9-2019

The Interaction of Attention and Memory on the Reorienting Negativity

John C. Moses

The Graduate Center, City University of New York

How does access to this work benefit you? Let us know!

Follow this and additional works at: https://academicworks.cuny.edu/gc_etds

Part of the Cognitive Neuroscience Commons, and the Cognitive Psychology Commons

Recommended Citation

https://academicworks.cuny.edu/gc_etds/3371

This Dissertation is brought to you by CUNY Academic Works. It has been accepted for inclusion in All Dissertations, Theses, and Capstone Projects by an authorized administrator of CUNY Academic Works. For more information, please contact deposit@gc.cuny.edu.
THE INTERACTION OF ATTENTION AND MEMORY ON THE REORIENTING NEGATIVITY

by

JOHN C. MOSES, M.A.

A dissertation submitted to the Graduate Faculty in Psychology in partial fulfillment of the requirements for the degree of Doctor of Philosophy, The City University of New York

2019
The Interaction of Attention and Memory on the Reorienting Negativity

by

John C. Moses

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

Date

Robert Melara, Ph. D.
Chair of Examining Committee

Date

Richard Bodnar, Ph. D.
Executive Officer

Supervisory Committee:

Timothy Ellmore, Ph. D.
Matthew Hoptman, Ph. D.
Brett Silverstein, Ph. D.
Vivien Tartter, Ph. D.

THE CITY UNIVERSITY OF NEW YORK
ABSTRACT

The Interaction of Attention and Memory on the Reorienting Negativity

by

John C. Moses

Advisor: Robert Melara, Ph. D.

The three-stage model of distraction asserts that when we are presented with salient but task-irrelevant information, our sensory systems first detect the distracting stimulus by way of sensory memory buffers, which is indicated electrophysiologically by the mismatch negativity (MMN). Following detection, attentional resources are involuntarily allocated towards the processing of the distraction, as represented by the P3a. Finally, attentional resources are shifted away from the distracting stimulus and returned to the task-relevant information, as indicated by the reorienting negativity (RON). A great deal of research has focused on this last step in the model, largely centering around defining the mechanisms that modulate and produce the RON. From the previous research it has become clear that both attentional and working memory mechanisms play a role in the production of the RON. Research also suggests that these processes are represented in individual subcomponents of the RON. The current set of studies presented here sought to unpack how these two mechanisms work together to create the RON and allow for successful reorientation.

Study 1 investigated this relationship through a comparison of younger adults with older adults, a group known to have difficulties with both working memory and attention, on a modified auditory oddball task. Overall, the older adults were both less accurate and slower to respond to stimuli; however, they showed no sign of increased distractibility. This behavioral
difference was accompanied with smaller peak RON amplitudes for the older adults.

Interestingly, the correlation between the latency of the RON and behavioral success differed in direction between the two age groups, suggesting a central difference in the way the RON produces reorientation. Study 2 expanded on this relationship by separately manipulating both attention and working memory within an oddball paradigm. Results indicated that the specific interactions between the two RON mechanisms are more complex than previous research has suggested. In general, the results demonstrate that, in certain circumstances, participants switch from a greater reliance on working memory mechanisms to dependence on attentional processes and vice versa. This is evidenced by unexpected increases and decreases in the amplitude of the RON as well as opposing correlations found between RON amplitude and accuracy. On the whole, these two studies confirm that both attentional and working memory manipulations modulate the RON. However, the current studies also suggest that these processes both individually as well as interactively produce the RON and that the separation of the two mechanisms is not as strongly defined by the subcomponent of the RON as has been suggested in previous research.
Throughout the writing of this dissertation I have relied on the expertise and guidance of my advisor, Dr. Robert Melara; his support has been greatly appreciated. As well, I would like to acknowledge my family and friends for their constant encouragement throughout this project. Finally, I would like to thank my partner for her continued support and love, which has made this project possible.
# TABLE OF CONTENTS

- **Introduction** .................................................................................................................. 1
- **Background** .................................................................................................................... 2
- **General Characteristics of the RON** .............................................................................. 4
  - **Scalp Topography** ......................................................................................................... 4
  - **Subcomponents** ............................................................................................................ 7
- **Relationship to other ERPs** ............................................................................................ 10
- **Population Characteristics** ............................................................................................. 14
  - **RON in Special Populations** ......................................................................................... 14
  - **RON Across the Lifespan** ............................................................................................. 17
- **Underlying Mechanisms** ................................................................................................ 21
  - **Deviance Strength** ........................................................................................................ 22
  - **Working Memory** .......................................................................................................... 23
  - **Predictive Cues** ............................................................................................................ 25
- **RON Paradigm** ................................................................................................................. 28
  - **Stimuli** .......................................................................................................................... 28
  - **Standard After a Deviant** ............................................................................................. 34
- **Brain Behavior Relationship** ........................................................................................... 37
- **Study 1** ............................................................................................................................ 39
- **Introduction** ..................................................................................................................... 39
Aim 1: Methodology ................................................................. 39

Aim 2: Expand on Previous Research ........................................ 40

Methods .................................................................................. 42

Participants ............................................................................. 42

Stimuli and Procedures ............................................................ 42

EEG Recording ........................................................................ 44

Data Analysis ........................................................................... 44

Statistical Analyses ................................................................. 45

Results ..................................................................................... 46

Behavioral ............................................................................... 46

Distraction ERPs ..................................................................... 47

Correlations ............................................................................ 48

Discussion ............................................................................... 49

Age Effect ............................................................................... 49

Brain/Behavior ....................................................................... 51

Three Stage Model ................................................................. 53

Post-Deviance RON ................................................................. 54

Study 2 ..................................................................................... 55

Introduction ............................................................................. 55

Aim1: Multiple mechanisms .................................................... 56
Interaction of Attention and Memory on RON

Aim 2: Peak Voltage Correlation ................................................................. 57

Methods ............................................................................................................. 58

Participants ........................................................................................................ 58

Stimuli and Procedures ..................................................................................... 58

EEG Recording .................................................................................................. 59

Data Analysis ...................................................................................................... 59

Statistical Analyses ........................................................................................... 60

Results .................................................................................................................. 62

Behavioral .......................................................................................................... 62

Distraction ERPs ............................................................................................... 63

Correlations ........................................................................................................ 64

Discussion ........................................................................................................... 65

Behavioral Distraction ....................................................................................... 65

Deviance Strength .............................................................................................. 66

Working Memory ............................................................................................... 69

Brain/Behavior ................................................................................................. 70

General Discussion ............................................................................................ 71

Multiple Mechanisms ....................................................................................... 72

Brain/Behavior ................................................................................................. 74

Limitations ......................................................................................................... 75
Interaction of Attention and Memory on RON

Tables ...........................................................................................................................................77

Figures ........................................................................................................................................82

References .....................................................................................................................................109
LIST OF TABLES

Table 1. Study 1 Stimuli Values ............................................................................................................77
Table 2. Significant ANOVA Effects for Behavior ..............................................................................77
Table 3. Significant ANOVA Effects for Voltage in Deviant minus Standard-Before ............78
Table 4. Significant ANOVA Effects for Latency in Deviant minus Standard-Before .............78
Table 5. Significant ANOVA Effects for Latency in Standard-After minus Standard-Before..78
Table 6. Significant Correlations Between RON Latency in Deviant minus Standard-Before and Reaction Time ........................................................................................................78
Table 7. Study 2 Stimuli Values ........................................................................................................79
Table 8. Significant ANOVA Effects for Behavior ..............................................................................80
Table 9. Significant ANOVA Effects for Behavior with Congruency ..............................................80
Table 10. Significant ANOVA Effects for Voltage in Deviant minus Standard-Before ..........80
Table 11. Significant ANOVA Effects for Voltage with Congruency in Deviant minus Standard-Before ..................................................................................................................81
Table 12. Significant ANOVA Effects for Voltage in Standard-After minus Standard-Before .81
Table 13. Significant Correlations Between RON Voltage in Incongruent minus Standard-Before and Standard-After Accuracy ..........................................................................................81
Table 14. Significant Correlations Between RON Voltage in Congruent minus Standard-Before and Standard-After Reaction Time ......................................................................................81
LIST OF FIGURES

Figure 1. Study 1 Pitch Task Design ................................................................. 82
Figure 2. 160 Channel ABC Montage ............................................................... 83
Figure 3. RON-Timing Justification ................................................................. 84
Figure 4. Young/Old Accuracy ........................................................................ 85
Figure 5. Young/Old Reaction Time ................................................................. 86
Figure 6. Reaction Time: Trial-Type X Age X RON-Timing Interaction .............. 87
Figure 7. Reaction Time: Trial-Type X Age Interaction for Reaction Time in Late Producers ... 88
Figure 8. Deviant minus Standard-Before Grand Average Difference Waves .......... 89
Figure 9. Topographic Voltage Maps at RON Peak ........................................... 90
Figure 10. Deviant minus Standard-Before MMN Peak Voltage: Age Effect .......... 91
Figure 11. Deviant minus Standard-Before P3a Peak Voltage: Age Effect .......... 92
Figure 12. Deviant minus Standard-Before RON Peak Voltage: Age Effect .......... 93
Figure 13. Standard-After minus Standard-Before Grand Average Difference Waves .... 94
Figure 14. Standard-After minus Standard-Before RON Latency: Age X RON-Timing Interaction 95
Figure 15. Deviant Reaction-Time X RON Latency Correlation for Young .......... 96
Figure 16. Standard-After Reaction-Time X RON Latency Correlation for Young .......... 97
Figure 17. Standard-After Reaction-Time X RON Latency Correlation for Old .......... 98
Figure 18. Standard-Before Reaction-Time X RON Latency Correlation for Old .......... 99
Figure 19. Example of Early and Late RON Peaks in Perfect/High Condition .......... 100
Figure 20. Deviant minus Standard-Before Grand Average Waveforms ........................................ 101
Figure 21. Accuracy: Trial-Type X Imbalance X Distraction Interaction ........................................ 102
Figure 22. Reaction-Time by Trial-Type: Trial-Type X Imbalance X Distraction Interaction .......... 103
Figure 23. Reaction Time: Imbalance X Congruency Interaction .................................................. 104
Figure 24. Deviant minus Standard-Before MMN Voltage: Imbalance Effect ............................... 105
Figure 25. Deviant minus Standard-Before Early-RON Voltage: Distraction Effect .................... 106
Figure 26. Deviant minus Standard-Before Early-RON Voltage: Imbalance X Congruency Interaction .......................................................... 107
Figure 27. Standard-After minus Standard-Before Late-RON Voltage: Imbalance X Distraction Interaction ........................................................................ 108
Introduction

Our sensory systems gather an amazing amount of information from the surrounding environment. While we are unable to process all this information, we are able to very expertly select specific information within the stream for further processing. Despite this ability, certain stimuli are able to steal our attention, distracting us from whatever task we are attempting to complete at the moment. Titchener (1924) describes this reflexive type of attention as “an attention that we are compelled to give and are powerless to prevent” (p. 268). The mechanisms, stimuli, and neural correlates of distraction have a long history of study, but only relatively recently have researchers begun to investigate the process of recovering from distraction such that we can continue and complete the previous task. One possible brain signature of this process of recovery is the reorienting negativity (RON).

The current set of studies seeks to clarify a generally overlooked aspect of the RON, namely, its specific connection to behavior. The most reliable indicator that distraction has occurred in an experimental setting is a decrease in accuracy and an increase in response time. Behavioral recovery is seen as the return of these behavioral measures to pre-distraction levels. Questions remain, however, about whether the underlying neural processes of the RON play a part in this behavioral recovery and, if so, in what direction that relationship exists. Beyond this question of whether a connection exists, the behavioral correlation allows us to investigate the specific contributions of the various cognitive mechanisms that have been shown to affect the RON to behavioral success. The current studies further aim to explore the interactions that might exist between the multiple mechanisms related to the RON, namely attention and working memory. Much of the previous research, as will be described below, has focused on the
individual mechanisms related to the RON. However, very little work has been undertaken to examine the ways in which the mechanisms might combine or separate to form specific patterns of processing.

Background

Prior to the discovery of the RON, a great deal of research into the mechanisms of distraction employed a variant of the so-called oddball task. In the classic version of this task, a stream of stimuli is presented in quick succession to a participant. Infrequently, a deviant or novel stimulus is presented, breaking the pattern of standard stimuli. An example of this classic version of the task might be a simple shape discrimination task, in which a participant must respond to whether a shape is a circle or a triangle, with the circle being presented 95% of the time.

Distraction research often implements a variant of this design in which task-relevant and task-irrelevant stimuli are embedded in different objects or modalities. An example of this type of research would be a study in which participants discriminate visual stimuli, such as shapes, being presented equiprobably. Preceding each visual presentation, an auditory stimulus is presented. This auditory stimulus is either a high-probability standard sound or a low-probability deviant (i.e., change in pitch) or novel sound (e.g., dog barking). The presentation of the deviant or novel sound reliably produces distraction as seen in decreased accuracy and increased reaction time to the visual stimulus. However, distraction often depends on the deviant sound involving a large difference from the standard.

While this paradigm was successful in producing distraction, Schröger and Wolff (1998b) note that it presents a major difficulty to research into distraction, in that it is unable to separate the different possible mechanisms underlying the distraction process. According to the authors,
the first of these mechanisms might be a so-called ‘new-afferent-elements-activation’ mechanism. This mechanism, theoretically, detects the differential refractoriness of brain structures responding to the task-relevant and the task-irrelevant stimuli. This mechanism depends on the deviant stimulus being very different from the standard, such that different structures respond to the stimuli. The second mechanism is described as a purely memory-related mechanism, which detects a change, or mismatch, from a regularly occurring standard and a deviant. This mechanism relies on the standard being presented with a high probability in the stream of sounds, such that a memory trace can be formed. The authors argue that in order to study the memory mechanism separately from other mechanisms, a paradigm must be able to produce distraction with small variations between the standard and the deviant.

In order to deal with the shortcomings of earlier paradigms, Schröger and Wolff (1998b) developed another modification of this methodology in which task-relevant and task-irrelevant features are integrated into the same stimulus. In its first implementation, a participant was presented with a stream of tones each consisting of either a long or short duration, discriminating between the two with a button press. The large majority of these tones had a standard frequency; however, infrequently, the pitch changed to produce a completely task-irrelevant variation. The study itself consisted of three conditions that varied the degree of difference between standard and deviant frequency (small: 50 Hz, medium: 200 Hz, large: 500 Hz). As opposed to traditional paradigms, even the small change condition produced reliable distraction, giving credence to the memory-based mechanism hypothesis. The researchers also derived a difference brain wave between the event-related potentials (ERPs) time-locked separately to the standard and the deviant stimuli. They found that, in addition to the behavioral distraction, distraction-dependent changes appeared in both the MMN and P3a ERP components, two notable distraction-related
brain mechanisms that will be discussed in more detail later in this review. Moreover, the researchers identified in the same difference wave a late negativity occurring subsequent to the P3a.

In a follow-up study investigating this late negativity, Schröger and Wolff (1998a) followed the same procedure but varied the task-relevancy of the stimuli. The distraction condition exactly followed the methodology above. In the attend condition, participants responded to whether the tone was a standard or a deviant, making the deviants task-relevant. In the ignore condition, participants simply read a book of their own choosing while ignoring the sounds. Both the distraction and attend conditions produced longer reaction times to the deviant trials than to the standards, indicating distraction was produced in both conditions. Electrophysiologically, all three conditions produced the MMN and the distraction and attend conditions produced a subsequent P3a. Yet only the distraction condition produced a late negativity approximately 400-600 ms following the stimulus, which they termed the reorienting negativity (RON). The distraction condition was the only condition in which both task-relevant and task-irrelevant features appeared. For behavioral success in the distraction condition, participants must be able to reallocate attention back towards the task, after the task-irrelevant feature has captured attention. Given this logic, the researchers hypothesized that late ERP negativity reflects reorientation back towards a task following distraction.

**General Characteristics of the RON**

**Scalp Topography.** The RON, in general terms, is a voltage change that is measured with an electroencephalogram (EEG). EEG is a noninvasive technique involving the placement of electrodes on the scalp to measure indirectly the voltage and timing of ionic current within the brain. Several different types of analyses can be performed on the voltage data from EEG. For
example, voltage data can be time-locked to stimuli from individual trials and then averaged. Averaging cancels out all of the random and irrelevant voltage fluctuations and leaves behind only the voltage information produced in response to the stimulus. The data can be further broken down into specific positive and negative peaks, known as event-related potentials (ERPs), within each trial-type. The RON itself involves an additional calculation because it appears within the difference wave of two different types of trials. This difference calculation allows us to determine the voltage change that occurs from one type of stimulus to another. In the case of the RON, we are able to see the difference in voltage that occurs from the standard to the deviant, giving us insight into the brain’s response to distraction and subsequent reallocation of attention.

The RON is centralized primarily over frontal EEG sites (Correa-Jaraba, Cid-Fernández, Lindín, & Díaz, 2016; Escera, Yago, & Alho, 2001), peaking anywhere between 300-750 ms after stimulus onset (Getzmann, Falkenstein, & Wascher, 2015; Munka & Berti, 2006). Given that this negativity has such a large latency window, researchers have employed two different techniques for defining its voltage and latency. The first of these is simply finding the local maximal negativity within the given time window, as Schröger and Wolff (1998a) did in the initial description of the RON. In an attempt to deal with the fact that the RON is generally less sharply defined than many other ERPs, some researchers have applied a method in which they first identify the peak of the negativity within the grand average. They then average the voltage of the individual waves within a 20-100 ms window centered on the peak latency in the grand average (Berti, Grunwald, & Schröger, 2013; Horváth & Bendixen, 2012). This method allows for an easily attainable measurement of the voltage of RON, but does permit analyses of peak latency. Latency information, as will be described later in this review, has been shown to be
malleable based on different circumstances. Thus, the latter method fails to fully describe the RON. However, this method does give a sense of the prolonged nature of the RON, with its time-course occurring over an extended period of time.

