target stimuli and, in some cases, reduce response accuracy (e.g., Parmentier, 2014; Schröger, 1996). Deviance distraction results from the violation of predictions (Bendixen & Schröger, 2008; Bendixen, Schröger, Ritter, & Winkler, 2012; Berti, 2012; Schröger et al., 2007), with behavioral distraction resulting from the time penalty associated with the orientation of attention to—and its controlled reorientation from—the deviant stimulus (Munka & Berti, 2006; Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008) and the reactivation of the relevant task set in working memory (Berti, 2008; Roeber, Berti, & Schröger, 2003). As reviewed by Parmentier (2014), behavioral and electrophysiological measures of distraction do not always correlate. For example, behavioral distraction can vary independently of P3a (Wetzel, Schröger, & Widmann, 2013), whereas P3a and RON can vary independently of behavioral distraction (Horváth, Czigler, Birkás, Winkler, & Gervai, 2009). For simplicity, because the present study was concerned with behavioral deviance distraction, we hereafter refer to the latter simply as *deviance distraction*.

Compared with the plethora of studies examining the impact of aging on distraction provoked by crosstalk interference, the impact of age on deviance distraction has received little attention. Interestingly, and contrary to what is observed with crosstalk interference, aging appears to increase deviance distraction in cross-modal tasks and not in same-modality (auditory) tasks.

Two cross-modal oddball studies consistently reported a marked increase in behavioral deviance distraction in older compared with young adults (Andrés et al., 2006; Parmentier & Andrés, 2010). Four studies examined the effect of old age on deviance distraction using a same-modality duration discrimination task in which participants categorized sounds as short or long while ignoring rare and unpredictable changes in pitch. Three of these found identical degrees of deviance distraction in young and older adults (Getzmann, Gajewski, & Falkenstein, 2013; Horváth et al., 2009; Mager et al., 2005), whereas one reported a sizable increase in distraction in older compared with young adults (Berti et al., 2013). Finally, using a task in which standard and deviant irrelevant sounds preceded visual or auditory digits (presented in separate blocks) that participants categorized as odd or even, we found an age-related increase in deviance distraction in the cross-modal task but no effect of age on distraction in the auditory task (Leiva, Parmentier, & Andrés, 2015). However, because irrelevant and target stimuli were temporally and perceptually decoupled—and may, therefore, have helped to distinguish the two and inhibit the first—we would argue that the strongest test of the effect of age on same-modality deviance distraction is provided by the duration discrimination task.

Even if three out of four studies using auditory duration discrimination converge in suggesting that age does not increase deviance distraction in a same-modality oddball task, such a conclusion must still be considered with caution, for two reasons. First, the duration discriminability studies were limited to the auditory modality—they did not examine deviance distraction in the visual modality (which has been shown elsewhere to yield reliable deviance distraction; Bendixen et al., 2010; Berti & Schröger, 2001, 2004). Second, with the exception of Getzmann et al. (2013), these studies used small participant samples and were underpowered. Indeed, the numbers of young and older adults, respectively, were nine and nine (Horváth et al., 2009), 21 and 17 (Mager et al., 2005), and 11 and 11 (Berti et al., 2013). Getzmann et al. used a larger sample for their statistical analyzes: 35 young adults and two groups of 32 older adults (high performers and low performers). Under the hypothesis that deviance distraction operates irrespective of modality boundaries (i.e., that age affects same-modality and cross-modal deviance distraction equally), and taking the size of the effect of aging on distraction in the cross-modal oddball task as reported by Leiva et al. (2015) as a benchmark (d = 0.783), the statistical powers of past studies using the duration discrimination task were .551 (Berti et al., 2013), .478 (Horváth et al., 2009), .761 (Mager et al., 2005), and .936 (Getzmann et al., 2013, comparing younger adults and low-performing older adults).[1] It therefore appears that only Getzmann et al. had adequate power; most critically, the one study that reported a significant effect of aging on distraction in a same-modality oddball task (Berti et al., 2013) did not. Low sample sizes yield low statistical power, which in turn increases the risk of false positives and inflates effect size estimates for significant effects (Button et al., 2013).

[1] Power was calculated using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007) for a one-tailed t-test comparison of independent samples and a Type I error probability of .05.

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Interestingly, it is worth pointing out that the just-discussed studies also reached diverging results with respect to the effect of aging on the electrophysiological indexes of deviance distraction. For example, whereas three studies found no effect of aging on the MMN response (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005), Berti et al. (2013) reported weaker MMN amplitude in older adults. In contrast, Berti et al. (2013) found no effect of age on P3a and RON, whereas the other studies reported delayed or reduced P3a and RON (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005).

In summary, although aging is commonly regarded as reducing the ability to inhibit distractors (e.g., Andrés et al., 2008; Hasher & Zacks, 1988; Lustig et al., 2007), this effect appears to be mitigated by sensory constraints, and two different lines of work contrast with each other. On the one hand, some have argued that aging increases distraction when target and distractor stimuli are presented in the same modality, especially the visual one (Guerreiro et al., 2010). On the other hand, evidence from studies measuring deviance distraction found an age-related increased in distraction in cross-modal tasks (Andrés et al., 2006; Parmentier & Andrés, 2010; Leiva et al., 2015) but not in purely auditory tasks (Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005; but see Berti et al., 2013). In our view, the conclusions from these two lines of work are not as contradictory as they may at first seem, for we would argue that they relate to distinct definitions of the concept of *distraction*. In the first group of studies, distraction was defined as crosstalk interference, which relates to the competition for selection and action between two stimuli activating the same task set. Because selection of a stimulus against a competing distractor (and the response afforded by the first against that afforded by the second) can be expected to require more inhibitory control when the two stimuli share a modality (because sensory information cannot be used as a selection criteria), aging can be expected to enhance such distraction. In contrast, deviance distraction relates to the cost of reorienting attention to a target following the capture of attention by an unexpected irrelevant stimulus (e.g., Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008) and is, therefore, fundamentally distinct from crosstalk interference. When deviant and target stimuli are presented in distinct sensory modalities, attention is involuntarily directed to the deviant stimulus' irrelevant modality, and control is required to reorient it toward the relevant one. Leiva et al. (2015) suggested that aging selectively affects this cross-modal shift. If this is the case, one would predict no effect of aging on deviance distraction in same-modality oddball tasks. Some findings support this hypothesis (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005), with the notable exception of Berti et al. (2013). As described earlier, however, most of these studies lacked adequate statistical power, and all were limited to the auditory modality. The aim of the present study was to test the hypothesis that age does not increase deviance distraction in same-modality oddball tasks by (a) using the largest sample size to date (42 young and 42 older adults) to ensure adequate statistical power and (b) extending the study of same-modality deviance distraction (so far limited to the auditory modality) to the visual modality. Assuming an effect size similar to what we observed in a cross-modal task (Leiva et al., 2015), the statistical power of our experiment to detect a potential age-related increase of distraction was .972. Assuming the effect size calculated for the young and oldest participants of Berti et al.'s (2013) study (Cohen's $d = 1.04$),[2] it was .999.

Method

Participants

Eighty-four participants took part in this study: 42 young adults (32 female) ages 18–27 years ($M = 20.9$, $SD = 2.7$) and 42 older adults (30 female) ages 52–72 years ($M = 62.8$, $SD = 4.6$). The young adults were undergraduate students from the University of the Balearic Islands who participated in exchange for course credit or a small honorarium. The older participants were recruited through advertisement in a local newspaper and participated in exchange for a small honorarium. The Spanish version of the Mini-Mental State Examination (Lobo, Ezquerra, Gómez, Sala, & Seva Díaz, 1979) was administered to older participants to exclude those with potential cognitive impairment. All older participants exhibited performance within the healthy range ($M = 29.60$, $SD = 0.71$). The Spanish version of Weschler Adult Intelligence Scale—III vocabulary test (Yela & Cordero, 1996) was administered as a measure of crystallized intelligence, and, as expected, scores were significantly higher in older ($M = 13.2$, $SD = 1.5$) than in young ($M = 11.2$, $SD = 1.7$) adults ($d = 1.248$), $t(82) = 5.486$, $p < .001$. All participants reported normal hearing and normal or corrected-to-normal vision.

Material and Stimuli

The task involved the presentation of auditory stimuli, including short (200-ms) and long (400-ms) sinusoidal tones of 1000 Hz, 950 Hz, and 1050 Hz. All sounds were presented binaurally via headphones, with an intensity of approximately 75 dB (sound pressure level). Three versions of a visual stimulus consisting of a white triangle sustaining an approximate visual angle of 1.37° were also used. These differed with respect to the location of the triangle. The triangle was either centered on a fixation cross at the center of a computer screen or displaced by 10 pixels (~0.57° degrees of visual angle) up or down relative to that reference point.

Design and Procedure

Participants performed two duration discrimination tasks: one visual and one auditory. Both consisted of four blocks of 200 test trials each, with participants completing all blocks of a task before performing the other (separated by a 10–15-min break). The order of the tasks was counterbalanced across participants.

Auditory task. Participants categorized the duration of equiprobable short (200-ms) and long (400-ms) tones. In each block, 88% of trials used a 1000-Hz tone, hereafter referred to as the *standard tone*. The remaining 12% of trials used 950-Hz (6%) and 1050-Hz (6%) tones, hereafter referred to as *deviant tones*. The deviant tones were randomly dispersed among standard tones, with the constraint that they never occurred on consecutive trials.

[2] We thank Stefan Berti for kindly providing the behavioral data from Berti et al.'s (2013) study, which allowed us to measure the effect size of the increase in behavioral deviance distraction between their young (18–27 years) and older (59–66 years) groups.

Participants were instructed to concentrate on the duration task while ignoring the sounds' frequency and to respond as quickly and as accurately as possible by pressing the *1* or *2* key on a computer keyboard using two fingers from their dominant hand. The mapping of keys to responses (*short*, *long*) was counterbalanced across participants. Sounds were presented with a stimulus onset asynchrony (SOA) of 1,300 ms. Throughout the task, the computer displayed a white fixation cross sustaining an approximate visual angle of 1.37° at the center of an otherwise black screen.

Visual task. The task structure was identical to that of the auditory task, with the distinction that participants categorized the duration of a visual stimulus as short (200 ms) or long (800 ms). The decision to use a larger duration gap than in the auditory task was arrived at on the basis of pilot testing showing that visual durations of 200 and 400 ms were too difficult to discriminate for many participants. In each block, 88% of trials used a visual stimulus consisting of a small white triangle presented at the center of the screen in place of the fixation cross (*standard triangle*). On the remaining 12% of trials, this triangle was presented 10 pixels higher or lower (6% of trials each; *deviant triangles*). As in the auditory task, deviant stimuli were randomly distributed within each block, with the constraint that they never occurred on consecutive trials. Participants used the same keys as in the auditory task, with their mapping to durations counterbalanced across participants (but coherent across tasks for any given participant). Visual stimuli were presented with an SOA of 1,900ms. Participants were instructed to concentrate on the duration of the visual stimuli and to ignore the rare small changes in location.

Results

The proportions of correct responses (correct categorization of the digits: *odd* responses for odd digits and *even* responses for even digits) and mean response times (RTs) for correct responses (measured from the point in time defining the type of target; i.e., 200 ms after onset of the visual or auditory stimulus) were analyzed using 2 (age: young vs. older) × 2 (deviance: standard vs. deviant) × 2 (modality: visual vs. auditory) mixed-model analyses of variance (see Figure 1). Overall accuracy was good (M = .834, SD = .093) and showed a trend toward better performance in older (M = .852, SD = .108) than in young (M = .817, SD = .073) adults, $F(1, 82) = 3.298$, $MSE = 0.034$, $p = .073$, $\eta_p^2 = .039$. Accuracy was better in the auditory than in the visual modality, $F(1, 82) = 53.364$, $MSE = 0.021$, $p < .001$, $\eta_p^2 = .394$, and in the standard relative to the deviant condition, $F(1, 82) = 27.873$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .254$. The Age × Modality interaction was not significant, $F(1, 82) = 3.222$, $MSE = 0.021$, $p = .076$, $\eta_p^2 = .038$, although it showed a trend indicating greater advantage of old age in the visual than in the auditory task. The negative effect of deviant compared with standard stimuli did not vary with age, $F(1, 82) = 0.068$, $MSE = 0.001$, $p = .796$, $\eta_p^2 < .001$, or modality, $F(1, 82) = 0.028$, $MSE = 0.0008$, $p = .881$, $\eta_p^2 < .001$. Finally, the Age × Deviance × Modality interaction was not significant either, $F(1, 82) = 0.013$, $MSE = 0.0008$, $p = .911$, $\eta_p^2 < .001$.

RTs were significantly longer in the visual than in the auditory modality, $F(1, 82) = 17.321$, $MSE = 4{,}958.876$, $p < .001$, $\eta_p^2 = .174$, and in the deviant than in the standard condition, $F(1, 82) = 298.181$, $MSE = 175.302$, $p < .001$, $\eta_p^2 = .640$. Older adults were nearly significantly slower than young adults, $F(1, 82) = 3.766$, $MSE = 15{,}347.563$, $p = .056$, $\eta_p^2 = .044$. The Age × Modality interaction was not significant, $F(1, 82) = 1.818$, $MSE = 4{,}958.876$, $p = .181$, $\eta_p^2 = .022$, nor was the Deviance × Age interaction, $F(1, 82) = 0.220$, $MSE = 175.302$, $p = .640$, $\eta_p^2 = .003$. Deviance distraction was larger in the visual than in the auditory modality, as revealed by a significant Deviance × Modality interaction, $F(1, 82) = 60.568$, $MSE = 177.337$, $p < .001$, $\eta_p^2 = .425$. Finally, the Age × Deviance × Modality interaction was not significant, $F(1, 82) = 0.333$, $MSE = 177.337$, $p = .566$, $\eta_p^2 = .004$.

The results are clear: Deviant stimuli yielded significant distraction in both groups of participants and in both modalities, but, importantly, aging did not increase deviance distraction in either modality.[3] The results from the visual task show for the first time that older adults do not exhibit greater deviance distraction than do young adults. Results from our auditory task converge with this conclusion and with the results of Mager et al. (2005), Horváth et al. (2009), and Getzmann et al. (2013). They depart from the findings of Berti et al. (2013), however. Hence, to provide additional evidence for the null effect, we also used Bayesian techniques to determine the relative level of support for the null hypothesis.

We calculated the Bayes factor (BF): the ratio of the probability of the hypothesis that aging increases deviance distraction being true over the probability of the null hypothesis being true given the empirical data. Conventionally, BF values below ⅓ are considered to provide strong support for the null hypothesis, whereas values above 3 are considered to strong evidence for the experimental hypothesis (Dienes, 2011; Jeffreys, 1961). This technique required us to specify the effect size predicted by the experimental hypothesis, and it involved a comparison between a putative probability distribution of this effect and the effect measured in our participants. When the experimental hypothesis predicts the direction of the effect (as in our case), the putative probability distribution takes the shape of a half-normal curve with a mode of 0 and a standard deviation equal to the effect size predicted by the experimental hypothesis (Dienes, 2014).

To calculate BF in our auditory task, we set the standard deviation of the half-normal distribution to 34.09 ms—the size of the effect of aging on distraction measured from Berti et al.'s (2013) study. This gave the likelihood of the data given the hypothesis of an increase of distraction (LH_{effect}) with age as .0148 and the likelihood of the obtained data given the null hypothesis (LH_{null}) as .1213. Hence, BF was .1191—or strong evidence for the null hypothesis. Under a more conservative experimental hypothesis according to which the size of the effect of aging on deviance distraction would be, at most, that of the overall effect of aging on RTs in our sample (18.64 ms), LH_{effect} was .0269, LH_{null} was .1213, and BF was .2218, again providing strong evidence for

[3] At the request of an anonymous reviewer, we demonstrated that this conclusion holds when comparing young–older and older–older participants (on the basis of an age median split: participants age 63 years or younger vs. participants older than 63). *T* tests for independent samples were carried out on deviance distraction (RT deviant − RT standard) in both tasks (auditory and visual). No significant difference was revealed for the auditory, $t(40) < 1.00$, $p = .791$, or the visual task, $t(40) = 1.01$, $p = .319$, (both ds = 0.083).

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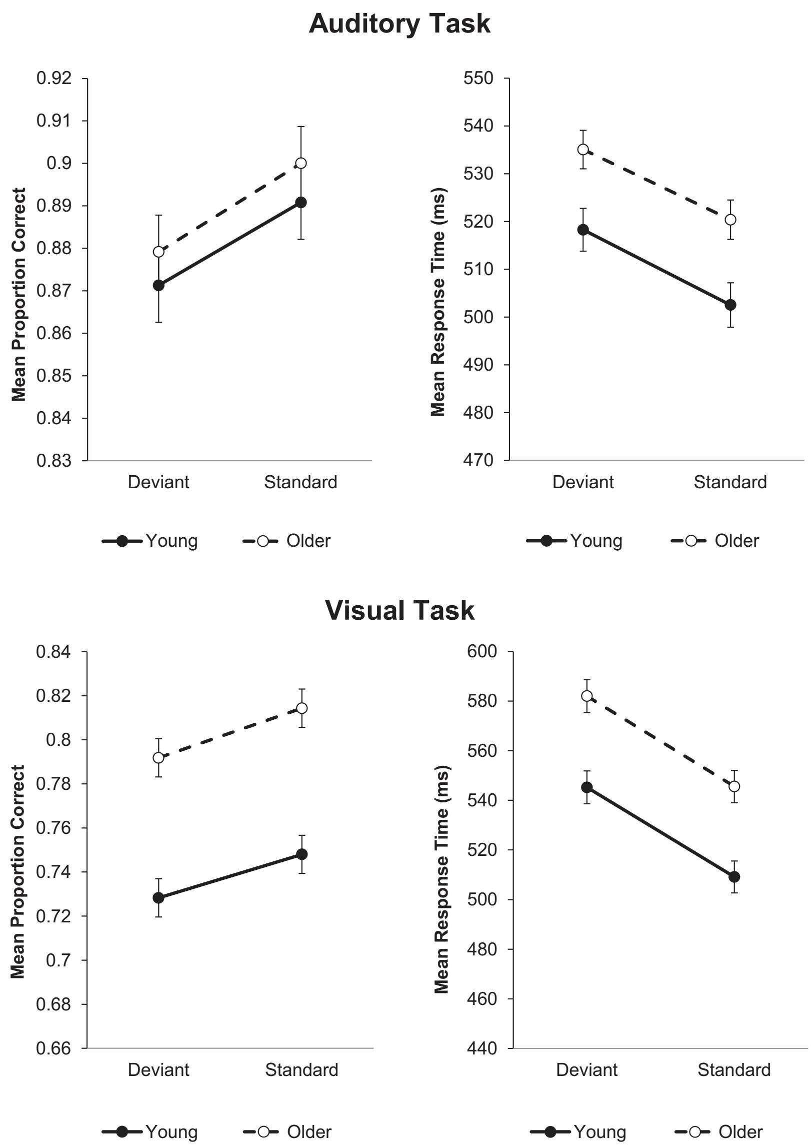

Figure 1. Performance in the auditory and visual oddball tasks as a function of age and type of irrelevant sound: mean proportions of correct responses and mean response times for correct responses. Error bars represent 95% confidence intervals for comparison of within-participant conditions (standard vs. deviant) when graphing mixed interactions (Jarmasz & Hollands, 2009).

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the absence of an effect of aging on deviance distraction. Finally, if one takes the size of the effect of aging on deviance distraction in the cross-modal oddball task of Leiva et al. (2015)—24.53 ms—as the maximum possible effect of aging on distraction in the present study, LH_{effect} was .0201, LH_{null} was .1213, and BF was .1657, again supporting the null effect.

We carried out similar analyses on the data from our visual task. Setting the standard deviation of the half-normal distribution to 34.09 ms (the size of the effect of aging on distraction from Berti et al.'s, 2013), LH_{effect} was .0120, LH_{null} was .0838, and BF was .143, providing strong evidence for the absence of an effect of aging on deviance distraction. Using effect size estimates based on the main effect of age on RTs in our visual task (36.14 ms) yielded an LH_{effect} of .0114, an LH_{null} of .0838, and a BF of .136. On the basis of the size of the age-related increase in distraction in a cross-modal oddball task (Leiva et al., 2015)—24.53 ms—LH_{effect} was .0166, LH_{null} was .0838, and BF was .198. In all cases, the BF analysis strongly supported the null effect.

Discussion

The aim of the present study was to examine the impact of aging on deviance distraction in visual and auditory oddball tasks. The results are unambiguous. In both modalities, deviant stimuli yielded longer RTs and fewer correct responses relative to the standard condition, but these effects did not vary with age. The

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results from our visual task demonstrate this for the first time, whereas the data from our auditory task replicate those from previous studies (Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005) and contrast with those of Berti et al. (2013). Given the substantial statistical power of our study and the unambiguous support for null effect provided by Bayesian analyses, we argue that the weight of evidence favors the view that deviance distraction in same-modality oddball tasks is not affected by old age.

It is unclear why Berti et al. (2013) found a large increase in distraction in their auditory task between their young and oldest adult participants. One unexciting explanation would be that their finding was spurious—a false positive. Such a possibility, inherent to any study relying on significance testing, is more likely in studies relying on small participant samples (Button et al., 2013). Alternatively, it may be that their task or participants presented with certain characteristics that might account for the discrepancy between their findings and ours. We note, for example, that our older participants were slightly older than Berti et al.'s (2013) and that we used a larger age range (52–72 years) compared with theirs (56–66 years). However this is unlikely to account for the discrepancy between our results and their conclusion unless one implausibly assumes that aging increases deviance distraction around the age of 60 but begins to produce facilitation in later years, thereby masking the effect of aging overall in our study. At any rate, an analysis of our data restricted to participants fitting the age ranges used by Berti et al. (2013) yielded the same results as those we reported earlier (see Appendix A). A distinct possibility is that Berti et al.'s (2013) older sample may have included some participants with undetected cognitive impairment, because they found no significant difference between young and older adults in crystalized intelligence measured by a vocabulary test. A similar test did show a significant advantage of old age in our sample, however, which is considered typical of healthy aging (Horn, 1970).

A second distinctive aspect of Berti et al.'s (2013) study was the higher levels of mean response accuracy produced by their participants on deviant and standard trials (92% and 96%, respectively) compared with ours (88% and 90%, respectively). It is unclear why their participants responded better than ours. One might hypothesize that it may have reflected the authors' use of a longer SOA (3,000 ms) than in past studies (Horváth et al., 2009 [1,600 ms]; Getzmann et al., 2013 [1,400 ms])[4] or the present study (1,300 ms), but we think this is unlikely, because there was no indication that their participants took longer in order to boost accuracy (in fact, Berti et al.'s, 2013, participants were significantly faster than ours[5]). One might argue that the higher levels of accuracy in Berti et al.'s (2013) study concentrated the effect of aging on RTs. However, this too is an unlikely explanation for the discrepancy between their study and ours, because by that logic, we should have observed an effect of aging on distraction as measured by response accuracy, which we did not. In any case, an analysis of our data restricted to participants with a mean proportion of correct responses of .90 or above produced the same results as we reported earlier (see Appendix B). Finally, one possibility that we cannot rule out or test is that the slow rate of presentation of trials and Berti et al.'s (2013) instructions emphasizing the requirement to respond correctly—"subjects were instructed to react as fast and as accurately as possible, but accuracy of responses was stressed" (p. 164)—may have influenced the strategy used by their older participants. Although it is unclear how this may have led to the large age-related increase in distraction they observed, the potential role of this specific aspect of their study should not be ruled out.

In view of our findings, we argue that aging does not increase distraction by deviant sounds when targets are presented in the same modality (auditory or visual), at least in the conditions in which we and others (Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005) have examined it. In contrast, past work indicates that aging does augment distraction in the cross-modal oddball task, in which attention shifts between sensory modalities (Andrés et al., 2006; Leiva et al., 2015; Parmentier & Andrés, 2010). These contentions have at least two implications, which we address in the following paragraphs. The first is that the effect of age on deviance distraction might operate at a level involving modality-dependent mechanisms, not at a modality-independent level. The second is that aging does not systematically yield a greater distraction effect and that the differential effect of age on cross-modal and same-modality interference and oddball tasks adds to the functional distinction between interference (as measured in Stroop-like tasks; e.g., West & Alain, 2000) and deviance distraction.

Although deviance distraction is observed in same-modality tasks (e.g., Berti & Schröger, 2004; Boll & Berti, 2009; Grimm et al., 2008; Schröger, 1996; Schröger & Wolff, 1998) requiring no shifts of attention across sensory boundaries, Parmentier et al. (2008) suggested that, in the cross-modal oddball task, one possible contributor to deviance distraction may be an involuntary shift of attention from the visual to the auditory modality and back to the visual modality when the target is presented. Such a proposition is consistent with evidence that shifts of attention between two stimuli come with a time penalty when the stimuli are presented in distinct sensory modalities (Miles, Brown, & Poliakoff, 2011; Rodway, 2005; Shomstein & Yantis, 2004; Turatto, Benso, Galfano, & Umiltà, 2002; Turatto, Galfano, Bridgeman, & Umiltà, 2004). There is also some evidence from young adults indicating that auditory deviants are especially disruptive when targets are visual compared with auditory (Bendixen et al., 2010). Altogether, it seems reasonable to propose that among the mechanisms participating in deviance distraction, the mechanisms underpinning the shift of attention across sensory boundaries may constitute the locus of the effect of age.

The second implication of our results is that aging is not inexorably accompanied by greater distractibility. Age did not increase deviance distraction in the auditory task, in line with prior work (Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005), nor did it affect distraction in the visual task. Although the notion that age presents with a reduced ability to inhibit irrelevant information is widespread, this may in part be

[4] The SOA used by Mager et al. (2005) remains uncertain as they did not provide that information.

[5] Direct comparison of overall RTs in our study and those of Berti et al. (2013) in fact shows that their young participants (M = 461.954, SD = 69.636) were nearly significantly faster than ours (M = 500.192, SD = 58.522), $t(51)$ = 1.855, p = .069, and that their older adults (M = 476.909, SD = 59.733) were significantly faster than ours (M = 518.833, SD = 51.061), $t(51)$ = 2.341, p = .023.

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attributable to the dominance, in the literature, of same-modality tasks (mostly visual) invoking crosstalk interference, which appear to yield genuine age-related increases in distraction (Guerreiro et al., 2010). Cross-modal studies have been rare, but both irrelevant speech (e.g., Beaman, 2005; Bell & Buchner, 2007; Belleville, Rouleau, Van der Linden, & Collette, 2003; Rouleau & Belleville, 1996) and Simon (Proctor et al., 2005, Experiment 1; Simon & Pouraghabagher, 1978) studies in which distractors were auditory and targets visual converge in suggesting that aging does not increase distraction. Such picture was convincingly presented by Guerreiro et al. (2010). From a theoretical perspective, we would argue that in tasks involving competition between a target and distractors, the modality separation between these may facilitate the selection of the target against the distractor. When both elicit competing activations through the same input channels, the overlap between target and distractor is greater, competition stronger, and high-order mechanisms exerting top-down control may be required. In such circumstances, aging increases distraction, consistent with the notion that attentional control is sustained by frontal regions and that these are especially affected by aging (Hartley, 1993; Raz, 2000; West, 1996).

It is also important to note that the inhibitory hypothesis of aging has been nuanced in its different versions, and, rather than being considered an all-or-nothing mechanism, on recent views, inhibition is considered to be a multifaceted function (see, e.g., Lustig et al., 2007; Nigg, 2000) in which some functions may be more susceptible to the effect of aging than are others. One important proposal is that the more effortful the inhibitory mechanism is, the more likely it will be to be affected by age (e.g., Andrés et al., 2008; Wnuczko, Pratt, Hasher, & Walker, 2012). This would be compatible with the idea that the switch between modalities in the cross-modal oddball paradigm may be more demanding than within-modality switches.

One notable exception to this conclusion is the study of Guerreiro et al. (2013), in which participants categorized target digits while ignoring concurrent distractor digits. In contrast with the studies cited earlier, these authors found that aging increased distraction in cross-modal versions of the task and not in same-modality versions. The authors did not offer a clear explanation of the apparent discrepancy between their findings and their own assessment of the literature (Guerreiro et al., 2010), but we note that their task may have been functionally distinct from Stroop or Simon tasks. Indeed, in the latter, distractors elicit strong automatic activations competing with the target (e.g., in the Stroop task, the word meaning activates lexical, semantic, and response codes that are part of the relevant set). In Guerreiro et al.'s (2013) task, participants performed *n*-back tasks in which they had to decide whether a target digit was identical to one memorized from a previous trial. It is plausible that the distractor digit did not automatically activate that task set (a distractor digit does not activate an "is this digit the same as that from the previous trial?" task set as automatically as a word activates reading). Hence, it is not clear that the task used by Guerreiro et al. (2013) constituted a strong example of a crosstalk interference task. If we accept such a contention, then the general picture from the existing literature would be that in crosstalk interference tasks, aging increases same-modality distraction and does not affect cross-modal distraction.

This latter conclusion is essentially orthogonal to the one that we derived from studies on deviance distraction (Andrés et al., 2006; Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005; Parmentier & Andrés, 2010). There, aging increased distraction in cross-modal but not in same-modality tasks. We view this double dissociation as evidence of the functional distinction between crosstalk interference and deviance distraction. We conclude that, in contrast to what is observed in same-modality interference tasks, aging does not appear to increase distraction by unexpected deviant stimuli in same-modality oddball tasks. We argue that this might be because the reorientation of attention toward the target stimulus requires more inhibition and control when a cross-modal shift must be performed. In sum, the apparent contrast between deviance distraction and crosstalk interference studies may in fact be regarded as instantiation of a coherent principle: The effect of irrelevant stimuli is greater in older adults whenever the mechanisms minimizing their impact invoke controlled attention. In crosstalk interference studies, when target and distractors have the same modality, selection of the first and inhibition of the latter require greater attentional control, and aging increases distraction. In deviance distraction studies, the reorientation of attention across modality boundaries is more demanding, and so, in this case, aging increases distraction in cross-modal oddball tasks but not in same-modality oddball tasks.

Finally, in view of the absence of an effect of aging on performance in our auditory oddball task, one might wonder whether the older participants used compensatory mechanisms to preserve performance. The notion of compensation has been proposed elsewhere in instances in which neural overactivation of certain areas (especially frontal; e.g., Cabeza et al., 2004) or a bilateralization of activity (e.g., Cabeza, 2002) have been observed in older adults while their levels of behavioral performance were equivalent to those of young adults (e.g., Reuter-Lorenz & Lustig, 2005). Reuter-Lorenz and Park (2014) proposed the concept of *compensatory scaffolding* to refer to a beneficial process that entails "the engagement of supplementary neural circuitry that provides the additional computational support required by an aging brain to preserve cognitive function in the face of localized or global neurofunctional decline" (p. 356). In the absence of neural data, we cannot rule out the possibility that our older adults used such compensatory mechanisms to maintain distraction at a level equivalent to that of young participants. That response accuracy was numerically greater in our older adults compared with the young may, for example, suggest that the former dedicated more effort to task. Reuter-Lorenz and Cappell (2008) argued that neural compensation can occur in relatively low-demand tasks but is not sufficient to mask deficits when tasks are more demanding. Because we argued that ipsimodal shifts of attention require less effort than cross-modal shifts, it may be that neural compensation allowed older adults to produce behavioral performance similar to that of young adults in same-modality oddball tasks (e.g., Getzmann et al., 2013) while exhibiting greater deviance distraction in cross-modal tasks (Andrés et al., 2006; Leiva et al., 2015; Parmentier & Andrés, 2010). Conversely, the hypothesis of some neural overactivation does not sit well with electroencephalogram data measured in the duration discrimination oddball task. Indeed, when such studies found an effect of aging on signal amplitude, it was in the direction of a decrease in activity—in MMN amplitude

(Berti et al., 2013), in P3a amplitude (Getzmann et al., 2013), or in RON (Getzmann et al., 2013; Mager et al., 2005)—not an increase.