In a singular study of its kind, Horváth, Maess, Berti, and Schröger (2008) attempted to localize the RON to specific areas of the brain. The researchers performed a duration discrimination task with deviant pitch with concurrent magnetoencephalography (MEG) measurements. This method, much like EEG, involves the measurement of brain activity on the scalp. However, while EEG measures the electrical fields, MEG measures the magnetic fields produced by the underlying electrical activity. The process of localizing source activity, for both MEG and EEG, involves the modeling of possible sources of activity based on a priori hypotheses and known models of the tissue and bone that comprise the head and brain. MEG is often the preferred method to perform localization, as magnetic fields are less distorted by tissue; however, they are somewhat less precise because MEG can only measure fields that are tangential to the actual current density, limiting MEG to localizing activity that originates in the sulci of the brain. Although there is no MEG equivalent to the RON, as is the case with many ERPs, the researchers defined activity occurring during the classic RON time window (400-600 ms). From this analysis, the researchers identified two neighboring dipoles at the left precentral sulcus. However, these dipoles were both frontal facing, meaning that they would have produced positive electrical activity over frontal EEG sites, disqualifying them as sources of the RON. Since this activity occurs at the same time as the RON and under the same conditions as the RON, the researchers hypothesized that these dipoles might represent some other aspect of the reorienting process. The precentral sulcus is within the primary motor cortex so activity here might denote some motor preparatory process associated with reorientation that has otherwise
not been identified with EEG techniques. While this is a somewhat disappointing outcome, these results are indicative of the complex nature of the reorienting process, with the RON indicating only a portion of the overall process.

In an alternative description of the underlying neural processes of the RON, Schröger, Giard, and Wolff (2000), shortly following the initial description, performed an auditory duration discrimination task with deviant frequency changes. The results were as expected, with the appearance of an MMN, P3a, and subsequent RON. However, the researchers also performed a scalp current density analysis (SCD) of the RON. This type of analysis measures the distributions of scalp current densities, the current that is tangential to the current lines produced by neural dipoles. From this type of measurement, it is possible to distinguish between separate neural generators within the brain from scalp voltage measurements. The researchers identified two distinct current distributions at early and late latencies of the RON. Specifically, the researchers found that the distributions were significantly different at the maximal current amplitude, occurring at 375-400 ms, as compared to the peak latency, occurring at approximately 500 ms, for the RON. Based on these two separate density patterns, the researchers hypothesized that the RON is produced from multiple generators both located in frontal areas, which together produce the reorienting process.

Subcomponents. In line with the evidence of multiple neural generators, several researchers have suggested that the RON actually consists of two distinct subcomponents (Berti, 2008, 2013; Escera et al., 2001; Munka & Berti, 2006). In the first study to identify the proposed early and late phases of the RON, researchers employed a multi-modal oddball task, separating the task-relevant and task-irrelevant features into different modalities (Escera et al., 2001). In doing so, Escera et al. (2001) were able to vary the asynchrony between the task-relevant (visual)
and the task-irrelevant (auditory) stimuli. In the short asynchrony condition, the previously defined RON was found between 580-695 ms; however, with a longer asynchrony, an additional smaller and earlier negative peak appeared at approximately 450 ms. Both the early and later negative peaks occurred over frontal cortex. The late phase was also shown to vary by the distractor type, with more behaviorally distracting novel auditory deviants producing larger amplitude. This finding seems to support the hypothesis that the RON, at least in its late phase, represents an attempt by the system to reorient after momentary distraction, with greater distraction producing a larger Late-RON. The researchers hypothesized that the early phase could possibly indicate a preparatory mechanism. SCD analyses revealed that the early phase of the RON reflected a neural population distinct from the late phase. The researchers speculated that the early phase was hidden in the short asynchrony condition, overlapping with the late phase due to the quick nature of the condition.

In an attempt to further characterize these subcomponents, Munka and Berti (2006) performed a similar audio-visual study while also varying the characteristics of the visual component. The visual stimuli consisted of numbers that were judged semantically (odd or even) or physically (size or color). The visual stimuli were preceded by either a standard or deviant frequency tone. Interestingly, both conditions produced a Late-RON, peaking 650-750 ms after stimulus onset; however, the semantic condition also produced an early phase, with a latency between 530-650 ms. The fact that only the semantic condition produced the early phase suggests that this component might reflect working memory processing, while the late phase relates to a more general attentional mechanism allowing for reorientation back to the original task.
Given that the foregoing studies employed a multi-modal design, it is conceivable that these subcomponents are merely an artifact of different types of perceptual processing. However, Berti (2008) provided evidence against this conclusion. In his study, participants performed an auditory duration discrimination task with infrequent deviant pitch changes. In the refocus condition, participants were instructed to respond to every stimulus, while in the reorient condition participants were instructed to ignore deviant stimuli and omit their response. The researcher argued that the refocus condition requires a fast switch to task-relevant information, whereas the reorient condition requires a more general preparatory mechanism for the upcoming trial following the deviant. In support of this theory, Berti noted that the refocus condition resulted in a negativity peaking at around 500 ms over frontocentral sites, whereas the reorient condition resulted in a negativity peaking around 700 ms over parieto-central sites, reflecting the early and late phases of the RON from earlier studies. Berti concluded that the early phase reflects a task specific refocusing while the late describes a more general allocation of attention.

While these studies make a compelling argument for redefining the RON as actually consisting of an early and late phase, it is important to note that this distinction is reported in only a small selection of studies. This might be due to a general overlapping of the two subcomponents as suggested by Escera et al. (2001). Additionally, all of these studies defined the RON by averaging the amplitude over the given time windows, calculated on the basis of visual inspection of grand averages, rather than defining specific peaks within each individual wave. While this is a common practice, as discussed previously, the fact that these two phases overlap between the studies, with the early phase occurring anywhere from 400 ms to 650 ms after onset and the late phase between 580 ms and 750 ms, warrants further investigation of specific subcomponent latencies. The researchers most likely employed this method of
averaging amplitudes over the time window as a way of dealing with the general variability that is inherent in difference wave calculations. Even if specific early and late peaks are not able to be distinguished from one another, exploring the largest peak within the entire RON time window might allow for a better understanding of the timing of RON as a whole.

What is clear from these studies is that the RON likely represents multiple mechanisms, reflecting different aspects of the reorientation process. The research seems to agree that at least one of these components involves a general attentional process, allowing for refocusing of attention back towards a task following distraction, evidenced in part by greater behavioral distraction occurring in tandem with a larger RON response. Additionally, the RON might represent preparatory and/or working memory mechanisms.

**Relationship to other ERPs.** The RON is often described as one component of a three-stage model of distraction. On this account, when presented with a deviant/distracting stimulus, the attentional system first automatically and pre-attentively detects the stimulus, as indicated by the Mismatch Negativity (MMN). Next the system orients towards the stimulus, sending attentional resources momentarily towards the irrelevant information, denoted by the P3a. Finally, a reorientation occurs back towards the task relevant information by way of the RON.

**MMN.** Traditionally, the MMN is defined as the brain’s automatic response to any change in auditory stimulation that exceeds the behavioral discrimination threshold. Although MMN has traditionally been defined for auditory processing, analogous activation for other sensory modalities has also been observed, including somatosensory, olfactory, and visual (Näätänen, Paavilainen, Rinne, & Alho, 2007). Like the RON, the MMN is calculated from the difference wave of deviants minus standards. Its maximal peak occurs over frontocentral and
central EEG sites, presenting as a negative displacement of the voltage. It reaches peak voltage anywhere between 75-250 ms after stimulus change, with decreasing latency as the degree of stimulus change increases (Näätänen et al., 2007; Horváth et al., 2008). At least two sources generate the MMN, namely, a bilateral supratemporal source and a right hemisphere frontal source.

The MMN is noted for being a pre-attentive change detector, so the locus of attention is irrelevant for its generation. This is why ignored stimuli produce an MMN (Cowan, Winkler, Teder, & Näätänen, 1993). The generation of the MMN is predicated on the auditory system having a short-term memory representation of what is defined as a standard/normal stimulus, so that it can detect a change. This is usually accomplished by interspersing low probability deviant stimuli within a stream of standard stimuli. In a study demonstrating this aspect of the MMN, Cowan et al. (1993) asked participants to listen passively to a stream of tones with a standard frequency, interspersed with tones of a deviant frequency. The participants were told to ignore the tones completely and simply read a text during the session. As predicted, the participants produced a clear MMN; however, it was only produced following at least three occurrences of the standard tone, demonstrating this requirement for a short-term memory representation. Related to this memory requirement of the MMN, it has been shown that the amplitude of the MMN decreases as the probability of a deviant stimulus increases. Sato et al. (2000) showed, for example, that in conditions where the deviant had a lower probability of occurring, the MMN to the deviant was larger in amplitude.

**P3a.** The P3a gets its name from being one of two subcomponents of the P3 ERP component, also known as the P300, with its counterpart known as the P3b. The P3 is a positive voltage deflection first described as occurring approximately 300 ms after stimulus onset, with a
range between 250-500 ms (Polich, 2007). Like its sibling, the MMN, the P3 is most regularly generated in oddball-like studies. The distinction between the two subcomponents lies primarily in task-relevance. Like the MMN and RON, the P3a is generated in response to infrequent task-irrelevant stimuli, while the P3b is primarily involved in task-relevant processing. The P3a appears at relatively short peak latency over central and parietal electrodes (Polich, 2007). The P3a is itself comprised of two different phases, with the early phase evident over central sites at approximately 230 ms after stimulus onset and the late phase over frontal electrodes at 315 ms. The early phase might serve as an index of deviance detection, whereas the late phase might reflect the actual orienting of attention towards the distracting stimulus (Escera, Alho, Winkler, & Näätänen, 1998). As with other subcomponent distinctions, this separation is not always demonstrated in data, likely a result of overlap.

**Relationship to RON.** Given the concurrency of the MMN, P3a, and RON, researchers have sought to identify their actual relationship, if such a connection exists. Sussman, Winkler, and Schröger (2003) demonstrated that by making the deviant stimuli fully predictable it is possible to prevent the P3a and RON altogether, while preserving the MMN. Participants in their study performed an auditory duration discrimination task with deviant pitches. However, before each tone, either a red or a green square was presented. In the unpredictable condition, the color of the square was randomized, providing no information. Participants were informed that the squares were irrelevant and instructed to ignore them. For the predictable condition, the color of the squares was matched to the pitch of the tones (e.g. red/low, green/high). These cues gave the participants two pieces of information, namely, that a tone was about to be presented and its relative pitch. Despite being task irrelevant, this information had a profound effect on the resulting electrophysiology to the tones. Both conditions produced a clear and comparable
MMN, while only the unpredictable condition produced the P3a and RON. The MMN appeared in both conditions presumably because it represents an automatic response to change that is not specific to the task. However, the P3a and RON seem to represent a more top-down process, which can be overcome with information about upcoming distracting stimuli.

In a more direct approach to understanding this trio of activity, Horváth, Winkler, and Bendixen (2008) sought to determine whether these three components individually co-vary with the preceding one, forming a strongly coupled chain. Previous research, as well as subsequent confirmation by the researchers, has shown that the MMN increases in amplitude with the number of repetitions preceding a stimulus change. Thus, if the trio are strongly coupled, both the P3a and RON should follow a similar pattern. In this study participants performed a tone duration (long/short) discrimination task, with each tone having either a high or low frequency. Unlike most other studies of this type, each combination of duration and tone was presented equiprobably, such that there were no deviant or standard sounds. Instead of the normal exploration of standards and deviants, the researchers sliced the data into micro-sequences based on whether a tone had a change (C) or a repetition (R) in frequency. They identified change-sequences (CC, CRC, CRRC, CRRRC) and repetition-sequences (CR, CRR, CRRR, CRRRR). As expected, the average voltage at the MMN time window showed increasing amplitude with increasing repetitions in change-sequences, but not in repetition-sequences. The P3a showed a similar pattern; however, the RON amplitude was unaffected by the micro-sequence length. Moreover, P3a and RON produced significantly different amplitudes as a function of micro-sequence length. Finally, P3a showed a significantly different pattern of amplitude change for the first and second pitch repetition, compared to the MMN and the RON.
Based on these results and the other studies above, it is clear that these three components represent distinct processes that, while often co-occurring, can operate separately from one another. Thus, we can comfortably assert that the RON represents a distinct and separate process with its own underlying mechanisms, not merely a continuation of the processes that comprise the MMN and P3a. Combined with the evidence that the RON reflects multiple mechanisms, the next step in understanding the RON is an exploration of the specific processes that the RON represents. There are several avenues of research that can offer insight into these mechanisms. First among these is an investigation of disrupted RON production in special populations and different age groups.

**Population Characteristics**

**RON in Special Populations.** Research has shown the RON to vary in its morphology and production among several special populations, possibly indicative of specific cognitive deficits.

**Schizophrenia.** Beyond the more sensationalized symptoms of schizophrenia, cognitive impairment has been shown to be one of the better predictors of global functioning over the course of the illness (Green, 1996; Green, Kern, Braff, & Mintz, 2000). Research points to early stage sensory and attentional processing as being a possible root of these impairments (Green & Nuechterlein, 1999; Javitt, 2009; Light et al., 2006). Jahshan et al. (2012) sought to investigate what effect different stages of schizophrenia have on the MMN, P3a, and RON. Individuals at risk for psychosis \((n = 26)\), recent-onset patients \((n = 31)\), chronic patients \((n = 28)\), and healthy controls \((n = 33)\) were compared in a passive auditory oddball paradigm. Participants watched a silent video while presented with standard and deviant duration tones. The use of a passive task
is a novel choice; previous research has shown that the RON only appears in conditions in which the deviant is task-relevant, which is, in fact, the basis of the theory of RON as reorienting (Schröger et al., 2000; Schröger & Wolff, 1998a). Nonetheless, Jahshan et al. (2012) were able to define a frontocentral RON by averaging the amplitudes at 350-500 ms after stimulus onset. Interestingly, the RON was reduced in amplitude for the recent-onset and chronic patients (but not at-risk individuals) relative to the healthy controls. The researchers concluded that changes in the RON, as well as the P3a, might indicate an early biomarker for schizophrenia.

In an ambitious study, Rissling et al. (2012) tested 429 schizophrenic patients and 286 healthy controls in a similar passive auditory oddball study. The researchers found significantly reduced MMN, P3a, and RON amplitude in schizophrenic patients relative to healthy controls with large effect sizes. Due to the large sample size, the researchers were able to perform structural equation modeling (SEM) to ascertain whether the amplitude deficits seen in schizophrenics involved unitary or multi-pronged processes. This method involves multivariate statistical analyses to analyze structural relationships. Results from SEM suggested that the deficits seen in the three ERPs effects reflected three independent processes, conveying separate mechanisms.

The use of the passive task in the two studies above is an interesting departure from earlier paradigms indicating that task-relevance is required for generation of RON. If it were the case that only the schizophrenics generated a RON, this would be easily explained as a consequence of the clinical diagnosis; however, these researchers report RON for healthy controls as well. The appearance of the RON could be due to the relatively large number of deviants used in the passive design (225) compared with studies that use an active design (160). An alternative explanation might be that the use of a silent video is ineffective in the passive
design at keeping participants’ attention from the tones. In early studies of the RON, researchers had participants read a book of their own choosing, which might have served as a better distraction from the auditory stimuli (Schröger et al., 2000; Schröger & Wolff, 1998a). Perhaps participants watching the video were not completely disengaged from processing the auditory stimuli and performing some task discrimination. Clearly, this passive task deserves further investigation in how it produces the RON; however, in terms of understanding the RON’s underlying mechanisms, it precludes any investigation of the relation of RON to behavioral outcomes.

**ADHD.** Attention deficit hyperactivity disorder (ADHD) is a neurodevelopmental disorder marked by inattentive and/or hyperactive-impulsive symptoms developing prior to age 12 (American Psychiatric Association, 2013). The distractibility associated with the disorder is often difficult to experimentally identify; however, children with ADHD have been shown to perform poorer on Stroop and flanker tasks, demonstrating a difficulty in inhibiting distracting stimuli. Gumenyuk et al. (2005) tested a group of 8-10 year old ($n = 11$) children with ADHD and age-matched controls ($n = 10$) in a visual discrimination task, with each visual stimulus preceded by a task-irrelevant high-probability standard or a low-probability novel sound. Increased distractibility was confirmed for the ADHD children from an increased response omission rate. In terms of brain response, the researchers found that the RON response, often referred to as the Late Negativity (LN) or Late Discriminative Negativity (LDN) for child samples, was both smaller in amplitude and shorter in latency in the ADHD group. However, in a very similar study, with similar behavioral results, no significant differences were found in the RON between ADHD children and healthy controls (van Mourik, Oosterlaan, Heslenfeld, König, & Sergeant, 2007).
Using a passive auditory oddball task, Yang et al. (2015) asked ADHD ($n = 15$) and healthy control ($n = 16$) children to play a video game while listening to a stream of either pure tones or Chinese lexical sounds, each with appropriate low probability deviants. In contrast to earlier results with ADHD using an active design, the researchers found that the ADHD children generated an enhanced RON relative to controls. One reason for the different outcomes between active and passive designs in ADHD research can be attributed to the large variability in behavioral outcomes within the ADHD population. Large variability in clinical populations presents a problem for RON research. While the ADHD population has clear memory and attentional shortcomings, which might present an opportunity to understand the mechanisms involved further, any investigation requires consistency, which is not afforded by this population.