In conclusion, our results suggest that aging does not increase the behavioral distraction yielded by rare and unexpected task-irrelevant changes in a stream of otherwise repeated stimuli when relevant and irrelevant stimuli are presented in the same sensory modality. This contrasts with the age-related increase observed in cross-modal oddball tasks, suggesting a selective impact of aging on attentional shifts across sensory modalities. This pattern of findings is the reverse of that observed in crosstalk interference studies, in which aging tends to increase distraction in same-modality tasks rather than cross-modal ones. We suggest that the mechanisms underpinning deviance distraction and crosstalk interference are functionally distinct and that the role of sensory modality is mediated by the extent to which the sensory separation of distractor and target information facilitates or hinders efficient stimulus processing.

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Appendix A

Analysis of Data Restricted to Age Ranges Similar to Berti et al. (2003)

We reanalyzed our data including only participants matching the age range used by Berti, Grunwald, and Schröger (2013): 18–27 years for young participants and 56–66 years for older participants. This resulted in the selection of 31 older and 41 young adults.

Analyses of Variance

The analysis of the proportions of correct responses showed no effect of age, $F(1, 70) = 0.670$, $MSE = 0.011$, $p = .416$, $\eta_p^2 = .009$, but a negative effect of the deviant compared with the standard sound, $F(1, 70) = 15.508$, $MSE = 0.0008$, $p < .001$, $\eta_p^2 = .181$. There was no Age × Sound interaction, $F(1, 70) = 0.026$, $MSE = 0.0008$, $p = .872$, $\eta_p^2 < .001$.

Response times were similar in older adults compared with the young, $F(1, 70) = 2.735$, $MSE = 6{,}594.866$, $p = .103$, $\eta_p^2 = .038$, and longer in the deviant relative to the standard condition, $F(1, 70) = 53.641$, $MSE = 125.655$, $p < .001$, $\eta_p^2 = .434$. The Deviance × Age interaction was not significant, $F(1, 70) = 0.625$, $MSE = 125.655$, $p = .432$, $\eta_p^2 = .009$.

Power Analysis

The power of our experiment restricted to the participants matching Berti et al.'s (2013) age range—for an estimated effect size based on their data (Cohen's $d = 1.04$), a one-tailed *t* test, and a Type I error probability of .05—was .996.

Bayes Factor Analysis

Given the effect size measured from Berti et al.'s (2013) data (34.09 ms), the likelihood of the data given the hypothesis of an increase of distraction with age (.0138), and the likelihood of the obtained data given the null hypothesis (.1106), the Bayes factor was .125—strong evidence in favor of the null effect.

(*Appendices continue*)

Appendix B

Analysis of Data Restricted to Participants With High Accuracy

We reanalyzed our data including only participants with a mean proportion of correct responses of .90 or above to make our data more comparable with those of Berti, Grunwald, and Schröger (2013) in that respect. This resulted in the selection of 18 older and 25 young adults.

Analyses of Variance

The analysis of proportions of correct responses showed a trend toward an effect of age, $F(1, 41) = 3.615$, $MSE = 0.001$, $p = .064$, $\eta_p^2 = .081$, with older adults performing slightly better than the young (a similar trend was reported by Berti et al., 2013), and a negative effect of the deviant compared with the standard sound, $F(1, 41) = 12.731$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .237$. There was no Age × Sound interaction, $F(1, 41) = 1.505$, $MSE = 0.001$, $p = .227$, $\eta_p^2 = .035$.

Response times were similar in older adults compared with the young, $F(1, 41) = 0.181$, $MSE = 5{,}372.141$, $p = .673$, $\eta_p^2 = .004$, and longer in the deviant relative to the standard condition, $F(1, 41) = 43.151$, $MSE = 92.728$, $p < .001$, $\eta_p^2 = .513$. The Deviance × Age interaction was not significant, $F(1, 41) < 0.001$, $MSE = 92.728$, $p = .987$, $\eta_p^2 < .001$.

Power Analysis

The power of our experiment restricted to the participants matching Berti et al.'s (2013) age range—for an estimated effect size based on their data (Cohen's $d = 1.04$), a one-tailed t test, and a Type I error probability of .05—was .952.

Bayes Factor Analysis

Given the effect size measured from Berti et al.'s (2013) data (34.09 ms), the likelihood of the data given the hypothesis of an increase of distraction with age (.0117), and the likelihood of the obtained data given the null hypothesis as (.0986), the Bayes factor was .119—strong evidence in favor of the null effect.

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Publication 4

Reorienting the mind: The impact of novel sounds on go/no-go performance

Reference

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Motivation

Attentional reorienting and response inhibition are usually studied in different paradigms, but recent work indicates that both might rely on similar cognitive and neural mechanisms. However, it remains unclear how they are related. In the present study we explored the potential link between attentional reorienting and response inhibition. Specifically, we aimed to test the hypothesis that deviant sounds may trigger response inhibition. To do so we used a modified stop-signal task to examine whether deviant sounds would facilitate response inhibition.

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OBSERVATION

Reorienting the Mind: The Impact of Novel Sounds on Go/No-Go Performance

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The present study explores the link between attentional reorienting and response inhibition. Recent behavioral and neuroscience work indicates that both might rely on similar cognitive and neural mechanisms. We tested 2 popular accounts of the overlap: The "circuit breaker" account, which assumes that unexpected events produce global suppression of motor output, and the "stimulus detection" account, which assumes that attention is reoriented to unexpected events. In Experiment 1, we presented standard and (unexpected) novel sounds in a go/no-go task. Consistent with the stimulus detection account, we found longer reaction times on go trials and higher rates of commission errors on no-go trials when these were preceded by a novel sound compared with a standard sound. In Experiment 2, novel and standard sounds acted as no-go signals. In this experiment, the novel sounds produced an improvement on no-go trials. This further highlights the importance of stimulus detection for response inhibition. Combined, the 2 experiments support the idea that attention is oriented to novel or unexpected events, impairing no-go performance if these events are irrelevant but enhancing no-go performance when they are relevant. Our findings also indicate that the popular circuit breaker account of the overlap between response inhibition and attentional reorienting needs some revision.

Keywords: attention reorienting, response inhibition, cross-modal oddball, go/no-go, circuit breaker

Flexible behavior in a constantly changing environment requires a cognitive control system that allows people to reorient perceptual attention to important stimuli occurring outside the focus of attention and to cancel or replace actions when novel information requires it. In the present study we explored the link between attentional reorienting and response inhibition in a go/no-go task. Attentional reorienting and response inhibition are usually studied in different paradigms. However, recent behavioral and neuroscience work indicates that both might rely on similar cognitive and neural mechanisms, but it remains unclear how they are related (Levy & Wagner, 2011). We tested two accounts of this overlap: the "circuit breaker" account, which proposes that attentional reorienting involves suppression of ongoing actions, and the "stimulus detection" account, proposing that response inhibition involves reorienting attention.

The "circuit breaker" account was initially developed in the attentional reorienting literature, and proposes that reorienting attention toward unexpected but potentially behavioral relevant stimuli relies on a ventral frontoparietal network that interrupts ongoing actions (for reviews, see Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002). This right-lateralized reorienting network overlaps strongly with the network that is activated on no-go or stop-signal trials. This has led some researchers to propose that the attentional "circuit breaker" activates a rapid inhibitory control mechanism that suppresses ongoing or planned responses (e.g., Arrington, Carr, Mayer, & Rao, 2000; Nobre, Coull, Frith, & Mesulam, 1999; Shulman et al., 2009). It is not surprising that this view has also gained traction in the response inhibition literature. For example, recent reviews on response inhibition speculate that attentional reorienting relies on the same inhibitory

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mechanisms as stopping in go/no-go and stop-signal tasks (e.g., Aron, 2011; Chambers, Garavan, & Bellgrove, 2009). Recently, this idea received support from computational (Wiecki & Frank, 2013) and empirical work (Wessel & Aron, 2013). In Wiecki and Frank's (2013) model, the right ventrolateral prefrontal cortex, which is typically associated with response inhibition, is responsible for detecting salient events and subsequently engaging a stopping mechanism. Wessel and Aron (2013) found that unexpected events slowed latencies in a seemingly unrelated task (see also Escera, Alho, Winkler, & Näätänen, 1998; Parmentier, 2008; Parmentier, Elford, Escera, Andrés, & San Miguel, 2008; Parmentier, Elsley, Andrés, & Barceló, 2011; Vachon, Hughes, & Jones, 2012). This slowing was associated with the activation of a neural network that was also activated on trials in which the presentation of a stop signal instructed subjects to cancel a planned response. Furthermore, corticospinal excitability was reduced when an unexpected stimulus occurred. Based on these findings, Wessel and Aron concluded that unexpected events cause distraction via the global suppression of motor output. Aron, Robbins, and Poldrack (2014) went even further and concluded that "any stimulus that is salient/infrequent/unexpected will recruit [motor] inhibition" (p. 179).

However, behavioral distraction caused by unexpected events could also reflect a time penalty associated with the orientation to (and away from) the unexpected novel stimulus (Parmentier et al., 2008, 2011). Therefore, the "stimulus detection" account proposes that the presentation of infrequent stimuli (in attentional reorienting paradigms) and no-go or stop signals (in response inhibition paradigms) activate a similar neural network because both require the reorienting of attention and detection of novel and infrequent stimuli (e.g., Hampshire, 2015; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010; Schröger, 1996; Parmentier, 2014; Parmentier et al., 2008, 2011). Indeed, some have argued that successful response inhibition primarily depends on the rapid detection of infrequent or unexpected events (in this case, the stop or no-go signal; e.g., Boucher, Palmeri, Logan, & Schall, 2007; Salinas & Stanford, 2013; Verbruggen, Stevens, & Chambers, 2014). For example, we have demonstrated that visual distractors impaired stopping when a visual stop signal was presented in the periphery (Verbruggen, Stevens, & Chambers, 2014). However, the distractors occurred frequently, and throughout the whole trial. Therefore, our previous study does not allow us to distinguish between the "circuit breaker" and "stimulus detection" accounts.

In Experiment 1, we contrasted both accounts by introducing novel (deviant) sounds in a go/no-go task. The main task was to respond to the location of the go stimulus but to withhold the response when a no-go stimulus was presented. Participants were told to ignore irrelevant sounds (novel or standards) presented before each go and no-go stimulus. The circuit breaker account predicts that presenting a rare novel sound should produce global suppression of motor output (e.g., Wessel & Aron, 2013), leading to an *impairment* on go trials (i.e., slower go responses) but an *improvement* on no-go trials (i.e., lower probability of responding), compared with presenting a standard sound. Thus, this accounts predicts that task-irrelevant processing (caused by the presentation of the novel sounds) should *enhance* inhibitory control in the primary go/no-go task (for a similar logic, see, e.g., Verbruggen, Adams, & Chambers, 2012, who showed that response inhibition in a secondary task led to increased suppression of risky choice options in a primary decision-making task). In contrast, the "stimulus detection" account predicts that both go and no-go performance should be impaired (i.e., slower go responses and higher probability of responding on no-go trials) by the presentation of novel sounds because attention would be oriented away from the processing of the go/no-go signals.

Experiment 1

Method

Participants. Twenty (15 females) undergraduate students from the University of Exeter (M age = 20.45, SD = 4.21) participated for course credit.

Apparatus and stimuli. The experiment was run on a 21.5-in. iMac using Psychtoolbox (Brainard, 1997). The stimuli in the go/no-go task were the white letters W and M (0.8 cm × 0.8 cm), presented against a black background (see Figure 1). Go/no-go mapping (e.g., W = go; M = no-go) was counterbalanced. The letter appeared on the left or on the right (distance: 3 cm) of a central white cross (size: 0.8 cm × 0. 8 cm). Participants responded to the location of the go stimulus by pressing the left or right arrow keys on a computer keyboard using the left and right index finger, respectively.

On each trial, a sound preceded the go/no-go stimulus. There were two types of sounds. The standard sound was a 150-ms sinewave tone (frequency = 600 Hz). Novel sounds were short clips of environmental sounds (e.g., drill, hammer, rain, door, telephone ring), selected from a list of 60 sounds files (adapted from Escera et al., 1998), each with a duration of 150 ms. Sounds were selected randomly, with the constraint that "novel" sounds were not immediately repeated. The sounds were presented binaurally via headphones.

Procedure. Participants were instructed to respond as quickly and accurately as possible to the location of the go stimulus, but to withhold their response when a no-go stimulus appeared. They were told to ignore irrelevant sounds presented before each letter. They were also told not to move their eyes or blink between the presentation of the fixation cross and the execution of their response.[1]

Each trial started with the presentation of a fixation cross (see Figure 1). After 300 ms, the sound was presented. On 80% of the trials, this was the standard sound; on the remaining trials, a novel sound was presented. Then, 50 ms after the irrelevant sound's offset, a go or no-go stimulus appeared on the left or right side of the fixation cross. On two thirds of the trials, a go stimulus appeared, requiring a left or right response. On the remaining trials, a no-go stimulus appeared, instructing participants to withhold their response.

The response deadline was adjusted using a 3-down/1-up tracking procedure. After every three correct go responses the deadline decreased by 50 ms, pushing participants to respond faster; when they failed to respond in time the deadline was increased again by 50 ms.

[1] We plan to use this task in EEG experiments. In such experiments, participants are instructed not to blink or move their eyes to reduce EEG artifacts. To allow a direct comparison between experiments, we used the same instructions here.

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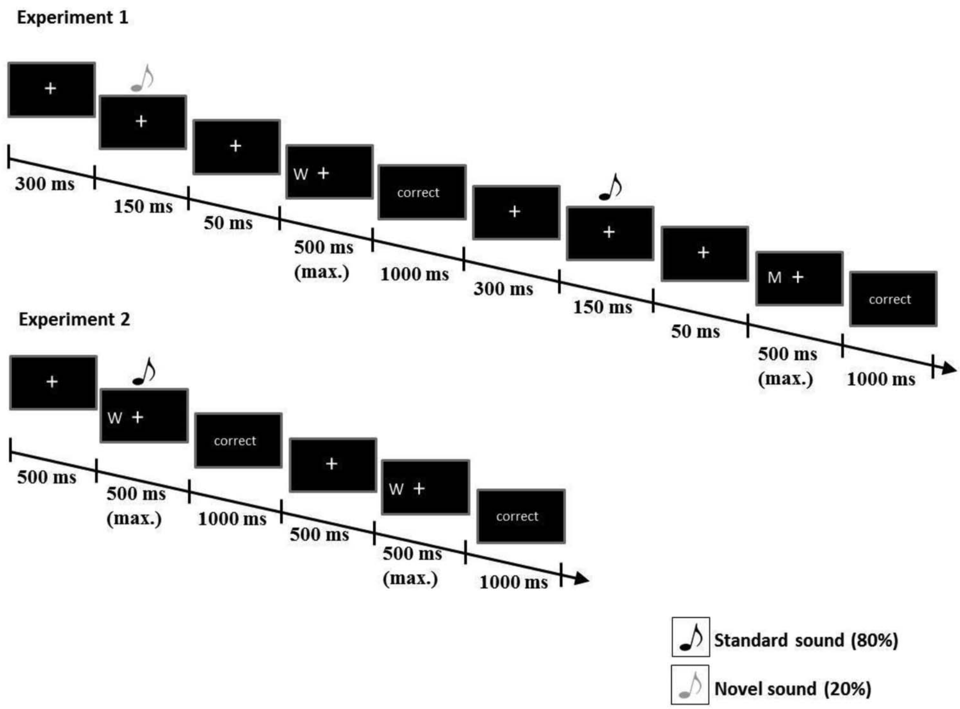

Figure 1. Schematic illustration of the tasks. Experiment 1: On every trial, participants responded to the location of the go stimulus (e.g., *W*), but tried to withhold their response when a no-go stimulus appeared (e.g., *M*). Irrelevant sounds (80% standard, 20% novel) were presented before each letter, and participants were told to ignore them. Experiment 2: The task was the same as in Experiment 1, but the sounds (80% standard, 20% novel) and visual stimuli were presented together. The sounds acted as no-go signals. Two trials of every experiment are illustrated. max. = maximum.

The deadline was not adjusted after a no-go trial. We used separate tracking procedures for standard-sound and novel-sound trials.

At the end of each trial, participants received feedback in the center of the screen for 1,000 ms. On go trials, "correct" appeared when they responded correctly to the location of the letter, "incorrect" when they pressed the wrong key, and "too slow" when they did not respond in time. On no-go trials, "correct" appeared when they withheld their response and "do not respond" when they responded.

Participants performed 15 blocks of 60 trials. At the end of each block, we presented the mean reaction time (RT), number of incorrect and missed go responses, and the percentage of correctly stopped responses. Participants had to pause for 15 s before they could start the next block. The total duration of the experimental session was approximately 45 min.

Analyses. Data were processed and analyzed using R (R Development Core Team, 2014). For estimations of effect sizes, we used Hedges' g_{av} (Lakens, 2013). All data files and R scripts used for the analyses are deposited on the Open Research Exeter data repository (http://hdl.handle.net/10871/17644).

The probability of a correct go response was at ceiling (see Table 1), so we did not analyze it further. The probability of a missed go response was close to .20, indicating that the tracking procedure worked well.

Table 1
Performance on Go and No-Go Trials as a Function of Trial Type in Experiments 1 and 2

Dependent variable	Experiment 1						Experiment 2			
	Novel		Standard		No sound		Novel		Standard	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
p(correct)	.995	.007	.990	.010	.964	.029				
p(miss)	.197	.009	.210	.004	.210	.004				
RT	318	21	313	22	306	38				
p(resp|no-go)	.402	.137	.362	.140			.178	.105	.325	.121

Note. Consistent with our previous work (Verbruggen & Logan, 2009), *p*(correct) is the ratio of the number of correct responses to the number of correct and incorrect responses: *p*(Correct)= Probability of correct responses on go trials; *p*(miss) = probability of missed go responses; RT = Average reaction time for correct go responses; and *p*(resp | no-go) = probability of responding on a no-go trial.

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Results and Discussion

Descriptive statistics appear in Table 1. Go RTs were significantly longer for novel-sound trials (318 ms) than for standard-sound trials (313 ms), $t(19) = 2.40$, $p = .03$, $g_{av} = .21$. Figure 2 shows that the whole RT distribution was shifted to the right for novel-sound trials. Furthermore, the probability of responding on no-go trials was higher for novel-sound trials (.402) than for standard-sound trials (.362), $t(19) = 2.63$, $p = .02$, $g_{av} = .28$. These findings are inconsistent with the "circuit breaker" account. Instead, they provide support for the "stimulus detection" account: attention was orientated to the unexpected novel stimulus; this interfered with detection of the go and no-go stimuli, producing impairment for both trial types.

Experiment 2

We propose that the results of Experiment 1 are inconsistent with the circuit breaker account. However, salient events may not directly suppress motor output but "reset" controlled processing in the primary task (Corbetta et al., 2008). Because not going requires a decision (Gomez, Ratcliff, & Perea, 2007; Verbruggen, McLaren, & Chambers, 2014), this "reset signal" could lead to the automatic execution of a prepotent response on no-go trials. Therefore, in Experiment 2 sounds acted as the no-go signal. The "stimulus detection" account predicts that no-go performance should improve if the novel sound is the actual no-go signal, whereas the "reset" version of the circuit breaker account predicts a performance cost.

Method

Participants. Twenty-four (20 females) undergraduate students from the University of Exeter (M age $= 18.75$, $SD = .79$) participated for course credit.

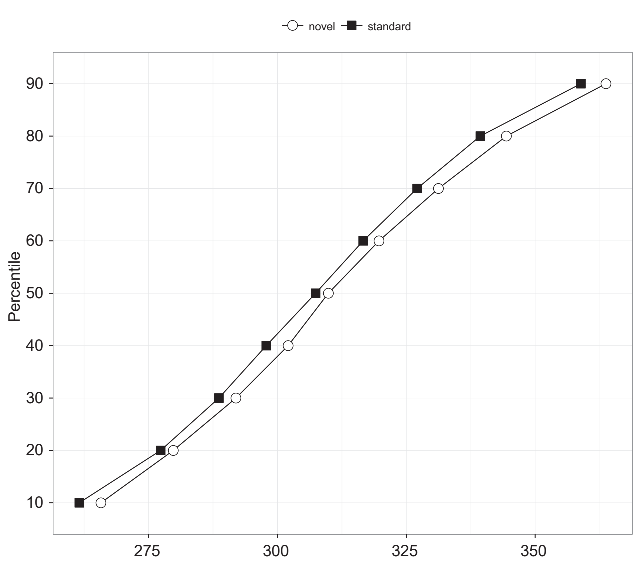

Figure 2. Distribution of response times in the standard and deviant conditions of Experiment 1.

Apparatus, stimuli, procedure, and analyses. These were the same as in Experiment 1, except for the following: Sounds were presented at the same moment as the visual stimuli and acted as the no-go signal. Participants were instructed to respond to the location of the go stimulus. The letter *M* was used for half of the participants; the letter *W*, for the others. On one third of the trials, a sound was presented at the same time as the visual stimulus, instructing participants to withhold their response. The no-go stimulus was either the standard sound (80% of the no-go trials) or a novel sound (20% of the no-go trials). No sounds occurred on go trials.

Results and Discussion

Descriptive statistics for go and no-go trials appear in Table 1. Here we focus on no-go trials only (i.e., no sounds were presented on go trials). Consistent with the "stimulus detection" account, probability of responding was *lower* for novel-sound no-go trials (.178) than for standard-sound trials (.325), $t(23) = 7.86$, $p < .001$, $g_{av} = 1.28$. Again, this pattern is consistent with the stimulus detection account.

General Discussion

This study explored the link between attentional reorienting and response inhibition in a go/no-go task. Results of Experiment 1 showed that novel sounds presented before the primary-task stimulus impaired performance on both go and no-go trials. This is consistent with the finding that visual "noise" or distractors can impair the detection of visual stop signals (Verbruggen, Stevens, & Chambers, 2014), and provides further support for the "stimulus detection" account. Furthermore, Experiment 2 showed that novel sounds did produce an improvement on no-go trials when they represented the no-go signal. Thus, novelty impairs no-go performance when the sounds are task-irrelevant, but it enhances no-go performance when the sounds are task-relevant.

We recently proposed that response inhibition and other forms of action control require both attentional and response selection (Verbruggen, McLaren, & Chambers, 2014). Biased competition accounts of visual attention assume that attentional selection is a competitive process: The stronger the response to a particular object, the weaker the response to other objects (e.g., Beck & Kastner, 2009; Bundesen, 1990; Desimone & Duncan, 1995; Duncan, 2006; Kastner & Ungerleider, 2000). This competition has also been observed across modalities (Duncan, 2006). Thus, when novel and possibly important stimuli are presented, processing of other stimuli will be suppressed. This leads to a performance cost when the novel stimuli are task-irrelevant (Experiment 1), and leads to a performance benefit when they are task-relevant (Experiment 2).

The results of Experiment 1 are inconsistent with the "circuit breaker" account as it stands, which claims that responding is suppressed when unexpected or potentially relevant stimuli are presented (Aron et al., 2014; Corbetta et al., 2008; Corbetta & Shulman, 2002; Wessel & Aron, 2013; Wiecki & Frank, 2013). Wessel and Aron (2013) found that corticospinal excitability was temporarily reduced when an unexpected stimulus occurred. However, in Experiment 1 we found increased responding on novel-sound no-go trials, which is inconsistent with the idea that unexpected events inhibit motor activity. Recent computational work can help to reconcile these findings. Traditionally, researchers assume that responses are stopped via direct inhibition of response units (e.g., Boucher et al., 2007). However, Logan, Yamaguchi, Schall, and Palmeri (2015) showed that blocking the input to these go units could also stop responses. Deviant sounds direct attention away from the main task; this could temporarily block the sensory input to the motor system on go trials and subsequently reduce go activity. In other words, the blocked-input account predicts decreased go activity on novel-sound trials, but this is achieved by removing go input rather than by direct suppression of motor activation (cf. Logan et al., 2015). Note that on no-go trials, blocking of input would lead to increased responding because the decision not to go is impaired. Future computational work could compare the block-input and the motor-suppression versions of the circuit breaker account, and whether there are situations in which both mechanisms might be in play.

In conclusion, we tested two accounts, which describe the interplay of reorienting attention and response inhibition. Our results are consistent with the "stimulus detection" account, underlining the importance of reorienting our attention in order to detect the unexpected signals and consequently cancel or replace our actions.

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Publication 5

The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study

Reference

Leiva, A., Andrés, P., Servera, M., Verbruggen, F., & Parmentier, F. B. R. (in press). The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study. *Developmental psychology*.

Motivation

The motivation for this study was two-fold. First, some recent work has suggested that deviance distraction may reflect response inhibition triggered by deviant sounds and that it is mediated by working memory capacity (WMC). The relationship between these variables remains however somewhat speculative and has so far not been explored within-participant. Second, there is evidence that both WMC and response inhibition change across the life span (improving from childhood to adulthood and declining from adulthood to old age). Hence one may wonder whether these variations may in part explain the variation observed in deviance distraction across age groups. We present the first study to explore the relationship between deviance distraction, WMC and response inhibition across three age groups (children, young and older adults). Its aim was to determine the extent to which deviance distraction is predicted by WMC and response inhibition and whether these may account for the variation in deviance distraction across age groups.

The role of age, working memory and response inhibition in deviance distraction: a cross-sectional study

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Abstract

Sounds deviating from an otherwise repeated or structured sequence capture attention and affect performance in an ongoing visual task negatively, testament to the balance between selective attention and change detection. While deviance distraction has been the object of much research, its modulation across the life span has been more scarcely addressed. Recent findings suggest possible connections with working memory and response inhibition. In this study we measured the performance of children, young and older adults in a cross-modal oddball task (deviance distraction), a working memory task (working memory capacity) and a response inhibition task (ability to voluntarily inhibit an already planned action) with the aim to establish the contribution of the latter two to the first. Older adults exhibited significantly more deviance distraction than children and young adults (who did not differ from each other). Working memory capacity mediated deviance distraction in children and older adults (though in opposite directions) but not in young adults. Response inhibition capacities did not mediate deviance distraction in any of the age groups. Altogether the results suggest that while the increase in deviance distraction observed in old age may partly reflect the relative impairment of working memory mechanisms, there is no straightforward and stable relation between working memory capacity and deviance distraction across the life span. Furthermore, our results indicate that deviance distraction is unlikely to reflect the temporary inhibition of responses.

Keywords: deviance distraction; working memory; response inhibition; lifespan; aging

The cognitive system is equipped with mechanisms ensuring a certain level of selective attention (the ability to filter out task-irrelevant stimuli in order to concentrate on a task at hand) to reduce the risk of distraction. However, selective attention is balanced by other mechanisms ensuring that unexpected but potentially important stimuli can break through attentional filters and capture our attention (e.g., in order to detect the sound of a fire alarm while sitting in a library and immersed in the reading of a book). While adaptive, this ‘attentional capture’ mechanism also presents one downside when the unexpected stimuli are task-irrelevant: distraction. Although often innocuous, distraction can have non-negligible consequences in certain settings and groups of individuals (e.g., distraction in the classroom can affect learning outcomes; distraction while driving a vehicle can lead to accidents, etc.). Distraction by unexpected stimuli can easily be measured and studied in laboratory conditions using oddball tasks in which participants attend and respond to some stimuli (e.g., visual digits) while ignoring rare and unexpected changes in a sequence of task-irrelevant sounds. While evidence indicates that attentional functions mature during childhood and decline in old age, there has been no study comparing children, young adults and older adults on such task. Furthermore, the association with maturation and decline of other cognitive functions remains unclear. This study addressed these issues.

Deviance distraction

Sudden changes in a sequence of otherwise repeated or predictable sounds, referred to as deviant and standard sounds respectively, have been demonstrated to capture attention and distract participants away from an ongoing task (e.g., Bendixen, Roeber, & Schröger, 2007; Schröger, 1996; Schröger, Kotz, & SanMiguel, 2015; Parmentier, 2008, 2016; Parmentier, Elsley, Andrés, & Barceló, 2011). This type of attention capture has largely been studied from an electrophysiological perspective and is characterized by a triumvirate of specific brain responses (e.g., Horváth, Winkler, & Bendixen, 2008; Schröger 1996, 1997, 2007; Schröger & Wolff, 1998a,b): mismatch negativity (MMN), marking the detection of change (Näätänen, Paavilainen, Rinne, & Alho, 2007) or the violation of predictions (e.g., Bendixen et al., 2007; Paavilainen, Arajärvi, & Takegata, 2007; Schröger, Marzecová, & SanMiguel, 2015; Winkler, 2007); P3a assumed to indicate the involuntary orienting of attention towards a perturbing event (e.g., Escera, Alho, Schröger, & Winkler, 2000; Friedman, Cycowic, & Gaeta, 2001; Polich 2007); and reorientation negativity (RON), reflecting the reorientation of attention toward the target stimulus and the reactivation of the relevant task-set in working memory (e.g., Berti, 2008; Berti & Schröger, 2003, 2004; Munka & Berti, 2006).

Deviant sounds also produce clear behavioral distraction (e.g., Schröger, 1996; Schröger, Giard & Wolff, 2000) by delaying responses to target stimuli. Note that in simple binary categorization tasks, response accuracy is typically high and by and large insensitive to deviant sounds. Therefore, most studies have focused on the reaction time cost. For simplicity, we will hereafter refer to behavioral deviance distraction as deviance distraction (see Parmentier, 2014, for a review). Deviance distraction has been argued to reflect, in part, the time penalty associated with the orientation of attention to and from the deviant stimulus (Parmentier, Elford, Escera, Andrés, & SanMiguel, 2008). Furthermore, evidence demonstrates that deviance distraction results from the violation of the cognitive system's predictions rather than from the rarity of the deviant stimuli per se (e.g., Bendixen, SanMiguel, & Schröger, 2012; Schröger, Bendixen, Trujillo-Barreto, & Roeber, 2007; Parmentier et al., 2011). While the capture of attention is undoubtedly triggered by the occurrence of the deviant stimulus, deviance distraction can nevertheless be modulated in a top-down fashion (e.g., Parmentier & Hebrero, 2013; Sussman, Winkler, & Schröger, 2003) or through general factors such as aging (Andrés, Parmentier, & Escera, 2006; Parmentier & Andrés, 2010), as discussed in the next section.

Deviance distraction and age

While studies on the effect of age on deviance distraction are relatively few, two sets of studies can be distinguished: developmental studies comparing children to young adults, and aging studies comparing young to older adults. Since the ability to ignore irrelevant information is closely related to the maturation and decline of brain structures (e.g., Fuster, 2002), one can expect to observe some age-related variation in deviance distraction. Typically, the ability to filter out irrelevant information improves from childhood to young adulthood and declines in older age (e.g., Andrés & Van der Linden, 2000; Berman & Friedman, 1995; Hasher & Zacks, 1988; Lustig, Hasher & Zacks, 2007; Wetzel, Widmann, Berti, & Schröger, 2006).

Results from developmental studies on deviance distraction have generated somewhat inconsistent results, however. Some reported a reduction in distraction as children grow older (e.g., auditory: Wetzel and Schröger, 2007; Wetzel, et al., 2006; auditory-visual: Gumenyuk et al., 2001). For example, using a duration categorization task, Wetzel et al. (2006) found greater distraction by deviant sounds in children aged 6-8 compared to young adults, but no difference between children aged 10-12 and young adults. On the other hand, others found no effect of age on deviance distraction across childhood (e.g., auditory: Horváth, Czigler, Birkás, Winkler, & Gervai, 2009; Wetzel, Widmann, & Schröger, 2009; auditory-visual: Ruhnau, Herrmann, Maess, Brauer, Friederici, & Schröger, 2013). For example, Wetzel et al. (2009) did not report differences in behavioral distraction between children aged 7-8 and young adults, but the latter exhibited better cognitive control when cues announced the presentation of a deviant sound. The determinants of the inconsistencies between developmental studies remain unclear, but some possibilities proposed include the nature of the distracter and its context (environmental sounds vs. artificial sounds such as sinewave tones) or the large variability of distraction effects in children relative to adults (Wetzel & Schröger, 2014).