**RON Across the Lifespan.** Research has shown that the production of the RON is strongly associated with age and varies throughout different age groups.

**Children.** As memory, attention, and other cognitive processes develop, so do the underlying brain mechanisms that control them. The development of the RON from childhood to adulthood might thus offer some insight into the development of reorienting. Very few studies have been performed in children that report the RON, presumably due to the difficulty associated with combining behavioral and EEG measures in this population, as noted by Wetzel and Schröger (2014). In one of the first studies to identify the RON in a sample of children, Wetzel, Berti, Widmann, and Schröger (2004) instructed children ages 5-6 to distinguish between pairs of animal sounds. The sounds were either from a standard or deviant location. Interestingly, the researchers found that both the MMN and P3a were absent from the grand averaged brain waves, whereas the RON was clearly visible at the normal RON latency, although with a more central/parietal distribution than the more frontal normally seen in adults. Behavioral distraction
in the children was comparable to that found in adults, suggesting that children do not differ greatly from adults in their ability to reorient following distraction.

In a subsequent study, Wetzel, Widmann, Berti, and Schröger (2006) compared children aged 6-8, aged 10-12, and young adults in a tone duration discrimination task with deviant pitch changes. Wetzel et al. manipulated the amount of distraction by varying the degree of change in pitch between the standard and deviant across conditions. RON amplitude showed a significant increase from younger children to older children, with the older children displaying an amplitude resembling the young adults, denoting a possible developmental step between those age groups in terms of reorientation. However, the adult-like amplitude seen in the 10-12 year olds was delayed by approximately 70 ms. Neither child group showed any effect of deviant strength on the RON, an effect seen in the adults. Interestingly, the 6-8 year old group showed a RON-like response in a condition in which they were told to completely ignore all sounds and instead watch a silent video. This negativity was preceded by a P3a, which indicates the children at that age were distracted despite not having any task to perform.

Ruhnau, Wetzel, Widmann, and Schröger (2010) investigated the specific role that working memory plays on the RON as it relates to age. Participants, children aged 9-10 and adults, performed a visual n-back task with an irrelevant sound, either standard or novel, preceding each visual stimulus. In the low load condition, participants determined whether the visual stimulus occurred at a predefined location. In the high load condition, participants had to determine whether the position of the visual stimulus matched or differed from its position two trials before, forcing working memory activation. Adults showed a normal amplitude frontally located RON and more negative deflection in the high-load condition. The children showed a much more complex RON activation, with SCD analyses presenting two frontal, one central, and
two parietal generators. Moreover, the peak was delayed in the children and not significantly affected by working memory load.

The RON seems to vary greatly in children depending on the paradigm that is producing it, likely related to the differing developmental time scales for the multiple mechanisms controlled by the RON response.

**Older adults.** A great deal of research suggests that healthy elderly increasingly struggle with working memory processing (for a review, see Zacks & Hasher, 1988), while also suffering from a decreased ability to inhibit distracting stimuli (Hasher, Lustig, & Zacks, 2007; van der Molen, 2000). One might therefore expect healthy elderly to show deficits in RON processing. In one of the first studies to investigate the RON in older adults Cona, Arcara, Amodio, Schiff, and Bisiacchi (2013) compared a group of younger adults aged 21-29 with a group of older adults aged 62-72 in a visual inhibitory control task. In the first condition, participants were presented a series of letters, interspersed with the target letters X and Y, responding only to the targets and ignoring all other letters. The second condition consisted of Go and No-Go trials. Participants were instructed to respond when X and Y alternated (Go) and withhold their response when X or Y repeated (No-Go). In both conditions, target letters never directly followed each other. To create time pressure and control for the degree of executive control necessary to complete the task, letters were presented for only 500 ms with no inter-stimulus interval (ISI). The researchers identified both a frontal and parietal RON. For both sites, the RON was significantly delayed in the older group as compared to the younger. The general slowing of the RON response was also seen in other ERPs (MMN, P3a), although to a lesser degree. Additionally, age modulated the strength of the parietal RON, with the older group having smaller amplitude. These age-related effects, however, did not extend to the trial-type
(detect, go, and no-go trials), with no significant age by trial-type interactions. The lack of a trial-type effect by age suggests that executive control, at least in terms of a unitary mechanism, does not explain the differences seen between the age groups. The researchers hypothesized that this pattern of results suggests a general slowing of attentional processes with age.

In an auditory/visual version of the Go/No-Go task described above, Correa-Jaraba et al. (2016) investigated the role of deviant and novel sounds. Young, middle-aged, and older adults performed a visual discrimination task in which they responded to letters and numbers with different button presses and withheld responses to triangles of different orientations. Preceding each visual stimulus was a tone with either a standard frequency, a deviant frequency, or a novel sound (e.g. phone ringing). Participants were told to ignore all sounds and only respond to the visual stimuli. As expected, younger participants had significantly faster reaction times than the other two age groups, demonstrating an age-related slowing effect. While the researchers did not find any significant differences between the novel and deviant stimuli, they did find that the middle-aged and older adults had a significantly later RON than the young group, mirroring the results of the study described above. The researchers note that the results seem to point to a delay in the production of the RON, as well as the P3a, supporting this idea of a general slowing of orienting and reorienting processes with age. They suggested that this slowing occurs between young and middle age adulthood, with no change thereafter.

Using a data set from a larger research project, Getzmann, Gajewski, and Falkenstein (2013) give even more credibility to the general slowing hypothesis. They compared younger and older adults in an auditory duration discrimination task with deviant frequencies. The older participants were delineated as either high performing or low performing, based on behavioral results. While there was no age effect on reaction times, the low performing participants had a
significantly lower accuracy than both the younger and the high performing older adults to the
deviant stimuli. However, the latter two groups did not significantly differ from each other
behaviorally. In regard to the ERPs, the three groups showed an interesting pattern. The young
produced a large P3a and an early and efficient RON. The low-performing older group had an
equally large P3a, while the old high-performing group had a significantly weaker P3a. Both
older groups produced a much weaker and later RON than the young. This pattern implies that
the high-performing older group benefited from reduced orienting towards the deviant stimulus,
as denoted by the smaller P3a, allowing for similar performance to the young. In examining the
entire older adult group (both samples averaged), the researchers found that both the MMN and
P3a amplitude were significantly correlated with behavioral change, whereas the RON was not.
The young showed no such correlations. Taken together, the results signify a breakdown in the
normal orienting/reorienting process. The older high-performing group seems to have
developed, either on purpose or by natural processes, a compensatory mechanism for dealing
with the decreased reorienting response, presumably from the general slowing mentioned above,
allowing for successful behavioral responses.

In general, the slowing of the RON response in older adults seems to be a reliable
phenomenon. Under closer investigation, it might be possible to connect this change in RON to
the changes in behavioral distractibility and recovery also seen in older adults.

Underlying Mechanisms

Several experimental manipulations have been shown to affect the production of the
RON, allowing for a fuller picture of the cognitive mechanisms associated with it.
Deviance Strength. Previous research has demonstrated that the amplitude of the MMN increases with the physical difference between standards and deviants (Amenedo & Escera, 2001; Tiitinen, May, Reinikainen, & Näätänen, 1994). Yago, Corral, and Escera (2001) hypothesized that this might be the case for both the P3a and RON. To test this, the researchers performed a visual discrimination task with deviant pitch changes in a preceding auditory stimulus. The researchers varied the percentage difference in frequency from the standard to the deviant tones, resulting in six different distinct tones (5%, 10%, 15%, 20%, 40%, and 80%). Interestingly, behavioral distraction effects were only seen in the 10% condition, with RT increasing from standard to deviant. In the 5% condition, reaction time actually decreased. Despite the lack of a consistent behavioral effect, the researchers found that the MMN, P3a, and RON amplitudes all increased with the rise in deviance, with the P3a and RON increasing at almost twice the slope of the MMN. Additionally, the increase seen was linear, contrasting the logarithmic relationships seen for many perceptual and psychophysical processes. The researchers speculate that the lack of behavioral distraction alongside observable electrophysiological effects may indicate that behavioral distraction only occurs at optimal levels of cerebral activation, as in the 10% condition. In this view, the larger distractor conditions produced larger overall activation which served to allow the participants to properly deal with the distraction. The inconsistent behavioral effects might also be partially explained by the use of an audio/visual paradigm, which often requires very large deviance changes to produce reliable distraction.

In a purely auditory version of the Yago et al. (2001) study, Berti, Roeber, and Schröger (2004) asked participants to perform a tone duration discrimination task, interspersing deviant pitches that varied from the standard frequency by 1%, 3%, 5%, and 10%. In contrast to Yago et
al., Berti et al. found that all levels of distractor strength lengthened reaction time, following a linear slope with the strength of the distractor. The increasing deviance was accompanied by increases in amplitude for the MMN, P3a, and RON. The MMN and the RON reached saturation at 5%, with amplitudes not differing significantly between 5% and 10% deviants. The P3a reached no such plateau. Additionally, at the 1% level, roughly 60% of trials did not result in RT prolongation. Analyzing these two types separately, the researchers found that only the trials with a RT distraction effect resulted in a P3a and RON, while the MMN was present on all trials.

Overall, the findings of these studies demonstrate that the physical characteristics of a stimulus do indeed have an effect on the magnitude of the RON and other distraction ERPs, as well as on the degree of behavioral success, suggesting a bottom-up influence on working memory in terms of the distraction effect. The saturation of the RON found by Berti et al. (2004) implies an upper limit to the RON, but that conclusion seems unlikely in light of the results of Yago et al. (2001). Alternatively, this plateau might indicate that the RON is not directly tied to distractor strength, but rather to the degree of reorientation that is needed following distraction. The degree of reorientation needed following distraction is not necessarily different in all conditions, and might represent an upper limit in the Berti et al. study, but not a universal upper limit. The lack of saturation for Yago et al. (2001) might be a result of the multi-modal nature of the paradigm used, activating separate mechanisms than the purely auditory study.

**Working Memory.** Investigating the role that working memory plays in the distraction process, Berti and Schröger (2003) varied the task load required for participants to perform an auditory duration discrimination task, with deviant frequency changes. The low load condition followed the normal parameters of an oddball paradigm, whereas the high load condition
required participants to withhold their response until the subsequent trial. Not surprisingly, the high load condition resulted in slower and less accurate responses overall. However, the distracting effect of the deviant trials was weaker in the high load condition than in the low load condition. This effect was attributed to overloading working memory, resulting in a decreased ability to deal with change and decreased distraction in the high load condition. Importantly, the behavioral effect in the high load condition was associated with decreased amplitude of the P3a and RON, but not the MMN. These results demonstrate the working memory does not seem to exert control over the early pre-attentive MMN change detection, but it is able to affect the later P3a and RON processes.

In a similar study, SanMiguel, Corral, and Escera (2008) varied working memory load in an auditory/visual oddball task. In the no-memory condition, participants were instructed to decide whether the two digits presented on the screen were the same or different, with either a standard or novel sound preceding the visual stimulus. The memory condition followed the same protocol; however, here participants had to decide whether the left digit on the current trial was the same or different from the left digit on the previous trial. Overall, participants were slower and less accurate in the memory condition, which was associated with a decreased distraction effect. The P3a was decreased in the memory condition but, quite surprisingly, the researchers found that the memory condition resulted in a larger RON, at odds with the results of Berti and Schröger (2003). The researchers explained the contradiction in terms of the amount of memory that must be reactivated after distraction. They argued that in the high load condition of Berti and Schröger’s study, participants were required to hold only the previous trial’s information in memory, thus involving the same degree of reactivation as in the low load condition. In the memory condition of SanMiguel et al., however, participants were required to
compare the current stimulus was that from the previous trial, thus necessitating reactivation of both trials following distraction.

Interestingly, up to the point of the RON, participants followed the same trajectory in both studies. The MMN, automatic change detection, was unaffected by the memory manipulation in both studies. The P3a, orienting towards distractor, was decreased in both studies, reflected behaviorally in the decreased distraction effect due to the deviant. Thus, the difference in the amount of memory reactivation seems to play an important role only in the RON. The difference in findings between the two studies might reflect the two phases of the RON. Munka and Berti (2006) describe these two phases as (1) refocusing of task-relevant information at the working memory level versus (2) a more general reorienting of attention mechanism (Escera et al., 2001). From this viewpoint, the decreased RON amplitude seen by Berti and Schröger (2003) reflects the reorientation of attention, following the same path as the decreased involvement of the P3a. The increased RON seen by SanMiguel, Corral, and Escera (2008) can then be seen as the greater involvement of working memory as it attempts to reactivate the task-relevant information needed for a successful behavioral response.

**Predictive Cues.** Sussman et al. (2003) were the first to show that the RON can be inhibited by predictive cues. Since then, further research has focused on the specifics of this effect and the mechanisms involved. Horváth, Sussman, Winkler, and Schröger (2011), in a complex study, sought to ascertain the particular information that is used in order to prevent distraction with a predictive cue. One explanation is that knowledge of the probability of the upcoming deviant allows for activation of some preparatory mechanism. Alternatively, specific information about the deviant stimulus might allow for its inhibition. Across two studies, participants performed a tone duration discrimination with predictive visual cues consisting of a
combination of color and position. In the fully predictable condition, the visual cues perfectly correlated with the upcoming auditory stimulus, providing information both about the probability of the upcoming stimulus as well as its specific pitch. In the unpredictable condition, visual cues varied with the same probabilities as the standard and deviant tones, removing any informational value of the visual cues. In the predictable sound condition, visual cues only gave information as to whether a stimulus was a deviant or a standard, but no information about the specific pitch of the stimulus. In several conditions, the researchers also varied the number of unique deviants that were presented to the participants, allowing for greater uncertainty about the specifics of the upcoming deviants.

The unpredictable conditions resulted in the classic presentation, with clear behavioral distraction and strong MMN, P3a, and RON components. The interesting findings come in the comparison of the fully predictable and predictable conditions. Both of these conditions resulted in some degree of reduction of behavioral distraction, with the fully predictable condition resulting in a significantly greater reduction. This result alone demonstrates that general information about the probability of an upcoming deviant allows for a reduction in distraction. However, it also shows that specific information is able to enhance the effect. Similarly, the RON was most affected in the fully predictable condition, with the predictable condition only showing a reduction in amplitude when there were only two possible deviants. These findings suggest that the process underlying the RON is primarily engaged when a participant is unprepared for the specific feature deviation.

Horváth and Bendixen (2012) modified these procedures to allow for a manipulation of the validity of cue information. Participants performed an auditory duration discrimination task with deviant frequencies. Preceding each tone was a gray square that was either above or below
Interaction of Attention and Memory on RON

a central fixation point. Valid cues were defined as the square in the high position corresponding to the high pitch and the opposite for the low cue. Given this setup, four different trial-types were possible: either a valid or invalid cue precedes the deviants and the corresponding standard trials. 80% of tones were preceded by valid cues and 20% by an invalid cue. Behaviorally, deviants slowed response time as compared to standards. Participants were slower to respond to tones preceded by an invalid cue. Most notably, the reaction time slowdown from standards to deviants was stronger for invalid cues than for valid cues. This pattern denotes an interesting interplay between deviance and validity, with the validity seeming to mimic as well as enhance the normal distraction effect seen in other studies.

The methodology allows not only the usual difference wave for deriving RON (deviant minus standard), but also a standard-after invalid cue minus standard-after valid cue RON, verified by its latency and location. Here, the researchers found that the amplitude of RON for standards preceded by a valid cue significantly differed from all other trial-types, while none of the other trial-types differed from each other. The finding identifies RON as particularly sensitive to cue information, more so than the MMN and P3a. Yet its specific relationship is not well understood, particularly its connection to the decrease in behavioral distraction seen with valid cues.

Horváth (2013) performed a similar study, but varied the cue-tone interval. Participants performed a tone duration task with visual cue information being presented either 663 ms or 346 ms before the tone. To ensure that both conditions allowed for an equal amount of preparatory time before the presentation of the tone, both the short and long conditions presented a visual cue at both time intervals. In the long cue-tone condition, both cues were always the same. In the short-cue condition, the first visual stimulus consisted of squares at both high and low positions,
thus restricting cue information to the second visual stimulus (i.e., shorter interval). The cue
effects mirrored Horváth and Bendixen (2012) for the long cue-tone condition, but were absent
for the short cue-tone condition, even though the cue-tone interval in the Horváth and Bendixen
study was similar to the short condition here. The lack of a result here is presumably due to
some interference between the first and second cue presentation. These studies also highlight the
difficulty of including multiple modalities into the investigation of the RON and other
distraction-related ERPs. The visual information not only produces separate visual ERPs, such
as the visual P3b, but also seem to actively complicate the signal analysis of the data.

The experimental manipulations that have been shown to affect the RON seem to mirror
the mechanisms put forth by Munka and Berti (2006), who noted that the RON comprises both a
general attentional and a working memory mechanism. The connection between these two
mechanisms, however, does not seem to be clear. Are these merely two independent systems that
overlap and form the RON or are they two parts of a larger system? Investigating this
relationship seems to depend on a better understanding of their contributions to behavioral
recovery as well as their differential effects on that recovery.