Regarding the effect of old age on deviance distraction, recent work allows clearer conclusions. Studies using purely auditory tasks (tasks in which the target and deviant features are embedded within the same stimulus, for example where participants must judge the duration of a sound while ignoring rare and irrelevant pitch changes) tend to show no age-related differences (Getzmann, Gajewski, & Falkenstein, 2013; Horváth et al., 2009; Leiva, Andrés, & Parmentier, 2015; Mager, Falkenstein, Störmer, Brand, Müller-Spahn, & Bullinger, 2005; but see Berti, Grunwald, & Schröger, 2013). This conclusion was confirmed and extended to the visual modality by Leiva, Andrés et al. (2015), who used the largest sample size to date and confirmed the absence of age-related difference using Bayesian analyses: deviant stimuli presented in the same modality as the relevant stimuli yielded distraction but to the same extent in young and older adults. In sharp contrast with these findings, studies using the cross-modal variation of the oddball task (that is, a task in which target and deviant features are temporally and perceptually decoupled, such as when participants categorize visual digits preceded by to-be-ignored sounds) typically show an increase in distraction in older adults (Andrés et al., 2006; Parmentier & Andrés, 2010). The contrast between the cross-modal and the same-modality oddball tasks was confirmed by Leiva, Parmentier and Andrés (2015) who compared these in a within-participant design. Hence aging appears to affect the mechanisms responsible for the orientation and re-orientation of attention across sensory boundaries, not those responsible for within-modality attentional shifts.

In sum, some evidence suggests a reduction of deviance distraction from childhood to adulthood, and such distraction increases in old age again when irrelevant and target stimuli are presented in distinct sensory modalities. However, the mechanisms through which age mediates deviance distraction remain unclear. Here we consider the possible role of two general factors that recent evidence has linked to deviance distraction and that, independently, have been shown to be sensitive to cognitive aging: working memory capacity and response inhibition. We briefly discuss these in the next sections.

Deviance distraction and working memory capacity (WMC)

Studies comparing low- and high-WMC individuals with respect to deviance distraction are few and the evidence thus far is mixed. On the one hand, two studies indicate that individuals with high WMC exhibit comparatively less deviance distraction. Sörqvist and colleagues found a negative correlation between working memory capacity and deviance distraction in a serial recall task (Sörqvist, 2010), and a reduced level of deviance distraction in participants with high WMC (compared to low WMC participants) in a cross-modal oddball task (Sörqvist, Nöstl, & Halin, 2012). These findings fit with the general view that high WMC confers better shielding against distraction (e.g. Heitz & Engle, 2007; Lustig et al., 2007; Unsworth & Engle, 2007). On the other hand, the correlation found by Sökvist between deviance distraction and WMC was relatively modest and obtained from a study in which deviant sounds were embedded in a stream of irrelevant speech in the context of a serial recall experiment. It is as yet unclear whether deviance distraction as measured in such circumstances is functionally identical to that typically measured in the oddball task. Furthermore, Roër, Bell and Marsh (2015), using a similar task but a larger sample than Sörkvist, found no correlation between deviance distraction and WMC. Hence, the exact relationship between these two factors remains unclear.

The present study will further explore this issue by examining whether age-related changes in deviance distraction may be due to changes in WMC. Abundant evidence indicates that WMC increases from childhood to adulthood and then declines in older age (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004; Gazzaley, Cooney, Rissman, & D'Esposito, 2005). If deviance distraction is in part correlated with WMC, then we should find greater deviance distraction in children and older adults compared to young adults and WMC should account for these differences. Any other pattern of results would question the hypothetical direct link between WMC and deviance distraction.

Deviance distraction and response inhibition

Recently several researchers have proposed that deviant sounds may impact on ongoing behavioural performance because they temporarily freeze all responses, and that attentional reorienting and response inhibition might rely on similar cognitive and neural mechanisms. The 'circuit breaker' account proposes that the reorienting response towards unexpected but potentially behavioral relevant stimuli relies on a ventral frontoparietal network that interrupts and resets ongoing actions (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002; see also Wiecki & Frank, 2013), allowing the selection of alternative information. This idea is supported by a recent study of Wessel and Aron (2013). Using a stop-signal task, which measures response inhibition

(Verbruggen & Logan, 2008), and a cross-modal oddball task, these authors showed a common brain activity for outright action-stopping in the stop-signal task and following deviant sounds in the oddball task. Furthermore, they also measured muscular responses (motor evoked potentials, or MEPs) to transcranial magnetic stimulation (TMS) of the primary motor cortex. MEPs are a measure of corticospinal excitability. Wessel and Aron (2013) found that MEPs were reduced following the presentation of a deviant sound, which led them to conclude that unexpected events cause distraction via global suppression of motor output.

Even though the notion of a 'circuit breaker' has received some support, its role in explaining behavioral deviance distraction is questioned by the results of a study by Leiva, Parmentier, Elchlepp and Verbruggen (2015). The authors used a go/no-go task. In this task, subjects are instructed to respond as quickly as possible when a go stimulus appears. On a minority of the trials, a no-go signal stimulus is presented, instructing participants to withhold their response. Leiva et al. found that irrelevant novel sounds preceding go/no-go stimuli impaired performance on both go trials (slower go responses) and on no-go trials (higher probability of responding). The latter contradicts the prediction from the circuit-breaker account, according to which the novel sounds should have facilitated the interruption of motor responses.

In the present study, we further explored the relationship between response inhibition and deviance distraction, and whether age-related changes in response inhibition capacities could account for changes in deviance distraction. Response inhibition, as is the case with WMC, has been shown to vary across the life span. Indeed, several authors have argued that the ability to inhibit a response improves through childhood (e.g., Bedard, Nichols, Barbosa, Schachar, Logan, & Tannock, 2002; Carver, Livesey, & Charles, 2001; Riderinkhof, Band, & Logan, 1999; van den

Wildenberg, & van der Molen, 2004; Williams, Ponesse, Schachar, Logan, & Rosemary, 1999; but see Jennings, van der Molen, Pelham, Brock Debski, & Hoza, 1997; Oosterlaan, & Sergeant, 1998; Schachar & Logan, 1990), a developmental trend that appears to be independent from speed of processing and working memory (Urben, Van der Linden, & Barisnikov, 2011). Work also suggests a slowing or relative impairment of response inhibition in old age (e.g., Andrés, Guerrini, Phillips, & Perfect, 2008; Kramer, Humphrey, Larish, Logan, & Strayer, 1994), though some found only limited evidence for this (e.g., Williams et al., 1999). A reduction in inhibitory control in old age may partly account for the age-related changes in deviance distraction. For example, slower inhibitory control could perturb the reorientation of attention toward the target stimulus and the re-activation of the appropriate task-set. The latter may be a consequence of the requirement to maintain simultaneous task sets active (Verheagen & Cerella, 2002).

The present study

As discussed above, a number of studies suggest a variation of deviance distraction with age, from childhood to old age. This evidence emerges from studies that either compared children with young adults, or young with older adults. Independently, in young adults, recent work suggests a possible involvement of working memory and response inhibition in deviance distraction. As we briefly reviewed above, each of these two factors varies with age, by and large improving from childhood to young adulthood and declining thereafter. We report the first study on deviance distraction comparing all three age groups (children, young and older adults) using the same cross-modal oddball task while measuring working memory capacity and response inhibition. Our goal was two-fold. First, we aimed to confirm that deviance distraction varies across the life span.

Second, and most importantly, we sought to establish the extent to which working memory and response inhibition contribute to deviance distraction and to what extent they can account for its age-related variation.

We presented groups of children, young and older adults with three tasks: a cross-modal oddball task, a working memory capacity task, and a stop-signal task. For the cross-modal oddball task we followed the general structure used in previous studies in which an irrelevant stimulus was presented immediately before a visual target (e.g., Andrés et al., 2006; Parmentier & Andrés, 2010; Parmentier et al., 2008). We used a stop-signal task created by Verbruggen, Logan, & Stevens (2008). In this task, subjects responded to visual shapes (go stimuli). On a minority of the trials, an extra auditory signal appeared after a variable delay, instructing participants to withhold the prepared response. The paradigm is currently one of the most popular response-inhibition paradigms (Verbruggen, Chambers, & Logan, 2013) because it allows researchers to estimate the covert latency of the stop process: the stop-signal reaction time (SSRT; see Figure 1). Finally, we used a working memory task based on Hale's developmental studies (Hale, Bronik, & Fry, 1997; Hale, Myerson, Rhee, Weiss, & Abrams, 1996; Hale, Rose, Myerson, Strube, Sommers, Tye-Murray, & Spehar, 2011) in which participants named the color of squares highlighted sequentially within a grid while simultaneously remembering their spatial location. This task requires the simultaneous processing and storage of information as does the more widely known OSPAN (Turner & Engle, 1989) task but presents the major advantage of being accessible to children.

--- Insert Figure 1 about here ---

We used regression methods to establish the extent to which age, WMC and SSRT (response inhibition) account for deviance distraction, and to examine whether age remained a significant predictor of deviance distraction once WMC and SSRT were taken into account. If WMC capacity predicts deviance distraction, as suggested elsewhere (e.g., Sörqvist, 2010), then we should find a positive relationship between these measures across age groups. If deviant sounds trigger motor inhibition through the mechanisms involved in the voluntary inhibition of actions (Wessel & Aron, 2013), then we should see a positive relation between SSRT and deviance distraction across age groups. Any pattern of data differing from these predictions would question the role of WMC and response inhibition in accounting for deviance distraction.

Method

Participants

One hundred and twenty two participants took part in this study: 39 children (17 females) aged 8-9 (*M* = 8.4, *SD* = .48), 44 young adults (33 females) aged 18-36 (*M* = 20.7, *SD* = 3.7) and 39 older adults (31 females) aged 55-77 (*M* = 64.7, *SD* = 5.6). Children attended a local primary school. Young adults were undergraduate students who participated in exchange for course credit or a small honorarium. The older participants were recruited through advertisements in a local newspaper and participated in exchange for a small honorarium. Adults and parents (in case of children) gave written informed consent. The Spanish version of the Mini-Mental State Examination (Lobo, Ezquerra, Gómez Burgada, Sala, & Seva Díaz, 1979) was administered to older participants to exclude participants with potential cognitive impairment. All older participants exhibited performance within the healthy range (*M* = 29.5, *SD* = .72). The WAIS-III vocabulary test (Seisdedos, Corral, Cordero, de la Cruz, Hernández, &

Pereña, 1999) was also administered to young and older adults as a measure of crystallized intelligence and, as expected, was significantly higher in older adults ($t(81) = 2.429$, $p < .05$; young: $M = 12.3$, $SD = 1.5$; older adults: $M = 13.2$, $SD = 1.9$, $d = .54$). All participants reported normal hearing, and normal or corrected-to-normal vision. The data of two children were excluded due to extreme distraction effects (more than 3 standard deviations above of the group's mean) in the Oddball task. The data of 8 children, 3 young and 9 older adults were excluded due to unreliable measures in the stop-signal task: negative SSRT estimates (indicating that they waited for the stop signal to occur) and abnormally high (> .80) or low (< .20) probability of responding on signal trial (non-central SSRT estimates are unreliable; Band, van der Molen, & Logan, 2003).

Material, stimuli and procedure

The study included three tasks: a cross-modal oddball task, the stop-signal task and a memory task. All tasks were presented on a 19 inch screen for young and older adults and on a 15.6 inch laptop for children (the testing of children took place at their school). The order of presentation of the oddball task, stop-signal task and working memory task was counterbalanced across participants.

Oddball task. The task involved the presentation of auditory and visual stimuli. The auditory stimuli included two sounds, one consisting of a 150 ms sine-wave tone of a frequency of 600 Hz, the other of a 150 ms burst of white noise. All sounds were presented binaurally via headphones with a level of approximately 75 dB SPL. The visual stimuli consisted of an image of a dog looking to the right or left side, presented at the center of the screen against a white background (see Figure 2). These stimuli sustained a visual angle of approximately 4.1º (3.21º on the laptop), with participants seated approximately 50 cm away from the screen.

--- Insert Figure 2 about here ---

In every trial, the participant's task was to indicate which way (left/right) a cartoon dog was looking while ignoring a task-irrelevant sound presented shortly before the appearance of the dog (see Figure 2). Participants were told that the main task was to feed the dog by pressing a response key corresponding to the direction in which the dog looked. If the dog looked to the left, participants had to press the numerical key 1 on the computer keyboard, and they pressed the numerical key 2 if it looked to the right. The dog's direction of gaze was random with the constraint that each direction occurred equally often across each block and type of trial (standard or deviant, see below). This random order was different for every participant.

The structure of every trial was as follows. Each trial started with a fixation cross at the center (1.146º- screen; 0.917º- laptop), which remained there for the whole duration of the trial except during the presentation of the visual stimulus (dog) and the feedback information, as illustrated in Figure 2. A 150 ms irrelevant sound was presented 800 ms into the trial and followed by a further 100 ms gap before the fixation cross was replaced by the visual stimulus (dog) for 200 ms. The irrelevant sound consisted of the 600 Hz sine-wave tone in 70% of trials (standard sound) and of a burst of white noise in the remaining 30% of trials (deviant sound). Standard and deviant trials were ordered quasi-randomly in a different order for every participant, with the constraint that deviant trials were never presented on consecutive trials. Following the presentation of the dog picture, the fixation cross re-appeared and remained visible for

900 ms. A feedback message was then displayed for 800 ms. If the participant's response was correct, a bowl full of food appeared at the location the dog was looking toward, and a happy smiley words "Muy bien" ("Very good") appeared. In the case of an incorrect response, the bowl full of food appeared on the opposite side of the dog's direction of gaze and a sad smiley with the red words "Has fallado" ("You have responded incorrectly") were presented. The words "No has contestado" ("You have not responded") appeared in grey color at the center of the screen if participants did not produce any response. Participants performed two blocks of 240 experimental trials each (each preceded by 12 standard practice trials). Participants were instructed to ignore the irrelevant sounds, to concentrate on the visual task, and to respond as quickly but as accurately as possible.

The stop-signal task. We used the Stop-it program developed by Verbruggen, Logan, & Stevens (2008). The task involved the presentation of visual and auditory stimuli (see Verbruggen et al., 2008). The visual go stimuli were a square and a circle (1.7º in the computer screen; 1.26º in the laptop) presented at the center of the screen in white on a black background. The auditory stop signals consisted of a 75 ms tone of a frequency of 750 Hz.

On go trials, participants judged the shape of the visual go stimulus (square or circle). Each trial started with a 250 ms fixation cross (1.26º- computer screen, 0.917º-laptop), followed by the presentation of the visual stimulus. The go stimulus remained on the screen for 1250 ms, or until a response was executed. Participants categorized the shapes by pressing the "Z" (square) and "–"[1] (circle) keys on the computer keyboard

[1] Note that on Spanish keyboards the "Z" and "-" keys are located on the left and right (respectively) of the lower row of keys.

using their index fingers. During the intertrial interval (2000 ms), a blank screen was presented.

On 25% of the trials (stop-signal trials), the presentation of the shape was followed by an auditory signal that instructed participants to withhold their response. The sound was presented after a variable stop-signal delay SSD (250 ms). The SSD was initially set at 250 ms and continuously adjusted according to a tracking procedure to obtain a probability of successful stop performance of .50. Each time a participant responded to the go stimulus on a stop-signal trial, SSD decreased by 50 ms (making the stop task easier). When the participant successfully stopped the go response on a stop-signal trial, SSD increased by 50 ms (making the stop task more difficult). When probability of responding is around .50, competition between going and stopping is maximal, and SSRT estimates are most reliable. Furthermore, the tracking procedure compensates for differences between participants, resulting in a similar p(respond|signal) for the different age groups.

SSRT was estimated using the integration method (Logan & Cowan, 1984; Verbruggen et al., 2013). The integration method assumes that the finishing time of the stop process corresponds to the nth RT, with n = the number of RTs in the RT distribution multiplied by the overall p(respond|signal). SSRT can then be estimated by subtracting mean SSD from the nth RT (Figure 1).

Participants performed three experimental blocks of 64 trials, with a 10 seconds pause between blocks. Feedback was provided after each block (the number of incorrect responses on no-signal trials, the number of missed responses on no-signal trials, the mean RT on no-signal trials, and the percentage of correctly suppressed responses). Participants were told to withhold their responses when a sound was presented (25% of the trials). No additional information was provided.