RON Paradigm

**Stimuli.** As has been discussed, the methodologies that produce the RON have
manipulated stimuli in various ways to produced different types of information. These variations
in methodology largely fall into three domains: modality, novelty, and type. The manipulation of
any and all of these domains have allowed for different types of investigations into this
distraction/recovery process, but at times come with specific consequences.
Interaction of Attention and Memory on RON

**Stimulus Modality.** As we have seen, the production of the distraction effect in these oddball tasks is a general phenomenon that does not seem to be relegated to a single modality-specific manipulation. The effect has been shown not only in purely auditory versions of the oddball task, but also visual, auditory-visual, as well as tactile-visual versions. The first two versions usually embed task-relevant and task-irrelevant features into the same stimulus object, while the cross-modal versions separate out these two aspects of the task into different stimuli. These cross-modal methodologies come with the noteworthy advantage that a researcher is able to separate task-relevant and task-irrelevant processing in time. This might prevent the overlap of the early and late phase of the RON, as can be seen with Escera et al. (2001). However, this methodology also requires a large difference between the standard and deviant stimulus to produce reliable distraction, as pointed out by Schröger and Wolff (1998b). This aspect makes it extremely difficult to carefully vary the strength of the distractor as was seen in comparing the results of Yago et al. (2001) and Berti et al. (2004).

Boll and Berti (2009) compared the efficacy of different types of deviants in a unique study in which participants responded to the duration of a combined auditory/visual stimulus, which consisted of a sound (of a specific pitch) and visual stimulus (at a specific position on the screen) presented concurrently. Participants were instructed to respond whether the combined stimulus persisted for a short or long duration. The researchers varied which aspect of the combined stimulus changed to create the deviant. In the auditory deviant condition, an irrelevant pitch change occurred; for the visual deviant condition the position of a triangle was varied; and in the combined auditory/visual deviant condition both the pitch and triangle position changed. All of these variations were irrelevant to the duration task. Behaviorally, all of the deviant types resulted in reaction time prolongation. The visual deviants, however, resulted in significantly
less behavioral disruption than the auditory and bimodal deviants whose effects were not statistically different. The behavioral effects were mirrored in the ERP results, with the visual deviants failing to produce a significant P3a and only a marginal RON, whereas the other two deviants followed the normal ERP progression with an MMN, P3a, and RON. Yet the researchers noted that the bimodal effect was not completely dependent upon the auditory aspect because the difference waves from these two conditions showed significant differences. Nonetheless, the differences seem to stem primarily from the combination of the auditory and visual processing, with the visual stimulus causing an N200, a visual ERP largely overlapping with the MMN.

Berti and Schröger (2001) compared the ability of visual and auditory stimuli to produce distraction and associated distraction ERPs. In separate auditory and visual conditions, participants were presented with a stream of stimuli and instructed to perform duration discrimination by responding to long stimuli and withholding responses to short stimuli. In the auditory condition, deviance was created with an irrelevant pitch change. In the visual condition, changing the position of a triangle on the screen produced deviance. As the auditory condition was primarily a recreation of previous studies, it is not surprising that the pitch deviants reliably produced reaction time prolongation as well as the normal MMN, P3a, RON progression. The visual deviants were not as reliable. Both short and long visual stimuli produced behavioral distraction. The short stimuli resulted in an occipital N200, followed by a P3a and RON. The researchers argued that the N200, for the visual system, denotes some of the same processing as the MMN. The long stimuli resulted in an N200 and a small P3a, but no RON. The researchers concluded that the absence of a RON may indicate an inherent difference in the way that the auditory and visual systems detect and process duration.
Evidence clearly suggests that the RON can be produced under multiple modalities in both unimodal and multi-modal designs. However, the studies reviewed here demonstrate that unimodal auditory designs might offer greater flexibility in methodology as well as more reliable production of both the behavioral and electrophysiological effects of distraction.

**Stimulus Novelty.** In contrast to the more controllable stimulus features such as pitch and duration, several studies have opted to employ novel sounds as the distracting stimulus, resulting in robust behavioral and electrophysiological effects. Experimentally, novel sounds refer to the use of primarily environmental sounds such as those produced by animals or machinery.

Berti (2012) compared the efficacy of rare versus novel stimuli as deviants in a multimodal oddball study. Participants were instructed to discriminate visually presented numeric digits that were preceded with task-irrelevant auditory stimuli. The standard stimulus in all conditions consisted of a tone with a specific pitch. In three conditions, the deviant was varied in its novelty and rarity. In the deviant condition the distractors consisted of a pitch change, while both the novel and rare conditions employed environmental sounds. In the novel condition each distractor was a unique sound presented only once throughout the task, while the rare condition employed only a single repeated environmental sound, thereby varying the rarity of the stimulus. Both the novel and rare conditions produced significant behavioral distraction, while the deviant condition did not. This pattern was mirrored in the electrophysiology. All three conditions produced the MMN, P3a, and RON; however, the P3a and RON were significantly more pronounced in the novel and rare conditions. This lack of significant behavioral effects in the deviant condition, and the smaller electrophysiological effects, are probably in part related to the use of the multimodal design, which requires strongly distracting stimuli, such as novel sounds. Importantly, the novel and rare conditions did not differ
significantly from each other in distraction effects, suggesting that the distraction effect depends only on an adequately strong distractor being presented infrequently, and not on the novelty of the sound itself.

Parmentier, Elsley, Andres, and Barcelo (2011) sought to answer more directly the question of why novel sounds are distracting in a multi-modal oddball task. Participants performed a visual digit discrimination task with preceding auditory stimuli. Auditory stimuli consisted of either a standard tone or a novel sound consisting of a burst of white noise. A novel sound rather than a standard sound followed most novel trials. This design allowed the researchers to distinguish between three possible hypotheses: rarity, expectation violation, and a perceptual change from one stimulus to another. The results showed that responses to novel sounds that followed other novel sounds were indistinguishable from standards, suggesting that the rarity of the novel stimuli did not inherently produce distraction. However, unexpected standards, those that followed a single novel stimulus, were behaviorally comparable to the unexpected novel stimuli, those that were preceded by a standard. Importantly, the standards that followed two consecutive novel stimuli, an expected perceptual change, produced shorter reaction times than unexpected conditions, but longer reaction times than predictable conditions without perceptual changes. The results suggest that the distraction caused by novel stimuli is a combination of both a violation of expectations as well as a result of a perceptual change.

A recent review of the relevant research concludes that the difference between regular deviants and novel distractors lies only in their ability to violate expectations, or possibly in the degree of perceptual difference, and not in some inherent characteristic of novel stimuli (Parmentier, 2014). This is an important qualification, as the use of novel stimuli, experimentally, poses issues for the careful control of the specific characteristics of the stimuli.
that are employed. For example, manipulation of the strength of a distractor would be impossible using novel stimuli without meticulous a priori measurement of distractibility in individual participants, which itself might lead to practice effects. As will be discussed later, one possible way to strengthen effect sizes of normal deviants would be to use integral features, such as pitch and timbre, which have been shown to produce larger distraction effects.

**Stimulus Type.** The choice of specific stimulus features plays a large part whether participants are distracted during selective attention tasks. Researchers have manipulated shape, position, duration, and color to produce deviance with varying degrees of success on visual distraction. Similarly, researchers have manipulated a multitude of auditory features including pitch, duration, location, and novel sounds. The most used methodology by far has been the duration discrimination task with deviant pitches. Schröger and Wolff (1998b) noted that the behavioral effects of pitch deviance in a duration task might indicate that the two auditory features are integral rather than separable. Integrality refers to the combined processing of multiple dimensions in the brain such that the processing of one affects the processing of the other. Yet this is likely not the case with pitch and duration as these two dimensions activate distinct neural structures. For example, fMRI evidence has shown that the MMN generators for duration and pitch are anatomically distinct from one another (Molholm, Martínez, Ritter, Javitt, & Foxe, 2005).

The most likely reason for reliable distraction with these stimuli is not the actual stimulus features chosen, but rather the design of the oddball task itself. Nevertheless, the perceptual change from one stimulus to another does play a role in producing distraction, a factor that can be manipulated to boost the distraction effect size. Pitch deviations within duration discrimination tasks have been shown to be reliable, but relatively weak distractors. As
mentioned above, employing integral auditory dimensions to the oddball task might allow for an even more robust distraction effect, possibly resulting in a stronger RON response, approaching the effect sizes seen for novel stimuli. One such integral pair is pitch and timbre (Melara & Marks, 1990). The timbre of a sound describes a sound’s quality. An example of this feature can be heard in the difference between a piano and a guitar playing the same pitch at the same intensity. Experimentally, timbre can be manipulated by varying the duty cycle, the ratio of on and off pulses of a square wave. Research in animals demonstrates that overlapping and interdependent neural populations are involved in the processing of pitch and timbre, suggesting strong integrality of these features (Bizley, Walker, Silverman, King, & Schnupp, 2009).

**Standard After a Deviant.** ERP research primarily investigates the brain’s responses to correct trials. This practice ensures that the RON, when measured as the difference of the deviant minus standards, represents successful reorientation back to the task, after a correct response was made. Yet research has shown that on trials that immediately follow a deviant, behavioral distraction can be measured, even after reorientation, in the form of prolonged reaction times and lowered accuracy, an effect termed post-deviance distraction. This continued distraction clearly demonstrates the complex nature of the distraction/reorientation process.

In one the first studies to investigate post-deviance distraction, Roeber, Widmann, and Schröger (2003) found in a duration discrimination task with location deviants that reaction times were significantly prolonged to the standards after a deviant (SA). In the converse task (i.e., location discrimination with duration deviants), reaction times trended in the same direction, but were not significant. A significant P3a accompanied the post-deviance in the duration task, but not the location task, mirroring the behavioral results. Interestingly, a clear and significant RON-like negativity, calculated as the difference between SA and all other
standards, was found in both tasks. This pattern of brain activity, as the authors noted, suggests that reorientation might be at the heart of post-deviance distraction, reflecting a continued effort by the system to reallocate resources back towards the task, despite having successfully navigated the deviant trial. The researchers note that the RON presented with a relatively sharp peak in the duration task (behavioral effect present), and a much less defined peak in the location task (behavioral effect absent), indicating that the morphology of the RON might vary in tandem with behavioral performance.

Roeber, Berti, Widmann, and Schröger (2005) reanalyzed four previous studies, categorizing deviant trials as either a response repetition or a response change trial. Repetition trials represented deviant sounds whose task-relevant feature was the same as the standard that directly preceded the deviant, while the task-relevant feature switched in change trials. Behavioral interference was significant across both trial-types, but more pronounced for the response repetition trials, seemingly suggesting a response bias towards change trials. P3a and RON showed larger amplitudes in the change trials, again suggesting that the system may be better equipped to deal with change than repetition. When the SA trials are analyzed in terms of these two trial-types, RT prolongation was only present in response repetition trials, ostensibly reflecting the greater behavioral effect to the preceding deviant trial. Despite the lack of behavioral significance on all trials, the RON was found in both the repetition and change trials for the SA trials. While not mentioned by the authors, it is worth observing that the behavioral post-deviance distraction seems to be better mirrored by the RON response to the deviants, rather than the SA’s, with larger amplitudes to the deviant repetition trials and more behavioral interference to the SA repetition trials. Perhaps behavioral outcomes of the RON are better reflected in the trials following a deviant rather than to the deviants themselves.
Getzmann, Falkenstein, and Gajewski (2014) investigated the neural correlates of post-deviance distraction in middle-aged and older adults. Participants performed an auditory duration discrimination task with deviant frequencies. As predicted, both age groups performed worse to the standards after a deviant than to those before; however, this effect was stronger for the older adults. Interestingly, in the standard-before minus standard-after difference wave the researchers demonstrated the normal MMN, P3a, and RON that are usually described in the deviant minus standard difference wave. Only the RON differed between the two age groups, with the older group having a significantly later RON. The researchers suggest that the RON might play a central role in age-related distraction measured in these trials.

Getzmann and Wascher (2016) delineated trials into five categories: Pre, Deviant, Post-1, Post-2, and Post-3, allowing for an investigation of the evolution of distraction from the trial prior to the reference trial to three trials after the reference trial. A syllable discrimination task with deviant auditory locations was used in samples of young and older adults. Behaviorally, the younger participants showed increased reaction times up to Post-1, returning back to Pre levels at Post-2. The older adults showed a tendency to take longer to return to Pre-Deviant reaction times, with Post-2 still differing from Pre trials. While the MMN and P3a decreased beginning at Post-1, the RON at Post 1 was not significantly different from that measured to the Deviant, indicating a continued process of reallocation of resources back towards the task. However, by Post 2, the RON was not measurable.

The presence of post-deviance presents a problem for deviant minus standard difference wave calculations. The group of standards used in these calculations would include some amount of post-deviance distraction, potentially blurring the full difference between the two types of variables. Several studies have dealt with this by simply omitting the SA trials from the
group of standards used in difference wave calculations. A more robust solution to this might be to restrict investigation to only the trials that directly precede a deviant, which would be the trials that presumably have the smallest degree of carryover from the deviants as they are the most temporally separated. This type of analysis would result in three trial-types: the standards before a deviant (SB), deviants, and the standards after a deviant (SA).

Current research has yet to define the specific relationship between the RON and behavioral success in the task, whether to the deviant or the standard that follows it. Logically, reorientation back to a task should result in decreased reaction times and increased accuracy. Thus, there should be some detectable correlation between behavior and the RON. In addition, as hinted by the results reviewed here, this behavioral connection might be better reflected in the response to the SA rather than the deviant itself.

**Brain Behavior Relationship**

In general, an individual’s ability to deal with distraction is largely unpredictable. Factors like age, distractor strength, and working memory involvement seemingly play a role in this process and as such, give some insight into possible outcomes. However, it is evident that the specific expression of the RON is indicative of this ability as well. Most extant results show concurrent effects of behavior and RON modulation during distraction tasks, but very little evidence has been reported showing any direct relationship between the RON and behavior.

In the first study to report any link between the RON and behavior, Getzmann et al. (2015) compared younger and older adults in a spoken word discrimination task, with words presented at either a standard or deviant location. As with previous studies, the researchers found that the RON was significantly delayed for the older adults. Importantly, though, they
found that for the elderly the latency of the RON was strongly correlated with performance ($r = 0.52$). Behavioral performance was measured as the inverse efficiency (IE), calculated by dividing the reaction time by the rate of correct responses, in an attempt to control for the speed/accuracy trade-off. The correlation demonstrates that for the older adults a better behavioral outcome is associated with an earlier RON. This finding is not surprising, in that previous research has shown that in general the older adults perform worse and tend to have a later RON than younger adults. While not significant, it is worth noting that for the young group the correlation was in the opposite direction, suggesting that that some other mechanism might be at play for this group that might be measurable under other conditions. If this is the case, it might denote that the two groups are relying on different mechanisms to perform the task.

Tusch, Feng, Holcomb, and Daffner (2017) reported a strong correlation ($r = -0.52$) between behavioral success and RON amplitude. The researchers defined behavioral performance as composite A’ scores, a measurement based on signal detection theory that combines measures of reaction time and accuracy. The study itself compared young, aged 19-30 years old, and elderly, aged 60-79 years old, samples on the effects of varying task load within a visual oddball task with preceding auditory stimuli. When the samples were collapsed across groups and conditions, the researchers noted that a larger RON was correlated with better performance, seemingly reflecting greater neural processing as evidenced by the more negative amplitude.

Both of the studies above report large correlations between the RON and behavioral performance. However, both seem to suffer from small effect sizes, with the first not finding significance for the young and the second only achieving significance when all groups and conditions were collapsed. Despite this, these studies demonstrate that the RON is sometimes
associated with the actual behavioral response following distraction. Several important questions remain.

Given that among the body of work pertaining to the RON so little research reports any correlation between behavior and the RON, it must first be determined whether these correlations are reliable and reproducible, or instead are specific to methodologies employed by individual researchers. Given the large amount of data showing concurrent behavioral and RON modulation, the former is likely the case.

**Study 1**

**Introduction**

This study is primarily an extension of previous research (e.g. Getzmann et al., 2015; Getzmann et al., 2013) which sought to (1) address several methodological concerns in the research pertaining to the RON, and (2) confirm and expand upon the previous findings, specifically regarding the brain/behavior correlations that have been reported by other researchers. This was accomplished in a study comparing younger and older adults in their performance of an oddball task.

**Aim 1: Methodology.** Many previous studies have measured the RON as the difference between the deviants and all standards, yet deviance processing continues at least into the standard that directly follows the deviant. Several studies have accordingly excluded these trials from the group of standards in order to eliminate their effect on the difference wave. Although Getzmann and Wascher (2016) found that the RON was not measurable to the second standard after a deviant, they did find that, at least for older adults, reaction times to these standards did not return to pre-deviance levels. Thus, we chose to compare the standards that directly precede
a deviant to the deviant and to the standards that directly follow the deviant. The standard-before trials have, by design, the least possible degree of post-deviance processing and provide the best trial type to compare against. We are able to assert more confidently that any behavioral or electrophysiological differences are truly due to the deviant. Moreover, by only analyzing the standard-befores, deviants, and standard-afters, and ignoring all other standards, we were able to consider the timeline of distraction, from before, during, to after distraction.

We also sought to address inconsistencies in the literature in producing distraction effects in this paradigm by employing the integral auditory dimensions of pitch and timbre. The same neural structures process these two dimensions, suggesting that processing of one inherently affects processing of the other. Thus, distraction can be expected to be stable and reproducible.

This study also introduced analysis of the standard-after minus standard-before difference wave to more appropriately measure the deviance-related processing of the RON. The comparison of these standards follows the so-called Hillyard Principle, which states that any comparison of two trials should only compare stimuli that are physically identical, as comparisons of physically dissimilar stimuli allow the possibility that characteristics of the stimulus rather than the psychological manipulation created the behavioral and neural effects.