Working memory task. We used a task similar to the one used by Hale et al. (1997; 1996; Fry & Hale, 1996). Two conditions were included: spatial (spatial memory) and spatial+verbal (working memory). The key measure of WMC was the span measured in the spatial+verbal condition but the spatial condition was included to assure that the spatial+verbal condition was more demanding than the spatial one. For both conditions the stimuli were Xs (1.5 cm wide x 1.8 cm high on the computer screen; 1 cm wide x 1.3 cm high on the laptop) that appeared one by one in a cell of a 4x4 grid (11.7 cm x 11.7 cm on the computer screen; 7.4 cm x 8.9 cm on the laptop) at the center of the screen. The stimuli were presented in six different colors (blue; RGB values: 19, 69, 181; brown, RGB values: 162, 108, 0; green, RGB values: 53, 173, 43; grey, RGB values: 93, 94, 82; pink, RGB values: 182, 0, 85; or red, RGB values: 206, 33, 30). The color of the stimuli appeared randomly, with the restrictions that no color occurred more than twice in a row and that each color appeared approximately equally often across each condition. An empty 4x4 white grid (11.7 cm x 11.7 cm- computer screen; 7.4 cm x 8.9 cm- laptop) was presented as the recall signal and a 600 ms tone to mark the end of the recall phase.

In each trial of the spatial condition, a fixation black square (1.8 cm x 1.5 cm- screen; 1.1 cm x 1.1 cm- laptop) appeared on a grey background (RGB values: 126, 123, 123) at the center of the screen until the participant pressed any key on the computer keyboard to initiate the trial. Then we presented a sequence of 4x4 grids with one of the locations filled with a “X” (its color varying across the trial). Each grid appeared for 1750 ms, followed by a grey screen for a duration of 250 ms. The participant’s task was to encode and memorize the locations so as to be able to recall them at the end of the trial (irrespective of their order). Following the last grid of the trial, an empty test grid appeared on the screen. Its duration varied with the length of the to-be-remembered sequence (3000 ms for sequences of two locations, and an additional 1000 ms per additional location). Participants had to recall and mark the locations in an empty grid in a sheet of paper. A 600 ms tone was then presented to mark the end of the recall phase. The number of grids per trial increased as the task progressed, from two to a maximum of twelve (with two trials per sequence length). No location was repeated within a trial.

In the spatial+verbal condition, the general procedure was identical but participants were required, in addition to performing the memory task, to name out loud the colors of the “X” symbols as they were presented.

In both tasks, participants performed four practice series, two with a single location and two with two locations. The experimental series started with sequences of two to-be-remembered locations and increased in difficulty by progressively increasing the sequence length by one location. The score was calculated based on the maximum sequence length for which at least one trial was performed correctly (that is, all locations were recalled correctly), with .5 point allocated to each trial of a given sequence length. The experimenter interrupted the task when both trials of a given sequence length were failed.

Results

In this section we focus on the key results for our study: deviance distraction in the oddball task and its relationship with WMC (score from the working memory task) and response inhibition (SSRT measure from the stop-signal task). Full analyses of the data in the stop-signal and memory tasks are reported in Appendix A. To estimate effect sizes, we used Cohen's d for between-subjects comparisons and d_{av} for within subjects comparisons (Lakens, 2013).

Oddball task

The mean RTs for correct responses (measured from target onset) and the proportion of correct responses were analyzed using 3 (age: children vs young vs older) x 2 (deviance: standard vs deviant) mixed-model ANOVAs.

Response times (see Figure 3) varied with age [$F(2,117) = 69.384$, $MSE = 11618.579$, $p < .001$, $\eta_p^2 = .543$] and were longer in children ($M = 584.04$, $SD = 96.69$) than in the young ($M = 383.78$, $SD = 51.75$), [$t(52.864) = 11.309$, $p < .001$, $d = 2.68$] and older adults ($M = 477.00$, $SD = 77.45$), [$t(74) = 5.340$, $p < .001$, $d = 1.24$], and longer in older ($M = 477.00$, $SD = 77.45$) than in the young adults ($M = 383.78$, $SD = 51.75$), [$t(81) = 6.513$, $p < .001$, $d = 1.45$]. Response times were longer in the deviant condition relative to the standard condition [$F(1,117) = 73.242$, $MSE = 213.559$, $p < .001$, $\eta_p^2 = .385$]. The deviance x age interaction was significant [$F(2,117) = 9.824$, $MSE = 213.559$, $p < .001$, $\eta_p^2 = .144$], as visible from Figure 3. While deviance distraction (longer RT after deviant compared to standard sounds) was significant in all three age groups [children: $t(36) = 2.319$, $p < .05$, $d_{av} = .099$; young: $t(43) = 5.121$, $p < .001$, $d_{av} = .225$; older: $t(38) = 7.448$, $p < .001$, $d_{av} = .358$], older adults were more distracted than children [$t(74) = 3.618$, $p < .01$, $d = .841$] or young adults [$t(63.754) = 3.690$, $p < .001$, $d = .842$]. In contrast children and young adults exhibited equivalent levels of distraction [$t(60.662) = .683$, $p = .497$, $d = .160$].

--- Insert Figure 3 about here ---

As expected for a binary categorization task with a stimulus-response compatible mapping, response accuracy (see Table 1) was high (M = .96, SD = .05) and did not vary with deviance [$F(1,117) < 1$, MSE = .0004, p = .351, η_p^2 = .007]. It did vary with age [$F(2,117) = 32.708$, MSE = .003, $p < .001$, η_p^2 = .359], with better performance in young adults (M = .98, SD = .01) relative to older adults (M = .96, SD = .05), [$t(41.279) = 2.994$, $p < .01$, d = .702] and children (M = .92, SD = .04), [$t(39.687) = 9.122$, $p < .001$, d = 2.22], and better performance in older adults (M = .96, SD = .05) relative to children (M = .92, SD = .04), [$t(74) = 4.062$, $p < .001$, d = .945]. The deviance x age interaction just reached significance [$F(2,117) = 3.148$, MSE = .0004, p = .047, η_p^2 = .051] and reflected a greater negative impact of the deviant sounds in older compared to young adults [$t(51.160) = 2.455$, $p < .05$, d = .571]. The difference between young adults and children [$t(52.258) = .810$, p = .422, d = .192] or between older adults and children [$t(74) = 1.410$, p = .163, d = .329] were not significant.

SSRT in the stop-signal task

As described earlier, the crucial measure to test our hypothesis was the SSRT. A one-way ANOVA revealed statistically significant differences of SSRTs across age groups [$F(2,99) = 20.056$, MSE = 5661.774, $p < .001$, η^2 = .29]. T-tests revealed that young (M = 248.760, SD = 50.28) and older (M = 235.365, SD = 51.732) exhibited shorter SSRTs than children (M = 344.984, SD = 112.810), [children vs. young: $t(39.029) = 4.428$, $p < .001$, d = 1.17; children vs. older: $t(42.384) = 4.904$, $p < .001$, d = 1.26]. SSRTs of young and older adults were similar [$t(69) = 1.095$, p = .277, d = .262].

The other performance measures in the stop task are reported in Appendix A (descriptive statistics and inferential statistics).

Working Memory Capacity

As expected, memory scores were lower in the spatial+verbal condition (M = 4.27, SD = 1.72) than in the spatial condition (M = 4.69, SD = 1.82), [t(121) = 3.575, p < .001, d_{av} = .241], confirming the greater cognitive demands of the first. Here we focus on the spatial+verbal (working memory) condition (the results from the spatial condition are reported in Appendix A) as our measure of WMC. A one-way ANOVA revealed statistically significant differences in WMC across age groups [F(2,119) = 35.531, MSE = 1.879, p < .001, η^2 = .37]. Children (M = 3.5, SD = .93) and older adults (M = 3.46, SD = 1.15) exhibited lower working memory capacity than young adults (M = 5.66, SD = 1.81), [children vs. young: t(65.959) = 6.952, p < .001, d = 1.49; older vs. young: t(73.811) = 6.685, p < .001, d = 1.45]. The WMC scores of children and older adults were similar [t(76) = .162, p = .871, d = .04].

Regression analysis

We carried out a linear regression analysis with age group, WMC and SSRT as independent variables and distraction (RTs deviant minus standard) as the dependent variable. The regression model accounted for a significant proportion of the variance: R^2 = .206, F(3,97) = 8.414, p < .001. Age group contributed significantly to the model's fit [$B_{\text{age group}}$ = 12.585, t(97) = 4.376, p < .001]. The contribution of WMC failed to reach statistical significance [B_{WMC} = -2.162, t(97) = 1.957, p = .053]. SSRT also did not correlate with deviance distraction (B_{SSRT} = .024, t(97) = .938, p = .351).

As reported earlier, the examination of the pattern of results in the cross-modal oddball task, the WM task and the stop-signal task reveals diverging effects of age. While older adults stood out for exhibiting greater distraction than the other two groups (which did not differ from each other) in the cross-modal oddball task, children stood out for their longer SSRT in the stop-signal task, and young adults stood out for their greater WMC in the WM task. Hence the results of our general regression are likely to mask possible differences in the relationship between deviance distraction, WMC and SSRT across the three age groups. For this reason, we calculated partial correlations within each age group to establish whether the pattern of contribution of WMC and SSRT changed as a function of age. We found no correlation between deviance distraction and SSRT in any of the age groups [children: $r(27) = .279$, $p = .143$; young: $r(38) = -.133$, $p = .415$; older adults: $r(27) = -.269$, $p = .159$] when controlling for WMC. When controlling for SSRT, we found a negative correlation between deviance distraction and WMC in older adults ($r(27) = -.594$, $p < .01$), a positive one in children [$r(27) = .387$, $p < .05$], and no correlation in young adults [young: $r(38) = -.114$, $p = .483$]. The opposite directions for the correlations between deviance distraction and WMC explain why the main effect of WMC was not significant in the linear regression analysis reported above.

Finally, to examine the possibility that general slowing might account for some of the above results, we replicated these analyses using the % increase in RT in the deviant condition of the oddball task [(RT deviant – RT standard) / RT standard] as our dependent variable. The results (presented in Appendix B) were similar to the analysis above, indicating that increased deviance distraction in order adults is not simply due to general response slowing.

Discussion

The aim of the present study was to examine the role of WMC and response inhibition on deviance distraction through the lifespan. Results from the cross-modal oddball task revealed significant deviance distraction in children, young and older adults, with significantly larger distraction in the latter compared to the other two.

Results from the oddball task revealed that while children aged 8-9 were overall slower than young adults, the two groups exhibited similar levels of deviance distraction (in line with Horváth et al., 2009; and Wetzel et al., 2009). This suggests that the mechanisms involved in ignoring the distracters might be sufficiently matured in children aged 8-9 years old, at least as revealed by behavioral performance in the oddball task. Consistent with past aging studies (Andrés et al., 2006; Leiva, Parmentier et al., 2015; Parmentier & Andrés, 2010), older adults exhibited greater deviance distraction than young adults, an effect hypothesized by Leiva, Parmentier et al. (2015) to reflect an increase in the cost of orienting and reorienting attention across sensory boundaries (Miles, Brown, & Poliakoff, 2011; Rodway 2005; Shomstein & Yantis, 2004; Turatto, Benso, Galfano, & Umiltà, 2002; Turatto, Galfano, Bridgeman, & Umiltà, 2004). Overall, these results are in line with the general view of a reduction of the ability to ignore irrelevant distractors with age (e.g., Hasher & Zacks, 1988; Lustig et al., 2007).

The results from the stop-signal task showed longer SSRT for children compared to young adults, in line with studies arguing that the ability to inhibit a response improves from childhood to adulthood (e.g., Bedard et al., 2002; Carver et al., 2001; Riderinkhof et al., 1999; van den Wildenberg, & van der Molen, 2004; Williams et al., 1999; but see Jennings et al., 1997; Oosterlaan, & Sergeant, 1998; Schachar & Logan, 1990). The absence of difference between young and older adults is inconsistent with previous studies reporting a longer SSRT in older adults (e.g., Andrés et al., 2008; Kramer et al., 1994; but see Williams et al., 1999). The relatively long RTs in all age groups of the present study suggests that participants adjusted attentional (e.g., Verbruggen, Stevens, & Chambers, 2014; Elchlepp, Lavric, Chambers, & Verbruggen, 2016) or response settings (e.g., Aron, 2011; Verbruggen & Logan, 2009). Such proactive control adjustments could have compensated for small deficits in 'reactive' stopping. Furthermore, Williams et al. (1999) suggested that the inhibition differences or deficits were observed primarily for the "very" old participants.

With respect to WMC, we found a reduction of WMC in children and older adults compared to young adults, in line with past research (e.g., Fry & Hale, 1996; Gathercole et al., 2004; Gazzaley et al., 2005; Hale et al. 1997; 1996) and the maturation and decline of the frontal cortex across the life span (Dempster, 1992; Goldman-Rakic, 1987; Raz, 2000; West, 1996).

The most critical aspect of our study, however, lies in the relation between deviance distraction on the one hand, and age, WMC and response inhibition on the other. The results of the regression analysis suggest that age mediates deviance distraction while WMC and response inhibition do not. However, the most important findings emerged from analyses performed within each age group. Partial correlations revealed a correlation between WMC and deviance distraction in children and older adults (though in opposite directions, discussed below), but not in young adults. Furthermore, response inhibition did not account for deviance distraction in any of the three age groups. The same pattern of findings was found when controlling for the participants' response speed in the standard condition of the oddball task (by measuring deviance distraction as the % increase in RT in the deviant condition relative to the standard condition).

Contrary to Sörqvist and colleagues (Sörqvist, 2010; Sörqvist et al., 2012), we found no significant negative correlation between distraction and WMC in young adults. One possibility for this discrepancy may lie with the use of different tasks to measure WMC. While we adopted the verbal-spatial task used by Hale and collaborators (Hale, et al., 1997; 1996; 2011) in order to make the task accessible to all three groups, Sörqvist and collaborators used the OSPAN task (Turner & Engle, 1989). However the task used to measure WMC is unlikely to be a determinant factor since Röer et al. (2015) used the OSPAN task and found no correlation between deviance distraction and WMC either. Hence the link between WMC and deviance distraction as measured in a cross-modal oddball task lies in a single study (Sörqvist et al., 2012) which has so far not been replicated (on the contrary, we have unpublished data from a larger sample failing to replicate these authors' finding).

We did however find a significant negative correlation between WMC and deviance distraction in older adults, which may reflect greater top-down cognitive control in individuals with greater WMC, as suggested by the link between WMC and executive functioning (e.g. Conway & Kane, 2001; Kane & Engle, 2003). Past research indicates that whereas performance on working memory tasks improves with brain development from childhood to early adulthood, it declines in the elderly (e.g., Gathercole et al., 2004; Gazzaley et al., 2005) as does the ability to ignore irrelevant information (Andrés et al., 2006; Lustig et al., 2007; Parmentier & Andrés, 2010). The present study indicates that the aging-related declines in WMC and interference control are related. It also fits the suggestion that working memory is involved in attentional capture. More specifically, the reorientation of attention following its automatic capture by the task-irrelevant sound and the reactivation of the relevant task-set when the task-relevant target appears may be underpinned by working memory processes (e.g., Munka & Berti, 2006; Hölig & Berti, 2010).

In contrast to older participants, children exhibited a positive relationship between WMC and deviance distraction in children. This certainly suggests that the relation between deviance distraction and WMC may be more complex than previously thought. Other studies (for example Roncadin, Pascual-Leone, Rich & Dennis, 2007; also see Gathercole, et al., 2004) have shown that the relationship between cognitive functions or between WM and inhibition may change across age groups. It is unclear why greater WMC reduced deviance distraction in older adults but increased it in children. While speculative, it is possible that this is linked to proactive control. Several researchers have argued that the development of executive control includes a transition from reactive control to proactive control (e.g. Munakata, Snyder, & Chatham, 2012). It is possible that young children with a higher WMC were more likely to exert proactive control by using the sounds as warning signals (e.g., Parmentier, Elsley, & Ljungberg, 2010). This could have made them more vulnerable to distraction by the deviant sound (see Blackwell & Munakata, 2014, for evidence of a tradeoff between proactive control and distraction in children). In any case, what our findings suggest is that the relationship between WMC and deviance distraction must be one evolving in complex ways across age.

The theoretical implications of our studies can be summarized as follows. First, our results suggest that individual differences in deviance distraction are not necessarily a reflection of variations in working memory capacity (e.g., Sörqvist, 2010). Thus, our study strongly suggests that the mechanisms underpinning deviance distraction must be distinct from those underpinning working memory capacity. However, our results indicate for the first time that the mitigation of deviance distraction by working memory capacity may vary with age. Therefore, further research will be required to explore the intricacies of the interaction between working memory capacity and deviance distraction.