**Aim 2: Expand on Previous Research.** In line with previous research we hypothesized that (1) older adults will perform worse behaviorally than the younger adults in regard to both accuracy and reaction time. As well, we hypothesized that (2) the peak amplitude of all three distraction-related ERPs (MMN, P3a, and RON) will be larger and more pronounced in the younger adults in comparison to the older adults, with RON showing the largest difference.
Of particular interest was the finding by Getzmann et al. (2015) that older adults show a connection between behavioral success and the latency of the RON, while younger adults do not. Previous research points toward a general-slowing for older adults. This theory states that decreases in behavioral success and dampening of neural responses in older adults are due to a quantitative slowing of the processes involved, rather than to any qualitative difference between young and old. If general-slowing explains the differences between the young and old, younger adults should present with a similar correlation between RON latency and behavior as older adults. However, some older adults are able to overcome the decreased amplitude of the RON and present behavioral success at the level of younger adults, indicating a possible compensatory mechanism in this group (e.g., Getzmann, Gajewski, & Falkenstein, 2013). If so, it would follow that either the young would have no correlation, as was found in the previous research, or that they might have an opposite correlation, indicating some difference in processing. We hypothesized that (3) behavioral performance will be correlated with the latency of the RON for both the older adults and younger adults.

The studies that have reported a correlation between the RON and behavior have employed behavioral measurements that combine accuracy and reaction time. Given that the noteworthy distraction effects are seen most often in reaction time data, we predicted that (4) RT will be the strongest correlate of the RON. Additionally, since the RON has been demonstrated as one of the major components involved in post-deviance distraction, we hypothesized (5) these correlations would extend to the standards that follow a deviant as well.
Methods

Participants. Participants were divided into two age groups. Initially, 15 younger adults and 17 older adults were tested. One younger adult was excluded from analysis due to chance level performance on the task. Seven older adults did not complete the task due to poor hearing and a subsequent inability to perform the task. The final sample consisted of 14 younger adults (4 males, 10 females) aged 18 to 22 years old (M = 19.43, SD = 1.16) and 10 older adults (2 males, 8 females) aged 67 to 80 years old (M = 73.6, SD = 3.95). Younger adults were recruited through the psychology research pool at The City College of New York, The City University of New York and were compensated with course credit. Older adults were recruited from nearby community centers and churches and were paid $10 per hour for participation.

Stimuli and Procedures. The nature of the procedures was explained fully, and informed consent was obtained from each participant; the Institutional Review Board of the City University of New York approved the protocol. After signing an informed consent form, participants were given the Edinburgh Handedness Inventory. All subjects were confirmed to be right-handed. The participants were then given audiometric testing following procedures set out by The British Society of Audiology (2004). In this test, average pure-tone hearing threshold levels are assessed at several frequencies, with average thresholds below 20 db considered within normal range. All participants included in the analyses fell within normal ranges for frequencies up to 2000 Hz, which fully encompasses the stimuli employed in the study. Following these tests, participants were given several practice trials to familiarize themselves with the task.

Stimuli were presented using Presentation® (Version 16.1, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). Stimuli consisted of rectangular-wave tones varying in
both duty cycle and frequency, resulting in four distinct tones: 490 Hz-20% duty cycle, 490 Hz-40% duty cycle, 510 Hz-20% duty cycle, 510 Hz-40% duty cycle. All tones were presented through Sennheiser HD280 Pro headphones presented at an intensity of 67 dB(A). Each tone lasted 100 ms with 10 ms rise and fall times. These specific tones were chosen based on pilot work demonstrating large distraction effects as well as equivalent levels of distraction between the conditions. Tones were presented with an ISI of 1000 ms with a 200 ms jitter, resulting in intervals ranging randomly between 800-1200 ms. All four tones were presented in both conditions but with differing presentation probabilities. Blocks consisted of 150 trials with each block type being repeated four times, resulting in a total of 16 blocks and a total of 2400 trials for each participant.

In the pitch condition (as depicted in Figure 1), participants performed a pitch discrimination task in which they decided whether the tone was 490 Hz or 510 Hz. Participants were told to be as fast and accurate as possible and to ignore any changes in timbre. In the pitch20 block-type, 70% of tones had a 20% duty cycle (35% at 490 Hz and 35% at 510 Hz) and the remaining 30% of trials had a 40% duty cycle (15% at 490 Hz and 15% at 510 Hz). The corresponding pitch40 block-type followed the same general rules, with the exception that 70% of trials had a 40% duty cycle and the remainder had a 20% duty cycle. In the timbre condition, participants performed a timbre discrimination task ignoring any variations in pitch. In the timbre490 block-type, 70% of trials had a frequency of 490 Hz and 30% of trials were 510 Hz. In the timbre510 block-type consisted of 70% 510 Hz tones and 30% 490 Hz tones. All trial probabilities can be seen in Table 1.

Participants responded with either a right button or left button mouse click, with each button corresponding to either rough/smooth (timbre) or low/high (pitch), depending on the
current condition. Both condition order and mouse buttons were counterbalanced between subjects. Any response with a reaction time of greater than 2000 ms was removed. In all conditions and block-types, deviants were preceded and followed by at least two standards, such that a deviant never directly followed another deviant. Participants were tested in a dark, quiet, and electrically attenuated room. Participants were instructed to blink as little as possible and fixate on a small white fixation cross presented on a computer monitor.

**EEG Recording.** Continuous EEG was measured at a sample rate of 512 Hz using the ActiveTwo BioSemi electrode system with a 168-electrode montage. In this system, the Common Mode Sense (CMS) active electrode and the Driven Right Leg (DRL) passive electrode form a feedback loop that pushes the average potential of the subject as close as possible to the ADC reference voltage in the AD-box. This allows these electrodes to be used as the voltage reference for the recording. Post-acquisition, data was re-referenced offline to the nasion.

**Data Analysis.** EEG data was processed and analyzed using the Fieldtrip Matlab package (Oostenveld, Fries, Maris, & Schoffelen, 2011). Independent component analysis was first performed for each participant. Independent components corresponding to eye movements and muscle artifacts were visually identified and removed. 1300 ms epochs were then calculated, including a 300 ms pre-stimulus baseline. Channels that from visual inspection contained consistently poor EEG morphology were removed on a block-by-block basis. To prevent bias during artifact rejection, trials were randomized and then visually inspected for artifacts. Following artifact removal, any channels that had been removed were interpolated based on nearby neighbors and restored. Reaction time and accuracy values were calculated from the artifact-free trials. EEG data was baseline-corrected, time-locked with a 30 Hz low-pass filter, and averaged. Three trial-types were identified and used for analyses: the standards
directly before a deviant (standard-before), deviants, and the standards directly after a deviant (standard-after). Data were categorized according to trial type and age group and collapsed across pitch and timbre conditions.

The peaks of MMN, P3a, and RON were measured in the deviant minus standard-before difference wave. Additionally, P3a and RON were measured in the standard-after minus standard-before difference wave. While there remains some ambiguity as to whether both subcomponents of the RON occur over frontal areas (Escera et al., 2001; Schröger et al., 2000) or whether they are separated over frontal and parietal areas (Berti, 2008; Cona et al., 2013), preliminary analysis of the data did not find any significant negative peaks over parietal areas. As such, analysis was performed on the average of 8 channels centered at Fz, as depicted in Figure 2. All peaks were identified as the maximal negative-going or positive-going peak within a particular latency window (MMN: 100-200 ms; P3a: 200-400 ms; RON: 400-750ms). Latency windows were chosen based on previous research and visual inspection of the individual waves.

**Statistical Analyses.** In reviewing the latencies of the RON for individual participants, peaks congregated in two latency windows separated by a gap of an approximately 56 ms (Figure 3). The latencies of these two peaks correspond reasonably well to the early and late subcomponents of the RON. We thus elected to measure the differential effects of each subcomponent indirectly by categorizing individual participants according to the latency at which their maximal RON peak falling into either an early (300-520 ms) or late (570-750 ms) RON (referred to as RON-timing from here forward) group. The early RON group comprised 7 young and 7 old participants, while the late RON group comprised 7 young and 3 old participants.
A series of repeated measures ANOVAs were conducted for both reaction time and accuracy comparing trial-type (standard-before, deviant, standard-after) with age (young, old) and RON-timing (early, late). In order to compare the ERP data, a series of two-way ANOVAs were performed comparing the latency and amplitude of the distraction ERP peaks with age and RON-timing. Bonferroni adjusted p-values are reported for individual comparisons. Where appropriate, Greenhouse-Geisser corrections along with adjusted degrees of freedom and corresponding epsilon values are reported. All statistical data analyses were performed using SPSS version 25.0 (IBM Corp, 2017).

We also conducted a series of Pearson correlations within each group to determine if the RON is associated with behavioral performance. We restricted these analyses to the RON in the deviant minus standard-before wave, due to the general weakness of the RON in the standard-after minus standard-before seen in other studies. Correlations were derived between RON amplitude and latency and standard-before, deviant, and standard-after behavioral measures for each group.

Results

Behavioral. Older adults (M = 83.80%, SD = 9.78) were 6.79% less accurate than younger adults (M = 90.59%, SD = 5.01) (see Figure 4), in line with predictions, (F(1,20)=5.185, p=0.0339, $\eta_p^2=0.206$). There was a significant main effect of trial-type on accuracy (F(1.536,30.717)=20.723, $\varepsilon=0.768$, p<0.0001, $\eta_p^2=0.509$), but no effect of post-deviance. Accuracy to deviants was significantly worse than to either standard-befores (p=0.0002) or standard-afters (p=0.0001), which did not differ from each other. There was no effect of RON-timing on accuracy.
Older adults (M = 596.27, SD = 92.94) responded 102 ms slower on average than the younger adults (M = 493.79, SD = 72.71), \( F(1,20)=22.346, p=0.0001, \eta^2_p=0.528 \). There was a main effect of trial-type (\( F(2,40)=36.131, p<0.0001, \eta^2_p=0.644 \)), with participants responding significantly faster to standard-befores than to either deviants (\( p<0.0001 \)) or standard-afters (\( p<0.0001 \)), which did not differ from each other, indicating a strong effect of post-deviance. We also found a significant two-way interaction between age and RON-timing, \( F(1,20)=17.885, p=0.004, \eta^2_p=0.472 \), and a significant three-way interaction among trial-type, age, and RON-timing, \( F(2,40)=3.930, p=0.0276, \eta^2_p=0.164 \). Figure 6 depicts these interactions. Although RTs do not differ by age in participants revealing early RON, in those with later RON young participants demonstrated significantly faster RTs. Moreover, the age difference in the late RON participants is significantly greater for the standard-after-deviant stimulus (278 ms) than to the standard-before-deviant (228 ms) or deviant (218 ms) stimulus. This general increase in difference between the age groups for the late-producers can be seen in Figure 7 in the increased slope of the standard-after trials as opposed to the other trial-types.

**Distraction ERPs.** As can be seen in Figure 8, the morphologies of the deviant minus standard-before grand average waves are generally comparable, with identifiable MMN, P3a, and RON components. However, age differences appear, especially in the RON time window, with younger adults showing sustained negativity following the P3a, while older adults have a brief and small negativity that subsequently peaks positively before dipping back towards zero. This difference can also be seen in the topographic voltage map. As seen in Figure 9, older adults, as expected, have a weaker and much less defined frontal negativity than younger adults in the RON search epoch.
All three distraction ERPs demonstrated a significant age effect in the deviant minus standard-before difference wave, with older adults generally producing weaker difference potentials than the younger adults. MMN was significantly greater in young than old, $(F(1,20)=14.457, p=0.0011, \eta^2_P=0.420)$, differing by 1.65 $\mu$V between groups (young: $M = -2.52$, $SD = 1.43$; old: $M = -0.87$, $SD = 0.46$) (Figure 10). P3a voltage was significantly more positive (young: $M = 1.08$, $SD = 1.63$; old: $M = 0.04$, $SD = 1.02$), $(F(1,20)=7.318, p=0.0136, \eta^2_P=0.268)$, and occurred significantly later (young: $M = 297.15$, $SD = 65.68$; old: $M = 249.80$, $SD = 69.64$), $(F(1,20)=7.587, p=0.0122, \eta^2_P=0.275)$, in young than old (Figure 11). Young adults produced a significantly more negative RON $(F(1,20)=5.737, p=0.0265, \eta^2_P=0.223)$, differing by 1.85 $\mu$V (young: $M = -3.46$, $SD = 1.99$; old: $M = -1.6$, $SD = 0.61$) (Figure 12).

RON-timing, as well, produced significant differences. Surprisingly, the RON latency in the standard-after minus standard-before wave resulted in a significant Age x RON-timing interaction $(F(1,20)=8.130, p=0.0099, \eta^2_P=0.289)$. Figure 14 shows that the young follow the same pattern between the two difference waves, with the Early-RON occurring before the late RON. However, the older adults do not differ in this way, producing equal average latency between Early and Late in the standard-after minus standard-before.

**Correlations.** For the younger adults, both the deviant $(r = -0.785$, $p=0.0008$, Figure 15) and standard-after $(r = -0.611$, $p=0.0204$, Figure 16) reaction times correlated negatively with the deviant minus standard-before RON latency (i.e., slower reaction times were associated with earlier RON latencies). By contrast, older adults revealed the opposite correlation $(r = 0.870$, $p=0.0011$, Figure 17), at least in RTs to standard-afters, with slower reaction times associated with a later RON latency. Unexpectedly, the same pattern appeared in RTs to the standard-befores $(r = 0.751$, $p=0.0123$, Figure 18). Fisher’s $r$-to-$z$ transformation confirms that the
correlation to standard-after reaction time was significantly different for the two groups
\( (z = -4.226, p < 0.0001) \). There were no other significant correlations with behavioral and
physiological data.

**Discussion**

**Age Effect.** This study generally follows well-established effects of age on the
distraction process. Previous research found three primary age effects in terms of deviance
processing. First, older adults usually perform worse behaviorally than younger adults. We also
found this effect, with the younger adults responding faster and more accurately than the older
adults. Some research (Hasher, Lustig, & Zacks, 2007; van der Molen, 2000) has found that
older adults are not only worse overall but experience more distraction than younger adults. Yet,
as with Cona et al. (2013) and Correa-Jaraba (2016), we found no interaction between trial-type
and age-group, indicating that the two groups responded in the same manner, with the primary
difference being a decrease in selective attention success. This finding is not necessarily
unexpected, as it seems to match up with the general-slowing theory of aging. Alternatively, the
fact that younger adults are as distracted as older adults might be explained by the use of integral
auditory dimensions. We chose these dimensions because they reliably produce distraction, but
their reliance on overlapping neural mechanisms may have led both groups to respond in the
same manner.

The second age effect most often seen in these types of studies involves the decrease in
peak voltage amplitude in older adults. In the current study, all three distraction-related ERPs
(MMN, P3a, and RON) were significantly dampened in the older adults. The older adults
showed the largest voltage drop for the RON in comparison to the MMN and P3a, indicating, as
others have suggested, that the RON might play some significant role in the overall decrease in behavioral success in the face of distracting stimuli. What is most striking about these voltage differences, however, is the clear change in variability seen between subjects in each group. As seen in Figures 10-12, the peaks for the older adults are very tightly packed, with very little inter-subject variability. The younger adults, on the other hand, present with a much wider range of peak voltages. Interestingly, for all three ERP components, each group’s minimum is approximately the same. This seems to indicate an overall dampening of the entire distraction process for the older adults, having reached some floor, with the RON being most sensitive to this dampening.

Finally, unlike previous research, this study did not find a delayed RON in older adults. This null result may be due to the relatively large latency window employed for the identification of the RON, which was chosen to encompass the latency windows of both the early and late subcomponents of the RON, as well as to match up with the actual peaks found in the data. As has been suggested by previous research (Escera et al., 2001), the inability to identify specific early and late phases of the RON in many studies is likely due to the overlap of the phases, resulting in a less defined and more prolonged RON. The current study hypothesized that it might be possible to measure the differential strengths of the early and late subcomponents indirectly by identifying the RON as the largest peak within the entire latency window of both subcomponents. In doing so, it was hypothesized that any correlations found to the latency of the RON might indicate some difference between the expression of the early and late phases of the RON.

Given this choice and the observation that there seems to exist a natural delineation in the RON latencies, we decided to identify subjects according to the timing of their RON.
Interestingly, this resulted in the finding that in terms of reaction time, young-adults and older adults who produced an earlier RON were not significantly different, meaning that the primary difference between the groups is due to the late RON group. Furthermore, the data suggest that the older late-producers are less able to return to pre-deviant levels by the time of the standard-after, showing a significantly larger slope between the two groups compared with the other two trial-types. We also found the latency of the RON found in the standard-after minus standard-before wave matched up with the early/late distinction for the younger participants but not for the older participants. We did not find any significant differences in voltage between the RON-timing groups, though. Given that the RON measured in the current study represents voltage from both phases of the RON, this is not surprising.

Brain/Behavior. The most interesting findings of the study involve the large opposing correlations seen between age groups. The correlation in older adults between RON latency and behavioral success mirrors that seen in previous research (Getzmann et al., 2015). In general, better reaction time to both the standard-befores and standard-afters is associated with earlier RON latencies in older adults. The fact that the RON correlates with the standard-after could indicate that the earlier the RON the more efficient the attentional control, resulting in decreased distraction for the older adults in the following standard-after and faster reaction times. The young, on the other hand, do not require greater efficiency, as their overall reaction times are significantly faster than the older adults. The opposite effects for the young to the deviants and standard-afters, both of which contain deviance processing, could indicate more complete attentional control, resulting in later RON latencies being associated with better behavioral outcomes.
Interestingly, in older adults RON was uncorrelated with the reaction time to the deviant. It seems that for the older adults the latency of the RON is associated only with processing of standard stimuli. Moreover, the fact that the reaction time to the standard-before and standard-after are significantly different makes this connection all the more surprising. Given that we know that the RON can exist outside of the deviant in post-deviant measurements of RON, we could assume that the RON is an indicator of some processing that is not a direct response to deviance, as seems to be the case with the MMN. In this sense, the RON could be seen as a more global process, which might explain the connection to the standards as opposed to the deviants. Yet the fact that the younger adults show an opposite effect (i.e., to only the deviants and the standard-afters) makes this line of reasoning less convincing.