A second implication of our study concerns the hypothetical relation between deviance distraction and response inhibition. Our results are clear-cut: neither the regression analysis nor the partial correlations carried out within each age group revealed any relation between SSRT and deviance distraction. These findings are inconsistent with the 'circuit breaker' account (Wessel & Aron, 2013; Wiecki & Frank, 2013), which proposes that the same response inhibition mechanism is activated by deviant sounds and stop signals.

Our study is the first to compare children, young and older adults and examine the relation between deviance distraction, working memory capacity and response inhibition across these three age groups. It constitutes a first step and thus presents some aspects that future studies may follow up on. For example, we observed a complex relation between working memory capacity and deviance distraction across age groups, but our study does not allow us to draw clear conclusions as to the inner workings of this relation. While we found significant difference between the three age groups across various measures, the inclusion of more age groups (e.g., very young versus older children, young-older versus very old participants) may help trace better the developmental dynamics of our key measures and their relations.

Conclusion

In conclusion, our results revealed that age modulates deviance distraction but that this relationship is not easily accounted for by age-related variations in working memory capacity or response inhibition. Working memory appears to exert distinct influences in children and older adults, while response inhibition did not exhibit any relationship with deviance distraction in any of the three age groups.

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Table 1. Mean accuracy rates for children, young and older adults as a function of the deviance (deviant versus standard). Values within brackets represent the standard deviation.

	Deviant	Standard	Distraction
Children	.919 (.049)	.919 (.042)	.0003
Young	.987 (.011)	.982 (.015)	-.004
Older	.955 (.039)	.967 (.035)	.011

Figure 1: Performance in the stop task can be modeled as a race between a go process, which is triggered by the presentation of the go stimulus, and a stop process, which is triggered by the presentation of a stop signal. The stop signal occurs after a variable delay (stop-signal delays; SSD). If the go process finishes before the stop process then response inhibition is unsuccessful and a response is executed; if the stop process finishes before the go process then the response is correctly withheld. The latency of the stop process (stop-signal reaction time; SSRT) is covert and must be estimated from the independent race model (Logan & Cowan, 1984). This can be done by subtracting mean SSD from the nth RT, with n = the number of RTs in the RT distribution multiplied by the overall p(respond|signal).

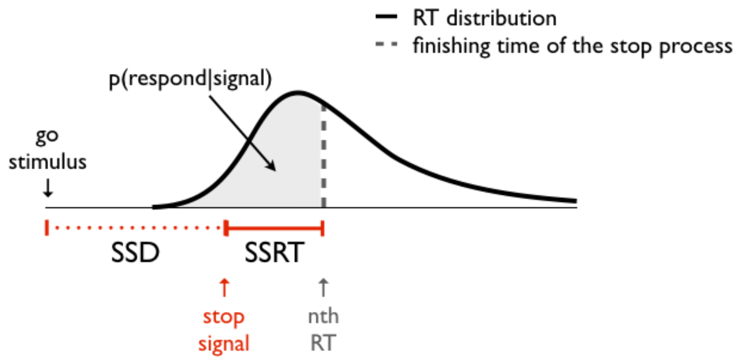


Figure 2. Illustration of the task procedure. Schematic illustration of one trial in the auditory-visual oddball task. In every trial, the participant's task was to indicate which way a cartoon dog was looking (left/right) while ignoring an irrelevant sound presented shortly before.

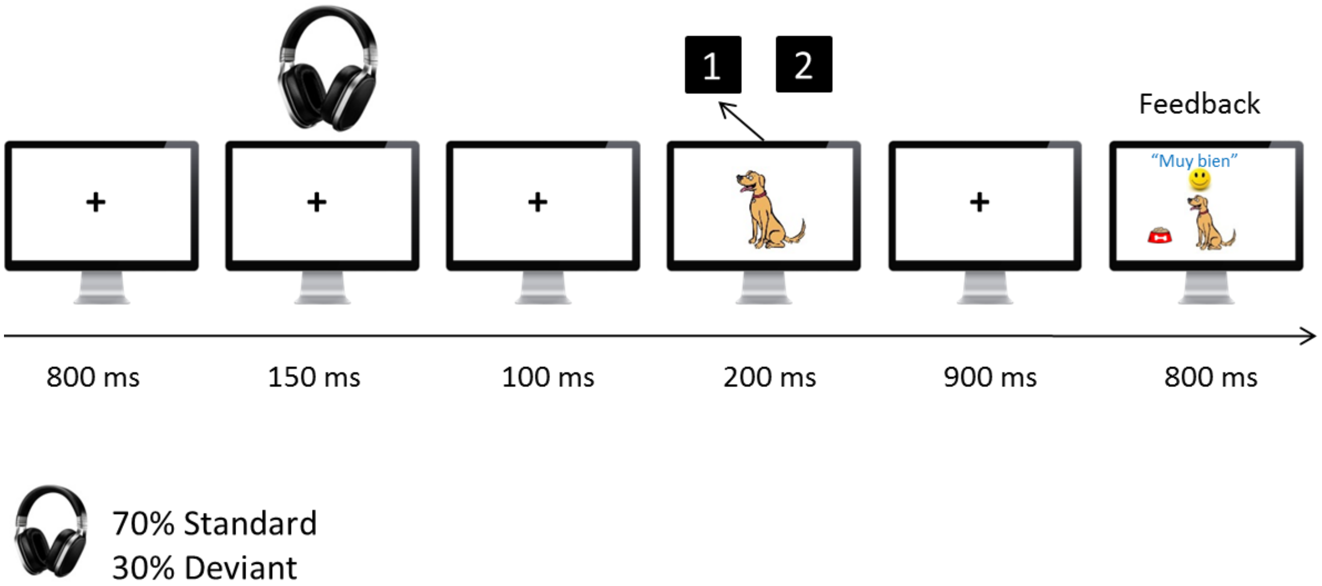
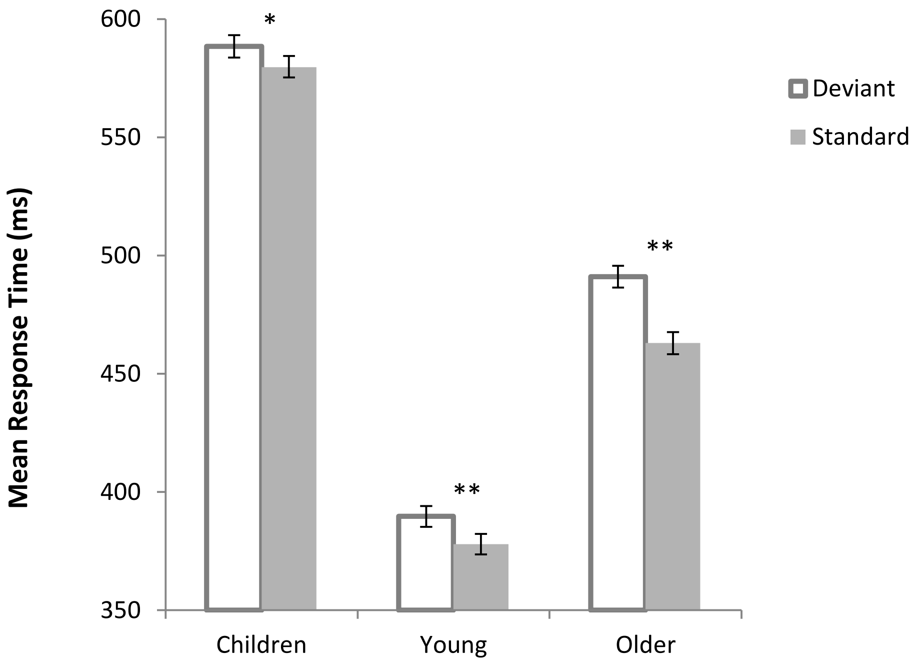


Figure 3. Mean response times for children, young and older adults as a function of the deviance (deviant versus standard). Error bars represent 95% CIs for comparison of within-participant conditions (standard vs deviant) when graphing mixed interactions (Jarmasz & Hollands, 2009). * p < .05, ** p < .001



APPENDIX A: Performance in the Stop-it and Spatial memory tasks

Performance in the Stop-it task

Probability of correct responses on go trials [p(correct)], Probability of missed Go Responses [p(miss)], Average Reaction Time (RT) for Correct Go Responses, Probability of Responding on a Signal Trial [p(resp|signal)], mean time to respond incorrectly in the stop trials (srRT), mean delay between visual and auditory stimuli along all stop signals trials (SSD) for children, young and older adults. P(correct) is the ratio of the number of correct responses to the number of correct and incorrect responses: p(correct) = correct/(correct + incorrect). P(miss) is the ratio of the number of omitted responses to the total number of no-stop-signal trials: p(miss) = missed/(correct + incorrect + missed). Values within brackets represent the standard deviation.

	Children	Young	Older
p(correct)	89.329 (7.247)	92.256 (9.743)	89.940 (8.313)
p(miss)	8.642 (6.961)	7.349 (9.79)	9.827 (8.130)
RT	847.968 (84.117)	804.822 (168.735)	887.190 (123.730)
p(resp|signal)	46.277 (5.155)	44.624 (5.126)	41.240 (3.935)
srRT	751.658 (95.538)	713.842 (170.862)	805.230 (121.057)
SSD	473.742 (154.849)	530.220 (180.863)	611.150 (134.185)

	$F(2,99)$	MSE	p	η^2
p(correct)	1.173	74.513	.314	.02
p(miss)	.740	72.771	.480	.02
RT	3.282	18132,323	.042	.06
p(resp|signal)	8.695	23.206	< .001	.15
srRT	3.837	18854.154	.025	.07
SSD	5.647	25757.153	.005	.10

Performance in the spatial memory condition

Mean spatial memory span (values within brackets represent the standard deviation). Spatial span varied significantly across age groups $F(2,119) = 40.615$, $MSE = 2.006$, $p < .001$, $\eta^2 = .41$.

	Spatial
Children	4.04 (1.39)
Young	6.22 (1.67)
Older	3.63 (1.10)

APPENDIX B: Analysis of data controlling for RTs in the standard condition of the cross-modal oddball task

We re-analyzed the regression and partial correlations using a proportional measure of slowing in the deviant condition: ($RT_{deviant}$ – $RT_{standard}$) / $RT_{standard}$. This measure allowed us to neutralize individual differences in the speed of responses in the standard condition. The results of this analysis replicate those reported in the results section.

<u>Regression</u>

The linear regression analysis included age group, WMC and SSRT as independent variables and distraction [$RT_{deviant}$ - $RT_{standard}$) / $RT_{standard}$] as the dependent variable. Age group explained distraction effect best ($B_{\text{age group}}$ = .027, $t(97) = 4.519$, $p < .001$) but SSRT (B_{SSRT} = 0.000002, $t(97) = .485$, $p = .629$) and WMC (B_{WMC} = -.004, $t(97) = 1.721$, $p = .088$) did not. $R^2 = .222$, $F(3,97) = 9.241$, $p < .001$.

Comparisons of regression models in which we rotated the factors allowed us to determine the percentage of variance uniquely explained by these factors. We found that age group explained 16.4% of the variance of the deviance distraction variable [R^2 change = .164, F(1,97) = 20.418, $p < .001$].

Partial correlations were computed to examine the relationship between WMC, SSRT and deviance distraction within each age group. No correlation was observed between SSRT and deviance distraction in any of the age groups when controlling for WMC: children ($r(27) = .302$, $p = .111$), young adults ($r(38) = -.109$, $p = .502$), and older adults ($r(27) = -.268$, p = .159). Controlling SSRT, WMC and deviance distraction correlated in older adults ($r(27) = -.536$, $p < .01$) and in children ($r(27) = .398$, $p < .05$) but not in young adults ($r(38) = -.131$, $p = .419$).

4. DISCUSSION

In this section I will briefly summarize and discuss the publications included in this dissertation. Because more a detailed discussion of each study is provided within each publication, this section will present an overview.

In *Publication 1*, we aimed to explore deviance distraction across sensory modalities, exploring whether distraction by deviant stimuli may derive from central mechanisms independently of the sensory modalities in which stimuli are presented. Using four experiments in which every target stimulus was preceded by an irrelevant stimulus, we manipulated orthogonally the modality of targets and irrelevant stimuli. The results showed that auditory irrelevant stimuli yielded distraction independently of the target's modality (visual or auditory), while visual deviants only produced distraction under very specific methodological conditions (when participants were forced to attend to the irrelevant visual stimuli and when potential attenuations by factors such as visual masking, spatial cueing of the target stimuli, or the visual distinctiveness of the deviant stimulus were controlled for). These results did not support the notion that deviance distraction involves central a-modal mechanisms but instead that auditory deviant stimuli are especially prone to capture attention and distract participants.

In *Publication 2*, we studied the effect of ageing on deviance distraction within and across sensory modalities. As part of the study, a group of young and older adults performed an oddball task in which irrelevant stimuli were presented auditorily while targets could be presented auditory or visually (in distinct blocks of trials). Distraction was observed in both age groups. Interestingly, an age-related increase in deviance distraction was observed when targets and irrelevant stimuli were presented in different sensory modalities but not when they were presented in the same modality. *Publication 3* confirmed the equivalent levels of deviance distraction when targets and irrelevant stimuli were presented in the auditory modality and extended the investigation to the visual modality using duration discrimination tasks. In these tasks stimuli were presented with rare and unexpected task-irrelevant changes in pitch (in the auditory task) or location (in the visual task). In both tasks, equivalent levels of distraction were observed in young and older adults. Additional analyses using the Bayes factor confirmed the absence of effect of ageing.

In *Publication 4*, we tested two potential accounts of deviance distraction: the "circuit breaker" and the "stimulus detection" accounts. The circuit breaker account (e.g., Corbetta et al., 2008; Corbetta & Shulman, 2002) supports the idea that unexpected but potentially relevant events activate a rapid inhibitory control mechanism that suppresses ongoing or planned responses (response inhibition). The "stimulus detection" account proposes that distraction by unexpected events and response inhibition activates similar neural mechanisms because both require the reorientation of attention and detection of unexpected stimuli (e.g., Hampshire, 2015; Parmentier, 2014; Schröger, 1996), not because deviant sounds trigger response inhibition. In Experiment 1, young participants performed a visual go/no-go task while irrelevant sounds were presented. They were told to ignore irrelevant sounds (novel or standards) presented before each go and no-go stimulus. Compared to standard sounds, novel sounds disrupted performance on go trials and did not facilitate the inhibition of responses in no-go trials, supporting the "stimulus detection" account. In Experiment 2, sounds (novel or standards) were presented simultaneously with visual stimuli and acted as no-go signals. The results showed that the probability of responding to no-go trials was lower for novel sound than for standard sound trials. Both experiments support the stimulus detection account, highlighting the orientation of attention to unexpected events, impairing no-go performance if these events are irrelevant but enhancing no-go performance when they are relevant.

Finally, in *Publication 5* we combined factors explored in our earlier experiments (age, response inhibition) and expanded the study by including WMC and enlarging the age span to include children. Children, young and older adults, performed a cross-modal oddball task, a WM task, and a stop-signal task. The results revealed deviance distraction in all age groups, and showed that older adults exhibited significantly more deviance distraction than children and young adults did (who did not differ from each other). Regression and partial correlation analyses revealed a complex and changing mediation of WMC on deviance distraction in children and older adults (in opposite directions) but not in young adults. Response inhibition did not affect deviance distraction in any of the age groups, in line with the results from young adults in *Publication 4*.