More likely, these differences imply greater reliance on one or the other subcomponent of the RON. Research suggests that the primary difference between the two phases of the RON is in their connection to top-down and bottom-up processes. The early phase of the RON has been described as primarily a working memory process, while the late phase indicates a more general attentional process connected to specific characteristics of the deviant stimulus. Using this account, late RON in younger adults corresponds with greater attentional processing, and so is associated with better deviance processing and faster reaction times in the deviants and standard-afters. By contrast, early RON in older adults corresponds with greater reliance on working memory processes, and so is associated with faster reaction times to standard-befores and standard-afters.

The question remains as to why benefits would be associated with reliance on opposing phases of the RON as is seen between the two age groups. It may be that with aging, as the overall attentional system begins to decline (Colcombe et al., 2003; Verhaeghen & Cerella,
2002), those participants who are able to compensate by employing working memory mechanisms are able to reach a greater degree of success than those who are not. In order to test this explanation, it would be necessary to classify older adults a-priori based on their working memory and attentional capabilities and then to attempt to link cognitive capability with the timing of the RON and overall behavioral success. This test, though, is based on the assumption that the early and late phases of the RON are differentially expressed in different participants, as well as the specific mechanisms that those two subcomponents play in the distraction process.

**Three Stage Model.** At first glance, the findings above do not seem to match up with the three-stage model of distraction. Here, deviance is quickly and automatically detected by way of sensory-memory buffers as indicated by the MMN (Stage 1). Subsequently, deviance detection may lead to attention being sent involuntarily towards the processing of the non-task-relevant deviant information, marked by the P3a (Stage 2). Finally, attention is shifted back towards the task-relevant information by way of the RON (Stage 3). The model suggests that older adults are relatively less able to detect the differences and subsequently send fewer resources towards processing the deviant related information and finally send fewer resources towards re-orienting, leading them to be less distracted than the younger adults. This description of the process involves two false assumptions. First, these three stages are not linear, in that the three ERP components have been shown to exist in the absence of one another. Second, this description assumes a correlation between voltage and behavior. As we have seen, one of the defining characteristics of the MMN is that it is correlated with deviance strength, but not necessarily with behavioral output (Bazana & Stelmack, 2002). But there is only one study that shows a voltage correlation for the RON and two (including the current study) to show a latency effect. This seems to indicate that these voltage differences are indicative of possibly the efficiency of the
process or possibly just their breakdown, but not necessarily the actual output of the mechanism. What does seem clear, though, is that the RON plays a large role in the behavioral success of both younger and older adults, given that the RON shows the greatest voltage difference and the strong correlations of RON latency with reaction time.

**Post-Deviance RON.** A final goal of this study was to test the efficacy of using the standard-after minus standard-before as a primary measure of the RON as that comparison follows the Hillyard Principle. Unfortunately, that does not seem to be the case. While both the P3a and RON are measurable and significantly different from zero at the standard-after, they shrink in voltage to such a degree that they are not distinguishable by age. It is likely the case, and has been seen in previous research, that this difference could be measurable, but small nuances between voltage and latency would be difficult to assess in more complex designs.

Taken as a whole, study 1 was successful in replicating many of the findings from prior research. Namely, the study found older adults are on average slower to respond and less accurate than younger adults, although we did not find any difference in distractibility between the age groups. The lack of distractibility differences between the age groups may be a result of the use of integral dimensions as opposed to separable as in previous research. As well, the study demonstrated that the older adults produce generally smaller peak amplitudes for all three distraction ERPs (i.e. MMN, P3a, RON), with the RON showing the largest voltage difference between the groups. In contrast to some research, the two groups did not differ in the latency of the RON, although, as mentioned previously, this is likely due to the time window in which the RON was identified. Similar to the findings by Getzman et al. (2015), the older adults in the current study demonstrated a significant correlation between behavior and RON latency. This study, however, is the first to identify a significant opposing correlation for the younger adults,
suggested a degree of divergent processing between the two groups, which is perhaps indicative of a difference in expression of the early and late phases of the RON. Beyond this, the study demonstrated that RON latency was correlated with behavioral performance to standard-befores and standard-afters for the older adults, indicating that this association might be relegated to processing of standards as a whole. In contrast, the younger adults showed the opposite correlation to only the deviants and standard-afters, suggesting that the correlation for this group reflects deviant processing. Overall, the methodological and analytical alterations to the previous research that this study expanded upon were successful in allowing for a more detailed and specific look at the RON in these two age groups.

**Study 2**

**Introduction**

Study 2 was a necessary next step to investigate the specific processes that have been shown to modulate the timing and strength of the RON (i.e. attention and working memory). The previous study indicated that the timing of the peak amplitude of the RON has opposite associations with behavioral success for younger and older adults, suggesting that the two age groups are employing different techniques to complete the task.

Prior research into the RON has primarily focused on defining the specific experimental manipulations, and thereby the associated cognitive mechanisms, that affect the neural processes underlying the production of the RON. From this research it has become clear that both working memory and attentional control seem to play a part in the production of the RON. However, research has pointed out that the concept of these to cognitive processes as singular and separate mechanisms is a false assumption (see Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001).
As such, it is not known whether changes to the amplitude and latency of the RON seen in previous research are describing the same cognitive process, or rather whether changes in the RON indicate neural responses to multiple cognitive mechanisms. Besides evidence that the RON is produced from multiple neural generators (Schröger, Giard, & Wolff, 2000), the primary evidence in favor of the RON responding to multiple processes lies in a single study that found that the early phase of the RON was only present in a condition in which participants had to make a decision based on the semantic characteristics of a visual stimulus as opposed to its physical properties (Munka & Berti, 2006).

In order to approach an understanding of what the two age groups in study 1 are doing differently from one another, the combined effects of both types of manipulations must be investigated. As such, study 2 sought to (1) disentangle the differential contributions of the two cognitive processes which have been shown to alter the production of the RON and to explore how they interact during reorientation. This study, as well, aimed to (2) investigate the connection RON peak voltage has to behavior.

**Aim 1: Multiple mechanisms.** Opposing correlations between reaction time and the RON latency in Study 1 suggested that younger adults differ from older adults in some fundamental aspects of distraction processing. The group differences also suggested that there are multiple mechanisms at play with regard to the RON, seemingly represented by its two subcomponents. Previous research backs this up and suggests that the RON represents both a general attentional mechanism and a working memory mechanism, both working towards moving attention back to task-relevant processing after being pulled away by a distracting stimulus. Research up to this point has worked to establish these mechanisms and has shown that manipulation of either process is able to affect the production and morphology of the RON.
However, the question remains as to how these mechanisms interact and combine to establish the reorientation process.

If, as has been suggested by other research, the two phases of the RON demarcate the two mechanisms of the RON we would expect that they would be differentially affected by the two experimental manipulations employed in this study. More specifically, we hypothesized that (1) the early-RON will be influenced by the distraction manipulation of the current study, which varies the degree of working memory involvement, with a smaller RON amplitude associated with less predictable deviants. As well, (2) the late-RON will be affected by the manipulation of distractor strength (referred to as the imbalance manipulation from here forward), which varies the pitch difference between the standards and deviants. Specifically, it is hypothesized that the amplitude of the RON will with distractor strength.

**Aim 2: Peak Voltage Correlation.** Study 1 was well suited to investigate the connection RON latency has with behavior, given the methodology employed to measure the RON. However, the use of a large time window meant that the two subcomponents of the RON were simultaneously measured, likely negating any correlation that RON peak voltage has with behavior. As this study seeks to separately measure the two subcomponents this study is better suited to find a connection, if it does exist. We hypothesized (3) that given the previous research showing a connection we would find a correlation and that the direction of the correlation would be highly dependent upon the condition in which it is found. As well, we hypothesized (4) that the standard after trials would the most reliable source of correlations given the findings of Study 1.
Methods

Participants. Sixteen adults (4 males, 12 females) aged 19 to 35 (M = 23.75, SD = 4.64) were recruited through the psychology research pool at The City College of New York, The City University of New York and were compensated with course credit.

Stimuli and Procedures. After consenting, participants completed the Edinburgh Handedness Inventory. All subjects tested as right-handed. The participants were then given audiometric testing, following the same procedures and the previous study. All participants fell within normal ranges. Participants were then given several practice trials to familiarize themselves with the task.

All tones were presented through Sennheiser HD280 Pro headphones presented at 67dB(A). Each tone lasted 100 ms with 10 ms rise and fall times. Tones were presented with an ISI of 1000 ms with a 200 ms jitter, resulting in intervals ranging randomly between 800-1200 ms. Participants were tested in a total of 12 conditions, each consisting of 101 trials. Each condition was administered twice, resulting in 24 blocks and 2,424 total trials per participant. Participants in each condition performed a timbre discrimination task in which they indicated with a mouse press whether a tone was 20% or 40% duty cycle, with all standard trials having a frequency of 500 Hz. The separate conditions consisted of varying the frequency values and probabilities of the deviants.

Conditions were grouped into three sets: low-imbalance, medium-imbalance, and high-imbalance. For the purpose of this study, imbalance refers to the frequency difference between the two deviant pitch values for each condition. The three sets were counterbalanced between participants. An identical baseline condition was included in each of these sets, consisting of
only standard trials. The frequency separation for the low-imbalance condition was 40 Hz (480 Hz / 520 Hz), 77 Hz in the medium-imbalance condition (463 Hz vs. 540 Hz), and 115 Hz in the high-imbalance condition (445 Hz vs. 560 Hz).

Within each imbalance level, there were three distractor conditions (filtering-distractor, positive-distractor, and perfect-distractor), which varied the probabilities of congruent and incongruent deviant trials. Congruency was defined arbitrarily as high frequency (520 Hz in the low-imbalance condition, 540 Hz in the medium-imbalance condition, or 560 Hz in the high-imbalance condition) paired with short (20%) duty cycle or relatively low frequency tones (480 Hz in the low-imbalance condition, 463 Hz in the medium-imbalance condition, or 445 Hz in the high-imbalance condition) paired with long (40%) duty cycle. 50% of trials involved congruent deviants in the filtering-distractor condition, 72% in the positive-distractor condition, and 100% in the perfect-distractor condition (see Table 7 for all tone probabilities).

Participants responded with either a right or left mouse click. Both condition order and mouse buttons were counterbalanced between participants. Responses exceeding 2000 ms were removed. In all conditions and block-types, deviants were preceded and followed by at least two standards; a deviant never directly followed another deviant. Participants were tested in a quiet and electrically attenuated room. Participants were instructed to blink as little as possible and fixate on a small white fixation cross presented on a computer monitor.

**EEG Recording.** EEG recording procedures exactly followed the procedures employed for Study 1.

**Data Analysis.** Data cleaning procedures followed the same techniques used Study 1. Trials were separated into standard-befores, deviants, and standard-afters. From these, deviant
minus standard-before and standard-after minus standard-before difference waves were calculated for each condition. In addition, deviants were split into congruent-deviants and incongruent-deviants. This allowed for congruent-deviants minus standard-befores and incongruent-deviants minus standard-befores difference waves to be calculated. Only the filtering and positive-correlation conditions were used in these difference waves, as the perfect-correlation condition did not include any incongruent-deviants.

Efforts to decompose RON into early and late subcomponents of varying strength, as in Study 1, were unsuccessful in Study 2 because a large proportion of the RON peaks identified between participants were not significantly different from zero. As an alternative, we employed a technique used by several other researchers studying the RON in which peaks are first identified in the grand average waves per condition (MMN: 80-150 ms; P3a: 220-330 ms; Early-RON: 300-520 ms; Late RON: 530-750). A 50 ms time window was then taken centered at this peak. The voltage was then averaged across this time window for each subject and condition. While this method precludes any comparisons of the latency of the ERPs, it does allow for identification of both the early and late subcomponents of the RON as separate peaks, rather than a combined peak as in the previous study. As can be seen in the voltage topography plots in Figure 19, both the Early-RON and Late-RON produce a significant frontal sink. The Late-RON presented an accompanying posterior source that was not visible in the Early-RON. The MMN, P3a, Early-RON, and Late-RON were identified in the deviant minus standard-before wave (Figure 20). The Early-RON and Late-RON were also identified in all other difference waves.

**Statistical Analyses.** To analyze reaction time and accuracy a series of three-way repeated measures ANOVAs were conducted with imbalance (high, medium, and low), distraction (filtering, positive-correlation, and perfect-correlation) and trial-type (standard-
before, deviant, and standard-after) as factors. In order to test the effect of congruency a separate set of repeated measures ANOVAs was performed on the behavioral measures with imbalance (high, medium, and low), distraction (filtering and positive-correlation) and congruency (congruent-deviants and incongruent-deviants) as factors.

In ERP analyses of the MMN, P3a and both RON subcomponents in the deviant minus standard-before wave, a series of two-way repeated measures ANOVAs were performed with imbalance (high, medium, and low) and distraction (filtering, positive-correlation, and perfect-correlation) as factors. Only the RON subcomponents were compared in the standard-after minus standard-before waves. The effect of congruency on RON was measured with a three-way repeated measures ANOVA, including imbalance (high, medium, and low), distraction (filtering and positive-correlation) and congruency (congruent-deviant minus standard-before and incongruent-deviant minus standard-before) as factors. Bonferonni adjusted $p$-values are reported for individual comparisons. Where appropriate, Greenhouse-Geisser corrections along with adjusted degrees of freedom and corresponding epsilon values are reported.

Despite the absence of significant behavioral correlations with the RON voltage in the Study 1, we hoped that by separating out the different mechanisms of the RON these connections might be more visible in this study. In order to limit the number of correlations run, we first collapsed imbalance across levels of distraction, resulting in high, medium, and low conditions for both congruent and incongruent deviants. In doing so, we are able to maintain measures of both attention and working memory. To further decrease the number of calculations, we only used the behavioral measures for the standard-afters, as we found these were the most reliable measures in Study 1.
Results

Behavioral. ANOVA of accuracy revealed main effects of imbalance (F(2,30)=33.778, p<0.0001, \( \eta_p^2 = 0.692 \)) and trial-type (F(1.059,15.883)=81.949, \( \varepsilon = 0.529, p<0.0001, \eta_p^2 = 0.845 \)). A significant two-way interaction was also found between imbalance and trial-type (F(2.208,33.115)=26.603, \( \varepsilon = 0.552, p<0.0001, \eta_p^2 = 0.639 \)), and a significant three-way interaction among distraction, imbalance and trial-type (F(3.203,48.041)=3.315, \( \varepsilon = 0.400, p = 0.0252, \eta_p^2 = 0.181 \)). As can be seen in Figure 21, the latter effect is primarily relegated to the deviants, with conditions remaining relatively equal for both the standard-befores and standard-afters, indicating little to no effect of post-deviance. Figure 21b demonstrates that, overall, accuracy decreases as imbalance increases from low to high. However, this trend is clearly affected by levels of distraction. The perfect-correlation condition shows a remarkably linear trend from low to high imbalance, whereas the introduction of the incongruent-deviants in the other conditions suggests a floor is being reached. The positive-correlation condition begins to level off at the medium imbalance, dropping another 4.55% at high, while the filter condition dropped only 1.98% from medium to high. There were no effects of congruence on accuracy.

As with accuracy, ANOVA of RT revealed main effects of both imbalance (F(2,30)=7.222, \( p = 0.0028, \eta_p^2 = 0.325 \)) and trial-type (F(1.286,19.296)=50.838, \( \varepsilon = 0.643, p<0.0001, \eta_p^2 = 0.772 \)). There was also a significant interaction between imbalance and trial-type (F(2.529,37.933)=3.304, \( \varepsilon = 0.632, p = 0.0164, \eta_p^2 = 0.181 \)) and distraction, imbalance and trial-type (F(3.778,56.676)=4.283, \( \varepsilon = 0.472, p = 0.0049, \eta_p^2 = 0.222 \)). As shown in Figure 22, participants responded fastest to the standard-befores, slowest to deviants, and intermediate to standard-afters, indicating an effect of post-deviance. Unexpectedly, as can be seen in Figure 22b, the three distraction levels interacted uniquely with imbalance. The filtering condition remained
relatively unchanged from low to high imbalance, whereas the positive condition showed the expected increase in reaction time with increasing deviance strength. The perfect condition increases from low to medium, but then makes a sharp decrease at the high-imbalance. Interestingly, this same effect can be seen in the filtering condition in the standard-before (Figure 22a) and standard-after (Figure 22c).

In congruity analyses of RT, there was a significant interaction between imbalance and congruence (F(2,30)=6.559, p=0.0043, $\eta_p^2=0.304$). As can be seen in Figure 23, on congruent trials RT during low imbalance is significantly faster than during both high (p=0.0117) and medium (p=0.0078) imbalance. The difference in RT between congruent and incongruent trials is marginally significant (p=.1072) when imbalance was low.

**Distraction ERPs.** For the deviant minus standard-before wave, ANOVA of the MMN voltage revealed a significant main effect of imbalance (F(2,30)=3.884, p=0.0316, $\eta_p^2=0.206$), with voltage decreasing as imbalance increased from low to high (Figure 24). Bonferroni post-hoc test confirms a difference only between low and high levels of imbalance (p=0.0400), with neither differing from medium imbalance. The P3a showed no significant effects. ANOVA of amplitude to Early-RON, however, showed a significant main effect of distraction (F(2,30)=3.569, p=0.0407, $\eta_p^2=0.192$). Reminiscent of the difference seen for the reaction time, The positive-correlation condition was marginally different from both the filter (p=0.081) and the perfect-correlation (p=0.106) conditions (Figure 25). Mirroring the reaction time results again, the congruence ANOVA resulted in a significant Imbalance x Congruence interaction (F(2,30)=4.662, p=0.0173, $\eta_p^2=0.237$). Bonferroni corrections revealed that the congruent and incongruent RON mirror each other up to the medium condition but diverge at high-imbalance
Interaction of Attention and Memory on RON

(Figure 26). The congruent is 2.302 μV more negative at high than the incongruent (p=0.0328). The Late-RON showed no significant differences in this difference wave.

The standard-after minus standard-before produced no significant differences in Early-RON amplitude; however, a significant distraction by imbalance interaction was found in Late-RON amplitude (F(4,60)=2.564, p=0.0473, 0.146). As can be seen in Figure 27, the medium condition follows the same pattern as the Early-RON in the deviant minus standard-before wave, with positive-correlation being less negative than the filter and perfect-correlation conditions. The low and high imbalance conditions follow opposite patterns with voltage rising from filter to positive-correlation to perfect-correlation at low imbalance, but the pattern reversing at high imbalance. It is interesting to note that only in the filter/low, filter/medium, perfect-correlation/medium, and perfect-correlation/high conditions are the difference waves negative in voltage, indicating that for the remaining conditions the standard-after was actually less negative in voltage than the standard-before. The late positivity in these conditions might reflect a similar mechanism as the late positivity seen in the grand averages of healthy elderly seen in Study 1.

Correlations. Only standard-after behavioral measures correlated with the RON (Tables 13-14). Both the medium (r = 0.601, p = 0.0139) and high (r = -0.566, p = 0.0222) imbalance conditions showed a significant correlation between standard-after accuracy and the Early RON voltage for the incongruent minus standard-before. However, they were in opposite directions. The medium imbalance condition showed a similar correlation for the Late RON in this same wave (r = 0.606, p = 0.0139). Finally, the congruent minus standard-before Early RON voltage showed a significant correlation with standard-after reaction time (r = 0.656, p = 0.0058) in the high imbalance condition.
Discussion

**Behavioral Distraction.** The task was clearly successful in creating behavioral distraction. Accuracy on deviant trials decreased with the strength of the deviance and was greater for congruent than incongruent deviants.

The reaction time results were more complex, however, departing slightly from expected outcomes and revealing a dependence on the interaction of the two experimental manipulations. Imbalance had no effect on RT in filtering condition. In the positive condition, participants were able at the low-imbalance to take advantage of the congruency, showing faster RTs, which then increased at the medium imbalance. This benefit at low-imbalance can also be seen in the imbalance by congruence interaction, with the low/congruent deviants having a significantly reduced reaction time. However, at high-imbalance the positive correlation seemed to be working against the participants, with reaction times reaching levels well above the filtering condition. A similar pattern emerged in the perfect correlation condition. At low-imbalance participants showed redundancy gain on congruent trials, with reaction times at the same level as the positive condition, possibly demonstrating that participants have reached a floor at this level. However, RTs increase from low to medium imbalance, and at a much steeper rate, presenting the worst reaction times of the study. The latter finding is counterintuitive because only two deviants appear in the perfect condition (versus four in the other conditions), which would imply that RTs would decrease overall. Even more surprising, the perfect condition shows a sharp decrease in reaction times from medium to high, with reaction times even lower than in the positive condition.
It does not appear that the differences between reaction time and accuracy in the correlation conditions are due merely to speed/accuracy trade-off. Otherwise one would have expected levels of imbalance to affect the two dependent measures in a similar way. It appears, instead, that reaction time reveals differential reliance on multiple mechanisms. In the positive condition participants were able to engage working memory mechanisms in an attempt to take advantage of the higher probability of congruent deviants, as compared to incongruent deviants. This strategy works with low-imbalance where the deviant is generally less distractive. At medium- and high-imbalance, the use of working memory begins to work against participants. The lack of activation of top-down working memory processes may be the reason why RT in the filtering-condition was largely unaffected by imbalance. The implication is that the two systems, attentional and working memory, work against each other during processing to prolong RT. This account also explains the disproportionate increase in RT from low to medium imbalance in the perfect-correlation condition: participants are attempting to activate working memory stores to an even greater degree, resulting in even greater prolongation.

The relatively large decrease in reaction time seen at high imbalance with perfect correlation suggests a switch between mechanisms. Following the logic above it may be that participants decrease their reliance on simple attentional mechanisms and move towards greater reliance on working memory. This switch to working memory may also be evident in the finding of a pronounced difference between the early and late phases of the RON in the perfect/high condition, as seen in Figure 19.

**Deviance Strength.** Manipulation of deviance strength is a well-established methodology to influence distraction processing. As it involves only a change in stimulus properties this manipulation is generally considered to affect bottom-up processes, used here to
manipulate the more general attentional aspect of the RON. While the mechanism underlying this manipulation may seem relatively implicit, the process by which it creates distraction, and more specifically its effect on the RON, is not well understood. One of the most reliable results of this manipulation is a correlation between deviance strength and the amplitude of the MMN, with greater deviance-strength resulting in a more negative MMN. This correlation is often used as evidence that the MMN involves a neural calculation of the difference between neural representations of stimuli. Along this logic, distraction is created by signaling degrees of difference, promoting automatic allocations of attention towards the distracting stimulus. This relationship was clearly duplicated in this study, indicating that the experimental manipulation was successful.

Counter to previous research, results from the current study do not show a main effect of imbalance on the early or late phases of the RON (Yago, Corral, and Escera, 2001; Berti, Roeber, and Schröger, 2004). However, in early RON we found an effect of imbalance modulated through congruency (Figure 26). Interestingly, while we found a generally linear relationship of imbalance on RON for incongruent trials, it is in the opposite direction as that described by previous researchers. Contrary to those previous studies, though, this is the specifically the early phase of the RON rather than an overlap of the two. If we think of this phase of the RON as working memory activation during reorientation, then this pattern makes sense, in that working memory activation does not benefit the process for the incongruent trials. This demonstrates that as deviance strength increases task difficulty, participants activate working memory processes less and less to the point of a near zero RON to the incongruent/high deviants.

The congruent trials seem to follow the same pattern as the incongruent trials for the low and medium imbalance conditions. In the medium imbalance condition, we again have evidence
of a mechanism switch with an increase in RON amplitude for the congruent/high deviants. Interestingly, this is reminiscent of the reaction time results for the perfect condition (not included in this analysis) that includes only congruent trials. It seems from these patterns that the RON system has a default mode activated on congruent and incongruent trials during low and medium imbalance. Only once the distraction reaches some specific point, seemingly between medium and high imbalance, does the system prioritize activations, deactivating the early-RON for incongruent trials at high imbalance and fully activating it at high imbalance for congruent trials.

We predicted that we would replicate the previous research for deviance strength in the late-RON, however this was not the case. The values we specifically chose did not allow for a clear delineation between the late-RON effects, perhaps due to a ceiling effect where participants are switching mechanisms. Despite this we observed an interaction in the late-RON between distraction and imbalance measured in the standard-after minus standard-before wave. It may be that in this specific study deviance processing has dropped enough by the time of the standard-after that this mechanism is more readily discernible. Interestingly, the perfect condition, consisting of only congruent trials, followed the expected pattern with increasing amplitudes associated with higher imbalance. This was not true in the filtering and positive conditions. The filtering condition showed a relatively large RON at low and medium imbalance, which then diminished in the high imbalance condition. RON was miniscule at all imbalance levels in the positive condition. The fact that the perfect condition shows a large late-RON at high imbalance and the congruent trials show a large early-RON at high imbalance demonstrates that the two phases of the RON are not mutually exclusive: An increase in one does not result in a decrease in the other. Thus, the mechanism switch evident in the results may not involve decreasing
available resources, but rather involve increasing the specificity of the mechanism being employed. Possible explanations for the varying patterns between the distraction conditions will be discussed later.

**Working Memory.** The distraction manipulation for this study was developed to activate working memory while avoiding some of the complications seen in previous studies. Much of the research focusing on the role of working memory on the RON has employed predictive cues. Cueing brings with it two primary complications. First, much of the research relies on cues that precede the deviant stimulus. As is apparent from work into post-deviant processing, this can lead to difficulties when attempting to separate purely deviant processing. This concern can be alleviated by presenting the cue simultaneously with the deviant stimulus in a separate sensory domain, such as vision. Yet this brings with it separate processing which can again affect the interpretation of the data. The goal in the distraction manipulation was to avoid these complications by embedding the memory information into the same stimulus. Beyond this, we did not cue presentation of a deviant, but rather cued task-relevant information using task-irrelevant information. In order to make use of this information, participants must process both the pitch and timbre of the stimulus as well as activate working memory to take advantage of any perceived correlations between the pitch and timbre of the deviant trials. While perhaps involving its own set of complications, the distraction manipulation activates working memory in a manner that the imbalance manipulation does not.

Previous research suggested that the RON amplitude would be greatest under conditions in which the participant was unprepared for the deviant, in this case the filtering condition (followed by the positive and then the perfect condition). However, unexpectedly, the current study found that RON amplitude was greatest in the perfect condition. One explanation is that
working memory load is least for the perfect condition (i.e., it only contains two deviants as opposed to four in the other conditions). Lower working memory load has been associated in previous research with a more negative RON (SanMiguel, Corral, & Escera, 2008). If this same logic is applied to the distraction x imbalance interaction for the late-RON we see that the RON follows the hypothesized pattern in the perfect condition because of the relative low degree of load on working memory. In the positive condition we see evidence of overloading of working memory, with the system unable to adapt to varying levels of imbalance given the increase in deviant stimuli and congruence. And in the filtering condition RON is larger during low and medium imbalance due to the lack of preparation given no correlation in the deviants. However, at high imbalance, we see the same switch as seen previously, with a large decrease in amplitude.

**Brain/Behavior.** Only the behavioral measures to standard-after-deviant correlated with RON amplitude, reminiscent of correlations reported in Study 1. If the behavioral response to the standard-after is seen as evidence of the success or failure of reorientation, these connections make sense. Yet the direction of the correlations varied between imbalance conditions. In the medium imbalance condition, a higher early-RON amplitude was associated in the incongruent minus standard-before wave with better accuracy to the standard-after, whereas the opposite was true in the high imbalance condition. In appearing only on incongruent trials, the result counters the previous understanding of the large increase in RON across imbalance on congruent trials (see Figure 26). This suggests some difference in mechanism in handling medium and high imbalance on incongruent trials, as we suggested previously for congruent trials. The fact that RON amplitude decreases with imbalance on incongruent trials is the primary evidence of a mechanism switch. Another possible explanation might be that there is some other variable that
differs between the medium and high imbalance conditions that leads naturally to an increase in RON amplitude rather than the expected linear relationship.

**General Discussion**

We set out with two primary goals in mind. The first was to explore possible connections between mechanisms involved in the production of the RON. The second was to investigate possible relationships between the RON and behavioral output. The results imply that the RON is more complicated than has been previously suggested.

In Study 1 we found that the RON significantly differed in amplitude between the younger and older adults while concurrently showing no difference in behavioral distraction, only overall levels of behavioral success. In addition to this, the two groups produced opposing correlations between RT and RON latency. Both of these pieces of evidence point to some alternate, or possibly compensatory, mechanism being employed by the older adults allowing them to reach distraction levels equal to the younger adults.

Study 2 bolsters these findings giving a more detailed picture of the RON as it relates to attention and working memory. We found that in the perfect-correlation condition, there was a large jump in RT between the medium and high imbalances. As well, between medium and high imbalance for congruent trials we found a large shift in RON amplitude. Again, medium and high imbalance for incongruent deviants showed correlations in opposite directions. Beyond these shifts between medium and high imbalance, we as well found a main effect of distraction for the early phase of the RON with a negative jump from positive-correlation to perfect-correlation. Alongside these voltage changes, we found evidence that the early and late phases of the RON are not mutually exclusive, with large amplitudes for both subcomponents at high
imbalance. These findings in connection with Study 1 verify the involvement of multiple mechanisms in the production of the RON and bring new evidence that these mechanisms as easily distinguished from one another as other studies have suggested.

**Multiple Mechanisms**

Previous research into the RON has focused primarily on the mechanisms that affect its production. Various manipulations lead to changes in the voltage and timing of the RON suggesting to some that it comprises at least two different processes, one that is based in attention and the other in working memory. Evidence for the identification of these two processes comes from two primary sources. First, experimental manipulations of attentional control (e.g. deviance strength) and working memory (e.g. load, cueing) seem to be the primary modulators of the RON. Secondly, Munka and Berti (2006) found that the early phase of the RON was only present in a condition requiring working memory activation. The current set of studies set out to investigate whether and how the attentional and working memory processes interact in producing the RON. The current results confirm that the RON can be altered by manipulations of both attention and working memory and in addition suggest that under certain circumstances there appears to be a degree of switching between these mechanisms.

Mechanism switching was first hinted at in the fact that despite differences in the RON production between the two age groups, the older adults did not show any evidence of increased distractibility. This evidence was maintained in the opposing correlations between the two age groups in the first study and further revealed in the opposing correlations observed in the second study. Moreover, evidence of switching is provided by the large and rather unexpected surges in RON amplitude that were found as a result of both imbalance and distraction manipulations. For
example, the amplitude shift observed between the medium and high imbalance conditions for congruent-deviants has not been found in previous research, and does not coincide with the findings for the MMN. This suggests a change from attention to working memory processing, as perhaps does the difference in RON magnitude between the positive and perfect distraction levels. If these voltage changes do in fact reflect a switch in mechanism, a similar explanation might be applied to the drop in RON amplitude with age, which however could also be attributed to a mere dampening of overall processing.

In order to give greater validity to these claims it would be necessary to repeat the second study with an enhanced number of levels of each manipulation. If we then were still to see large voltage jumps across levels it would give further evidence of an actual processing switch. If instead we observed gradual changes across levels, this would imply that instead of a switch, the amplitude changes actually represented differential reliance on multiple mechanisms.

It is important to note that evidence from the current studies does not support the claim that attention and working memory mechanisms identify tightly with different phases of the RON. However, perhaps the methodology for distinguishing the two phases was not robust enough to disentangle separate processes of the RON. Thus, the measurements might capture processing from both mechanisms at both early and late phases. This possibility can be evaluated only in a study that more explicitly separates in time the deviant and standard features of the stimuli, as was done in previous research. While this methodology presents complications, it seems to be the most successful way to separate out the two phases of the RON.
**Brain/Behavior**

The second goal of these studies was to investigate the ways in which the RON correlates with behavior. Overall, it appears that the production of the RON is strongly tied to behavioral outcomes, particularly for the standards that followed each deviant. The fact that behavioral response to the standard-after was the most reliable predictor of the deviant-minus-standard-before RON seems to indirectly support the claim that the RON reflects reorientation. The reorientation hypothesis relies primarily on only a handful of the initial studies of RON. The current study provides new evidence in favor of this hypothesis. If we make the assumption that the degree of post-deviance distraction is a direct result of the success of reorientation, then it follows logically that the RON should be correlated with behavioral responses to the standard-after. In order to give more credence to this assumption we would need to develop a methodology that is able to reliably vary the degree of post-deviance behavioral distraction, perhaps by way of memory load or a similar manipulation.

If this assumption is correct, then the behavioral response to the standard-after is an indirect measure of reorientation processing. Before reaching this conclusion, however, we must better understand the specific connections and directions. For example, it would be illuminating to repeat Study 1 with a population experiencing working memory or attentional impairments and then to compare the resulting correlations with those found in the current study’s undiagnosed young and old samples. Perhaps the shifts in processing we observed between young and old might be better understood as a difference in working memory or attention processing. It would be informative to investigate how the correlations change as more levels of imbalance are added.
Summary of Novel Findings

Study 1 hypothesized that under the correct experimental conditions it would be possible to demonstrate a relationship between behavioral success and the RON for both younger and older adults, and that this relationship would likely be divergent between the two groups. This was first study to show that to be the case, with the two groups showing opposing correlations between reaction time and RON latency. Furthermore, the specific trial types to which the RON latency was associated differed between the groups. These two findings demonstrate that the two age groups are engaged in some degree of disparate processing, which is represented in this connection between the timing of the RON and the reaction time. This fact suggests that the two groups are relying on separate cognitive mechanisms in order to complete the task successfully. However, this is ultimately only evidence that a difference exists between the groups and not specific evidence of multiple cognitive processes underlying the RON.

Study 2 was the first study in the literature to investigate the RON in terms of simultaneous manipulations of both attentional control (i.e. deviance strength) and working memory (i.e. congruency cueing). Unlike the MMN, whose voltage responded exactly as seen in previous research, the voltage of the RON was shown to be highly variable, demonstrating unexpected shifts in voltage. This was the case for congruent trials between medium and high imbalance, as well as for all deviants between the positive-correlation and perfect-correlation. These jumps in amplitude seem to suggest a shift in reliance upon multiple mechanisms. Beyond this, it was also demonstrated that accuracy to the standard-after trials was correlated with RON voltage in opposite directions for the medium and high imbalance conditions, again suggesting a difference of mechanism.
Limitations

A major limitation of this dissertation is that the methodologies used to define the RON differed between the two studies. In Study 1 we defined the RON as a specific peak for each participant over a time window that encompassed both phases of the RON. We selected the methodology used in Study 1 to match that used by previous researchers evaluating brain/behavior correlations. The Study 1 methodology enjoys the benefit of providing both a voltage and latency measure of RON. The methodology Study 2 also matches that of many RON researchers. In this methodology, we identified the peaks of both phases of the RON in the grand average and used that latency value to average the voltage over a 50 ms time window for each subject. The goal here was to define RON in a manner that enabled a clear distinction between the early and late phases. While the choice of methodology was purposeful it nonetheless complicates comparisons between the two studies. RON amplitude measured in the first study clearly combines early and late phases leading to ambiguity of the actual source. RON amplitude in the second study is a better approximation of the separate processing of the phases, but most likely still involves a degree of overlap between phases. This difficulty in defining the RON itself seems to be a general theme throughout the previous research and continues to be one for the current set of studies. Given that the RON is relatively less well-defined than other ERP components it would be interesting to implement the different methodologies employed by researchers to determine whether the conclusions reached from each are the same.
Interaction of Attention and Memory on RON

Tables

Table 1. Study 1 Stimuli Values.