The findings of *Publication 1* support the idea that deviance distraction may be underpinned by mechanisms that are modality-dependent. Auditory deviance distraction was observed in cross-modal and uni-modal conditions, but visual distraction was only observed under specific and restrictive conditions. The results from conditions involving auditory irrelevant stimuli are in line with previous studies using cross-modal or uni-modal tasks in which unexpected auditory stimuli elicited distraction (e.g., same-modal: Berti, 2008; Berti & Schröger, 2001, 2003; Horváth et al., 2009; Horváth et al., 2008; Horváth & Winkler, 2010; Jankowiak & Berti, 2007; Roeber et al., 2003; Schröger & Wolff, 1998; e.g., cross-modal: Andrés et al., 2006; Berti, 2012; Escera et al., 1998; Escera et al., 2002; Parmentier, 2008; Parmentier & Andrés, 2010; Parmentier et al., 2008; Parmentier et al., 2011). Distraction is observed when irrelevant stimuli are auditory, regardless of whether targets are visual or auditory. We observed distraction by sounds in a task in which irrelevant stimuli and targets were temporally and perceptually decoupled. However, this is not a necessary condition for this effect to occur, as indicated by the results of *Publication 3* in which both irrelevant and target stimuli formed part of the same perceptual object, as well as by prior work using auditory oddball tasks (e.g., Berti, 2008; Berti & Schröger, 2003; Schröger & Wolff, 1998). The notion of perceptual object may, however, be more relevant to the visual modality. Indeed, while *Publication 1* revealed no clear effect of visual deviant stimuli when irrelevant and target stimuli were presented as distinct and temporally decoupled stimuli, visual distraction has been observed in other tasks where both target and irrelevant information formed part of the same stimulus object (Bendixen et al., 2010; Berti & Schröger, 2001; 2004; 2006).

As discussed in the *Introduction*, and considering the results from *Publication 1*, it is unlikely that deviance distraction is underpinned by a central a-modal mechanism. Furthermore, Ljungberg and Parmentier (2012) compared cross-modal distraction in auditory-visual and tactile-visual oddball tasks within-participant and found no correlation between auditory and tactile deviance distraction. Finally, some evidence from auditory and visual duration discrimination tasks revealed some differences between auditory and visual deviance distraction with respect to their electrophysiological signatures (Berti & Schröger, 2001), again suggesting that deviance distraction involve modality-specific processes.

In sum, our cognitive system seems to be more vulnerable to distraction when deviant stimuli are presented in the auditory modality than when presented in the visual modality, at least when irrelevant and target stimuli do not form part of the same object. Having established that deviance distraction is not completely underpinned by central mechanisms operating irrespective of modality boundaries, we can go a step further and try to understand why unexpected events presented auditorily affect behavioural performance in functionally similar ways across paradigms while visual events do not. One may speculate that the processing of some stimuli characteristics is not equivalent in audition and in vision. For example, Berti and Schröger (2001) compared visual and auditory distraction using a duration (long vs short) discrimination task and reported stronger distraction in the auditory modality. Furthermore, the two modalities also differed in some aspects of the electrophysiological responses triggered by the deviant stimuli (the RON component was not elicited with long-duration visual stimuli).The authors suggested that the differences observed between visual and auditory distraction could be a result of a superior processing of the temporal information in audition than in vision (see also Bendixen et al., 2010).

Further evidence for the involvement of sensory codes in deviance distraction was also revealed indirectly through the differential effect of old age on distraction. While some studies reported an age-related increase in behavioural deviance distraction (Andrés et al., 2006; Parmentier & Andrés, 2010), others did not (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005). One important difference between these studies is that the former used cross-modal tasks in which the irrelevant stimulus was auditory and the target visual, while the latter used purely auditory tasks in which participants judged one feature of an auditory stimulus while ignoring another. Hence the data suggest that sensory boundaries and shifts across these are one of the factors underpinning behavioural distraction by deviant stimuli in cross-modal oddball tasks, and that old age is especially sensitive to such shifts.

In *Publication 2*, an age-related effect on deviance distraction was observed in the auditory-visual cross-modal task. The results are in line with previous studies using the same task (Andrés et al., 2006; Parmentier & Andrés, 2010). In contrast, an age-related effect on deviance distraction was not observed in the auditory uni-modal task. The results from the uni-modal task conform to previous studies using purely auditory tasks (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005; but see Berti el al., 2013). The uni-modal task used in *Publication 2* differs from past research using purely auditory tasks insofar as it temporally and perceptually decoupled irrelevant and relevant information (in a way similar to the way it is done in cross-modal oddball tasks). This decoupling might however have facilitated the selection of the target stimulus from the distractor and thereby decreased the demand on selection and inhibition processes. This in turn might have reduced the impact of ageing on distraction. In order to examine the potential role of this methodological characteristic, in *Publication 3* participants performed pure auditory (Getzmann et al., 2013; Horváth et al., 2009; Mager et al., 2005; Berti el al., 2013) and visual duration discrimination tasks in which relevant and irrelevant formed part of the same perceptual object. The results were similar to those from Publication 2, however: ageing did not increase deviance distraction in either modality. While the results from the auditory task replicated those from previous studies (Getzmann et al., 2013; Horváth et al., 2009; Leiva et al., 2015; Mager et al., 2005; but see Berti et al., 2013), the generalization of this pattern of results to the visual modality is new and bolsters the conclusion that ageing does not increase deviance distraction in uni-modal oddball tasks. The results from *Publications 2* and *3* point toward a specific effect of ageing on the shift between sensory boundaries. In doing so, the results also reinforce the conclusions that deviance distraction is not a modality-independent phenomenon (*Publication 1*).

The finding that old age increases cross-modal distraction by deviant stimuli and not uni-modal distraction contradicts Guerreiro et al.'s (2010) recent claim that age specifically affects uni-modal distraction. This conclusion is based on a review of 150 papers including tasks such as Simon tasks (e.g., Bialystok et al., 2004; Bialystok et al., 2008; Pick & Proctor, 1999; Vu & Proctor, 2008), Stroop tasks (e.g., Borella et al., 2009; Hartman & Hasher, 1991; Salthouse, Atkinson, & Berish, 2003; Verhaeghen, 1999) and Flanker tasks (e.g., Colcombe, Kramer, Erickson, & Scalf, 2005; Maylor & Lavie, 1998, Experiment 1; Zeef & Kok, 1993; Zeef et al., 1996) among other tasks. The apparent discrepancy between their conclusions and ours may potentially have resulted from a semantic confusion between two rather distinct types of distraction: deviance distraction and crosstalk interference. Crosstalk interference refers to the detrimental effect of irrelevant stimuli that elicit strong automatic activations competing with target processing (e.g., Flanker task: Maylor & Lavie, 1998; Colcombe et al., 2005; Samanez-Larkin, Robertson, Mikels, Carstensen, & Gotlib, 2009). In crosstalk interference studies, when target and irrelevant stimuli share the same modality, selection of the first and inhibition of the latter require greater attentional control, which may explain why such type of distraction increases with age. In these tasks, modality separation between target and irrelevant stimuli may facilitate the selection of the target against the irrelevant stimulus. When both elicit competing activations through the same input channels, the overlap between target and irrelevant stimuli is greater, competition is stronger, and high-order mechanisms exerting top-down control may be required. In such circumstances, ageing increases distraction. Deviance distraction is functionally distinct from crosstalk interference. Indeed, in the oddball task the selection of the target must not be made against the processing of the irrelevant stimulus because the two do not compete for action and therefore inhibition of competing responses need not be carried out. Instead, distraction in this case is thought to reflect the time penalty associated with the involuntary orientation of attention to and from the irrelevant stimulus (Parmentier et al., 2008). We would hypothesize that the reorientation of attention across modality boundaries may be more demanding. Thus, ageing may lead to increased distraction in cross-modal oddball tasks (but not in same-modality), because the pool of attentional resources available for the reorientation process is reduced in old age. An alternative explanation may be that the reorientation of attention across modalities may be slower in older adults. It may also be that cross-modal attentional shifts engage frontal networks, which have been shown to demonstrate accelerated deterioration in old age (e.g., Raz, 2000; West, 1996). Andrés et al. (2008), for example, suggested that tasks or conditions requiring a higher inhibitory control (inhibitory processes supported by the frontal cortex) are more sensitive to ageing than tasks requiring more automatic control (involving more posterior areas).

Ageing might also affect the shifts of attention between spatial locations highlighted by Parmentier et al. (2008) as one of the potential contributors to deviance distraction in the cross-modal oddball task. Some recent data by Getzmann, Falkenstein and Washer (2015) support the notion that older adults are slower in shifting their attention across spatial locations. Using an oddball task in which auditory deviance was defined spatially, these authors found a delayed attention capture and reorienting of attention (P3a and RON) to the relevant task in older adults relative to younger adults.

One additional factor to take into account to interpret the effect of old age on deviance distraction is the potential involvement of compensatory mechanisms used by older adults in order to preserve performance. Some authors proposed that older adults use compensatory mechanisms in the form of neural overactivation of certain areas (especially frontal, e.g., Cabeza et al., 2004) or a bi-lateralization of activity (e.g., Cabeza, 2002) to maintain levels of behavioural performance equivalent to that of young adults (e.g., Reuter-Lorenz & Lustig, 2005). Reuter-Lorenz and Cappell (2008) argued that neural compensation can occur in relatively low-demand tasks but is not sufficient to mask deficits when tasks are more demanding. We cannot rule out the possibility that compensatory mechanisms may have been at play in our studies. However, such notion would not by any means provide a clear explanation of our data, for it would require that such compensation be specific to, or significantly greater for, same-modality tasks than for cross-modal tasks. This seems unlikely. Furthermore, compensatory models that propose neural overactivation in older adults do not match existing electrophysiological work on deviance distraction which show a decrease in activity (in MMN amplitude: Berti et al., 2013; in P3a amplitude: Getzmann et al., 2013; in RON: Mager et al., 2005; Getzmann et al., 2013), not an increase.

The findings from *Publication 4* show that deviance distraction is not simply a manifestation of response inhibition. Indeed, contrary to the "circuit breaker" account (Aron et al., 2014; Corbetta et al., 2008; Corbetta & Shulman, 2002; Wessel & Aron, 2013; Wiecki & Frank, 2013), deviant sounds did not facilitate the inhibition of responses in a stop-signal task unless they themselves constituted the stop signals. These results support the "stimulus detection" account and are in line with recent work proposing that response inhibition and other forms of action control require both attentional and response selection (Verbruggen, McLaren, & Chambers, 2014). Verbruggen et al. (2014) proposed that action control in ever-changing environments can be broken down into the basic mechanisms of signal detection, action selection and action execution. At each of these stages, multiple sources of input compete for selection. Thus, when unexpected stimuli are presented, processing of other stimuli will be suppressed, leading to a performance cost when the novel stimuli are task-irrelevant (Experiment 1) and a performance benefit when they are task-relevant (Experiment 2).

Publication 5 confirmed the absence of a connection between deviance distraction and response inhibition (in line with *Publication 4*), and extended this observation beyond young adults by reporting similar findings in children and older adults. However, *Publication 5* went further by exploring the possible involvement of age-related difference in WMC in explaining the variation of deviance distraction across age groups. The results showed a positive correlation between WMC and deviance distraction in children, a negative one in older adults, and no correlation in young adults. The lack of correlation between WMC and deviance distraction in young adults, contrasts with the findings of Sörqvist and colleagues (Sörqvist, 2010; Sörqvist et al., 2012). One possibility for this discrepancy may lie with the use of different tasks to measure WMC (we adopted the verbal-spatial task used by Hale and collaborators while

Sörqvist and collaborators used the OSPAN task). However the task used to measure WMC is unlikely to be a determinant factor since Röer, Bell, Marsh, and Buchner (2015) used the OSPAN task and found no correlation between deviance distraction and WMC either. The negative correlation between WMC and deviance distraction in older adults, indicates that the ageing-related declines in WMC and interference control are related and that WM is involved in attentional capture. More specifically, the reorientation of attention following its automatic capture by the task-irrelevant sound and the reactivation of the relevant task-set when the task-relevant target appears may be underpinned by WM processes (e.g., Hölig & Berti, 2010; Munka & Berti, 2006). In contrast to older participants, children exhibited a positive relationship between WMC and deviance distraction in children. It is possible that this is linked to proactive control. It is possible that young children with a higher WMC were more likely to exert proactive control by using the sounds as warning signals (e.g., Parmentier, Elsley et al., 2010). This could have made them more vulnerable to distraction by the deviant sound (see Blackwell & Munakata, 2014, for evidence of a tradeoff between proactive control and distraction in children). In any case, what our findings suggest is that the relationship between WMC and deviance distraction must be one evolving in complex ways across age.

5. CONCLUSIONS

This thesis set out to improve our understanding of deviance distraction by examining the impact of a number of factors. Starting with an examination of the role of sensory modality (*Publication 1*), we found that auditory deviant stimuli (but not visual ones) yielded significant behavioral distraction in an ongoing task (visual or auditory). We therefore selected auditory distractors as our focus when proceeding to study the effect of aging on distraction. Across three studies (*Publications 2, 3 & 5*) we demonstrated that ageing increases distraction by deviant sounds when targets are visual but not when they are auditory, irrespective of whether irrelevant and relevant stimuli formed part of the same perceptual object or not. Our research then progressed to examine whether factors recently proposed to relate to deviance distraction, namely response inhibition (*Publication 4*) and WMC (*Publication 5*), may indeed explain the impact of deviant sound on ongoing performance in a visual task and its variation across the life span.

The main contributions of this dissertation can be summarized as follows:

(1) Deviance distraction should not be construed as an a-modal effect but, instead, a modality-dependent effect.

(2) Older adults exhibit greater deviance distraction across modalities but not within modalities.

(3) Deviance distraction does not reflect a temporary inhibition of responses.

(4) There is no clear link between WMC and deviance distraction when studied across age groups (children, young and older adults).

While leading to the publication of five peer-reviewed articles in international journals, the work presented in this thesis only constitutes one step in the investigation of the mechanisms underpinning distraction by unexpected stimuli. In some measure, the work presented here allows firmer conclusions than previously possible. This is especially the case regarding the selective effect of old age on cross-modal deviance distraction. It is also clear from our results that response inhibition does not account for deviance distraction. In other respects, this thesis opens new questions that will require future work. For example, the potential role of working memory capacity remains somewhat murky. Indeed, while working memory capacity did not account for deviance distraction across age groups, the two measures correlated in opposite direction in children (positive) and in older adults (negative). It is currently unclear how this should be interpreted.

We hope that this thesis will encourage further research in the field. Future work may for example seek to improve on some aspects of the work presented here. For instance, the study of distraction across the life span could be expanded by including more age groups or collecting data from a larger sample and treating age as a numerical predictor instead of a categorical one. Perhaps the most prominent issue relates to the specific effect of ageing on cross-modal deviance distraction, however. We put forward the hypothesis that such effect may reflect the slower orientation of attention across sensory modalities in older adults, or that such shifts may require greater attentional control, perhaps relying on more frontal areas (which are known to be especially affected in old age). Such propositions are speculative, however. Future work could include the measuring of cross-modal attentional shifts in the absence of deviant, for example by requiring participants to judge visual and auditory stimuli presented in a random manner in order to measure the cost of switching between modalities. If deviant sounds yield greater distraction in older adults because the latter experience greater difficulty in switching attention between modalities, then a correlation should be observed between deviance distraction and an independent measure of the modality switch cost. Future experiments could also test the proposition that the nature of the shift induced by deviant sounds in a visual task may not be so much related to the sensory modality *per se* but to spatial locations. For example, it is possible that deviant sounds may force a spatial shift of attention from the location of the expected visual target (centre of the screen) to the virtual location of the deviant sound's source (middle of the participant's head when sounds are presented binaurally through headphones). This could for example be explored by varying the spatial distance between the irrelevant sounds and the visual targets using carefully placed loudspeakers. If older adults experience greater difficulty (or take longer) to shift their attention from one location to another, then the effect of ageing should be expected to increase with the distance between the locations of the deviant sound and the visual target.

With respect to the relationship between WMC and deviance distraction, future work could take two forms. On the one hand, more effort should be devoted to understand the mechanistic way in which WMC and deviance distraction could possibly be related. In particular, WMC typically reflects not only a greater storage capacity but also typically correlates with greater attentional control and inhibition. Hence it may be that the results will depend in part on the task being used to measure WMC and the extent to which it taps the two components. On the other hand, future research should seek to study the possibility of an evolving relationship between WMC and deviance distraction. That is, rather than seeking to establish whether the first can account for the latter (an unlikely notion), researchers may wish to explore the extent to which participants of different ages may approach the oddball task differently, perhaps capitalizing on different strategies depending on their aptitudes. We note for example that in *Publication 5* children and young adults exhibited similar levels of deviance distraction, that children displayed a lower WMC than young adults and, interestingly, that WMC and deviance distraction correlated positively in children only. This suggests that children may have invoked mechanisms distinct from those applied by young adults in the oddball task.

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