<table>
<thead>
<tr>
<th>Type</th>
<th>Task</th>
<th>Block</th>
<th>Stimuli</th>
<th>p.</th>
<th>Stimuli</th>
<th>p.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pitch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20% DC</td>
<td>490 Hz</td>
<td>35%</td>
<td>510 Hz</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40% DC</td>
<td>490 Hz</td>
<td>35%</td>
<td>510 Hz</td>
<td>35%</td>
</tr>
<tr>
<td>Standards</td>
<td></td>
<td></td>
<td>490 Hz</td>
<td>35%</td>
<td>490 Hz</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>510 Hz</td>
<td>510 Hz</td>
<td>35%</td>
<td>510 Hz</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pitch</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20% DC</td>
<td>490 Hz</td>
<td>15%</td>
<td>510 Hz</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40% DC</td>
<td>490 Hz</td>
<td>15%</td>
<td>510 Hz</td>
<td>15%</td>
</tr>
<tr>
<td>Deviants</td>
<td></td>
<td></td>
<td>490 Hz</td>
<td>15%</td>
<td>490 Hz</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>510 Hz</td>
<td>510 Hz</td>
<td>15%</td>
<td>510 Hz</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Timbre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>490 Hz</td>
<td>490 Hz</td>
<td>15%</td>
<td>490 Hz</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>510 Hz</td>
<td>510 Hz</td>
<td>15%</td>
<td>510 Hz</td>
<td>15%</td>
</tr>
</tbody>
</table>

1. DC denotes the Duty Cycle
2. p. indicates the probability of stimulus occurrence

Table 2. Significant ANOVA Effects for Behavior

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Age</td>
<td>5.185, 1,20</td>
</tr>
<tr>
<td></td>
<td>Trial-Type</td>
<td>20.723, 1.536,30.717</td>
</tr>
<tr>
<td>Reaction</td>
<td>Age</td>
<td>22.346, 1,20</td>
</tr>
<tr>
<td>Time</td>
<td>Trial-Type</td>
<td>36.131, 2,40</td>
</tr>
<tr>
<td></td>
<td>Age X RON-Timing</td>
<td>17.885, 1,20</td>
</tr>
<tr>
<td></td>
<td>Trial-Type X Age X RON-Timing</td>
<td>3.930, 2,40</td>
</tr>
</tbody>
</table>
### Table 3. Significant ANOVA Effects for Voltage in Deviant minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>F</th>
<th>df</th>
<th>p</th>
<th>ε</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMN</td>
<td>Age</td>
<td>14.457</td>
<td>1.20</td>
<td>0.0011</td>
<td>0.420</td>
<td></td>
</tr>
<tr>
<td>P3a</td>
<td>Age</td>
<td>7.318</td>
<td>1.20</td>
<td>0.0136</td>
<td>0.268</td>
<td></td>
</tr>
<tr>
<td>RON</td>
<td>Age</td>
<td>5.737</td>
<td>1.20</td>
<td>0.0265</td>
<td>0.223</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Significant ANOVA Effects for Latency in Deviant minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>F</th>
<th>df</th>
<th>p</th>
<th>ε</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>P3a</td>
<td>Age</td>
<td>7.587</td>
<td>1.20</td>
<td>0.0122</td>
<td>0.275</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5. Significant ANOVA Effects for Latency in Standard-After minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>F</th>
<th>df</th>
<th>p</th>
<th>ε</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>RON</td>
<td>RON-Timing</td>
<td>8.363</td>
<td>1.20</td>
<td>0.0090</td>
<td>0.295</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Age X RON-Timing</td>
<td>8.130</td>
<td>1.20</td>
<td>0.0099</td>
<td>0.289</td>
<td></td>
</tr>
</tbody>
</table>

### Table 6. Significant Correlations Between RON Latency in Deviant minus Standard-Before and Reaction Time

<table>
<thead>
<tr>
<th>Condition</th>
<th>Young</th>
<th>Old</th>
<th>p</th>
<th>ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard-Before</td>
<td>ns</td>
<td>0.751 (p = 0.0123)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviant</td>
<td>-0.785 (p = 0.0008)</td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard-After</td>
<td>-0.611 (p = 0.0204)</td>
<td>0.870 (p = 0.0011)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 7. Study 2 Stimuli Values

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards</td>
<td>All</td>
<td>All</td>
<td>500 Hz</td>
<td>36%</td>
<td>500 Hz</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filtering</td>
<td></td>
<td></td>
<td>480 Hz</td>
<td>7%</td>
<td>480 Hz</td>
<td>7%</td>
<td>480 Hz</td>
<td>7%</td>
</tr>
<tr>
<td>Low</td>
<td></td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td></td>
<td></td>
<td>480 Hz</td>
<td>4%</td>
<td>520 Hz</td>
<td>4%</td>
<td>480 Hz</td>
<td>10%</td>
</tr>
<tr>
<td>Perfect</td>
<td></td>
<td></td>
<td>--</td>
<td></td>
<td>--</td>
<td></td>
<td>480 Hz</td>
<td>14%</td>
</tr>
<tr>
<td>Deviants</td>
<td>Medium</td>
<td></td>
<td>463 Hz</td>
<td>7%</td>
<td>540 Hz</td>
<td>7%</td>
<td>463 Hz</td>
<td>7%</td>
</tr>
<tr>
<td>Filtering</td>
<td></td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td></td>
<td></td>
<td>463 Hz</td>
<td>4%</td>
<td>540 Hz</td>
<td>4%</td>
<td>463 Hz</td>
<td>10%</td>
</tr>
<tr>
<td>Perfect</td>
<td></td>
<td></td>
<td>--</td>
<td></td>
<td>--</td>
<td></td>
<td>463 Hz</td>
<td>14%</td>
</tr>
<tr>
<td>High</td>
<td></td>
<td></td>
<td>445 Hz</td>
<td>7%</td>
<td>560 Hz</td>
<td>7%</td>
<td>445 Hz</td>
<td>7%</td>
</tr>
<tr>
<td>Filtering</td>
<td></td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
<td>20% DC</td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td></td>
<td></td>
<td>445 Hz</td>
<td>4%</td>
<td>560 Hz</td>
<td>4%</td>
<td>445 Hz</td>
<td>10%</td>
</tr>
<tr>
<td>Perfect</td>
<td></td>
<td></td>
<td>--</td>
<td></td>
<td>--</td>
<td></td>
<td>445 Hz</td>
<td>14%</td>
</tr>
</tbody>
</table>

1. DC denotes the Duty Cycle
2. p. indicates the probability of stimulus occurrence
### Table 8. Significant ANOVA Effects for Behavior

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Imbalance</td>
<td>33.778</td>
</tr>
<tr>
<td></td>
<td>Trial-Type</td>
<td>81.949</td>
</tr>
<tr>
<td></td>
<td>Imbalance X Trial-Type</td>
<td>26.603</td>
</tr>
<tr>
<td></td>
<td>Distraction X Imbalance X Trial-Type</td>
<td>3.315</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>Imbalance</td>
<td>7.222</td>
</tr>
<tr>
<td></td>
<td>Trial-Type</td>
<td>50.838</td>
</tr>
<tr>
<td></td>
<td>Imbalance X Trial-Type</td>
<td>3.304</td>
</tr>
<tr>
<td></td>
<td>Distraction X Imbalance X Trial-Type</td>
<td>4.283</td>
</tr>
</tbody>
</table>

### Table 9. Significant ANOVA Effects for Behavior with Congruency

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Imbalance</td>
<td>10.219</td>
</tr>
<tr>
<td></td>
<td>Distraction X Imbalance</td>
<td>4.470</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>Distraction X Imbalance</td>
<td>3.458</td>
</tr>
<tr>
<td></td>
<td>Congruence</td>
<td>6.559</td>
</tr>
</tbody>
</table>

### Table 10. Significant ANOVAEffects for Voltage in Deviant minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$F$</td>
</tr>
<tr>
<td>MMN</td>
<td>Imbalance</td>
<td>3.884</td>
</tr>
<tr>
<td>Early RON</td>
<td>Distraction</td>
<td>3.569</td>
</tr>
</tbody>
</table>
**Table 11.** Significant ANOVA Effects for Voltage with Congruency in Deviant minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early RON Distraction</td>
<td>4.618, 1.15, 0.0484, 0.235</td>
<td></td>
</tr>
<tr>
<td>Early RON Imbalance X Congruence</td>
<td>4.662, 2.30, 0.0173, 0.237</td>
<td></td>
</tr>
</tbody>
</table>

**Table 12.** Significant ANOVA Effects for Voltage in Standard-After minus Standard-Before

<table>
<thead>
<tr>
<th>ERP</th>
<th>Effect</th>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late RON Distraction X Imbalance</td>
<td>2.564, 4.60, 0.0473, 0.146</td>
<td></td>
</tr>
</tbody>
</table>

**Table 13.** Significant Correlations Between RON Voltage in Incongruent minus Standard-Before and Standard-After Accuracy

<table>
<thead>
<tr>
<th>Medium Early RON</th>
<th>Medium Late RON</th>
<th>High Early RON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium Accuracy</td>
<td>0.601 (p=0.0139)</td>
<td>0.606 (p=0.0129)</td>
</tr>
<tr>
<td>High Accuracy</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

**Table 14.** Significant Correlations Between RON Voltage in Congruent minus Standard-Before and Standard-After Reaction Time

<table>
<thead>
<tr>
<th>High Early RON</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.656 (p=0.0058)</td>
</tr>
</tbody>
</table>
Figure 1. Study 1 Pitch Task Design.

Tones were presented with one of two pitch values with either a high probability standard timbre or a low probability deviant timbre. Participants were instructed to ignore the timbre changes and only respond whether the pitch was high or low with a mouse click. The timbre task followed the same parameters, but participants responded to the timbre of the tone.
Figure 2. 160 Channel ABC Montage.

Channels chosen for averaging are outlined in black, centered around Fz. These 8 channels were chosen based on initial visual inspection of the data as well as an attempt to mimic the channels chosen by previous research.
Figure 3. *RON-Timing Justification.*

Based on visual inspection of the peaks an approximately 50ms gap was identified, represented in gray above, that generally matched with the latency windows of the early and late phases of the RON.
Figure 4. Young/Old Accuracy.

Accuracy is plotted for both age groups by trial-type. Young are significantly more accurate than the older adults. Participants responded significantly less accurately to deviants than both standard types. There is no significant post-deviance effect as standard-before and standard-after trials do not differ significantly. Error bars indicate standard errors across participants.
Interaction of Attention and Memory on RON

Figure 5. Young/Old Reaction Time.

Reaction time is plotted for both age groups by trial-type. The young are significantly faster than the older adults. Both groups responded significantly slower to both the deviants and standard-afters as compared to the standard-befores. There was no significant difference between deviants and standard-afters demonstrating a significant effect of post-deviance. Error bars indicate standard errors across participants.
Reaction time is plotted here for the standard-befores (A), deviants (B), and standard-afters (C). There was a significant three-way interaction of trial-type X age X RON-timing. The age X RON-timing interaction is clear, with the early-producers remaining relatively stable, while the two age groups show a significant difference for the late-producers. Error bars indicate standard errors across participants.
Figure 7. Reaction Time: Trial-Type X Age Interaction for Reaction Time in Late Producers.

The graph demonstrates the difference in slope seen for the late-producers. The deviants and standard-befores are generally parallel, while the standard-afters have a slightly larger slope. Error bars indicate standard errors across participants.
These are the grand average waves for the deviant minus standard-before comparison. (A) and (B) show each group individually, with standard error depicted in gray, as well as the three distraction ERPs marked. Graph (C) plots the two groups together, denoting that the morphology of the wave at the RON time window differs significantly between the two age groups, with the younger adults having a long and more sustained negativity, while the older adults have a much less-defined peak.
Figure 9. Topographic Voltage Maps at RON Peak.
The voltage topography is mapped here, plotted for a 50 ms time window centered at the peak of the RON from the grand-average. (A) depicts the voltage topography for the younger adults and (B) and (C) depict the voltage topography for the older adults. (A) and (B) are on the same scale and the difference between the two demonstrates the distinction in amplitude of the RON between the groups. However, when the scale is brought lower in (C), the general similarity in morphology can be seen.
Figure 10. Deviant minus Standard-Before MMN Peak Voltage: Age Effect.

The young have a significantly more negative MMN peak voltage than the older adults.
Figure 11. Deviant minus Standard-Before P3a Peak Voltage: Age Effect.

The young have a significantly more positive P3a peak voltage than the older adults.
Figure 12. Deviant minus Standard-Before RON Peak Voltage: Age Effect.

The young have a significantly more negative RON peak voltage than the older adults.
Figure 13. Standard-After minus Standard-Before Grand Average Difference Waves.

These are the grand average waves for the standard-after minus standard-before comparison. (A) and (B) show each group individually, with standard error depicted in gray. (C) plots the two groups together, showing that the overall morphology of the waves is generally comparable. Notably, the peaks are much smaller as compared to the deviant minus standard-before wave.
**Figure 14.** *Standard-After minus Standard-Before RON Latency: Age X RON-Timing Interaction.*

This graph shows that for the standard-after minus standard-before wave the younger adults follow the same timing as the deviant minus standard-before wave. This is not the case for the older adults who remain steady in latency. Error bars indicate standard errors across participants.
**Figure 15. Deviant Reaction-Time X RON Latency Correlation for Young.**

This graph demonstrates the negative correlation between the deviant reaction time and the RON latency in the deviant minus standard-before wave for the younger adults ($r = -0.785$, $p = 0.0008$). Longer reaction times are associated with earlier RON peaks.
Figure 16. Standard-After Reaction-Time X RON Latency Correlation for Young.

This graph demonstrates the negative correlation between the standard-after reaction time and the RON latency in the deviant minus standard-before wave for the younger adults ($r = -0.611$, $p = 0.0204$). Longer reaction times are associated with earlier RON peaks.
Figure 17. Standard-After Reaction-Time X RON Latency Correlation for Old.

This graph demonstrates the positive correlation between the standard-after reaction time and the RON latency in the deviant minus standard-before wave for the older adults ($r = 0.870, p = 0.0011$). Longer reaction times are associated with later RON peaks.
Figure 18. Standard-Before Reaction-Time X RON Latency Correlation for Old.

This graph demonstrates the positive correlation between the standard-before reaction time and the RON latency in the deviant minus standard-before wave for the older adults ($r = 0.751$, $p = 0.0123$). Longer reaction times are associated with later RON peaks.
**Figure 19. Example of Early and Late RON Peaks in Perfect/High Condition.**

(A) depicts the grand average difference wave for deviant minus standard-before at Perfect/High condition. The delineation between the early and late phases of the RON are depicted. (B) and (C) show the voltage topographies of 50 ms time windows centered at the early and late phases of the RON. Both phases show a clear frontal negativity. While the late phase has a corresponding posterior positivity, the early phase does not have the same clear distinction, suggesting that the two peaks might have separate generators.
Interaction of Attention and Memory on RON

Figure 20. Deviant minus Standard-Before Grand Average Waveforms.
Graphs show the grand average difference waves for the deviant minus standard-before comparison for all conditions. The MMN, P3a, Early-RON, and Late-RON peaks are all marked in red. As can be seen the distinction between the early and late phases of the RON waxes and wanes between the different conditions.
Interaction of Attention and Memory on RON 102

Figure 21. Accuracy: Trial-Type X Imbalance X Distraction Interaction.

Graphs show that the effect is largely relegated to the deviants (B), with the standard-befores (A) and standard-afters (C) remaining relatively stable between conditions, demonstrating that there is no post-deviance effect on accuracy. (B) shows a clear effect of imbalance with all levels of the distraction manipulation decreasing from low towards high. The distraction levels clearly affect this trend, though, with the perfect condition showing a linear trend, while the filter and positive conditions seem to reach a floor. Error bars indicate standard errors across participants.
These graphs depict the effect of trial-type, with participants responding fastest to standard-befores (A) and slowest to deviants (B), with standard-afters (C) averaging somewhere between, demonstrating an effect of post-deviance. (B) demonstrates that the three distraction levels interact with the imbalance levels with different patterns. The filter remains largely stable from low to high, and the positive condition follows the expected pattern rising from low to high. The perfect condition seems to suggest a mechanism switch, following the expected pattern from low to medium and then dropping at high. Error bars indicate standard errors across participants.
Figure 23. Reaction Time: Imbalance X Congruency Interaction.

Depicts the different patterns for reaction time based on congruency. Participants were significantly faster at the low condition for congruents as compared to the medium and high. There was no significant difference between the three levels for the incongruent deviants. Error bars indicate standard errors across participants.
Figure 24. Deviant minus Standard-Before MMN Voltage: Imbalance Effect.

Depicts the expected increase in peak negativity with distractor strength as has been described in previous research. Error bars indicate standard errors across participants.
The Early-RON voltage showed a significant effect of distraction, with Bonferroni comparisons showing a marginal difference between Positive and the other two conditions. Error bars indicate standard errors across participants.
The Early-RON showed a significant interaction of imbalance and congruency. Bonferroni corrections demonstrated that the congruents and incongruents follow the same pattern at low and medium, not significantly differing. However, at the high imbalance, the two diverge in opposite directions, with the incongruents continuing towards zero, while the congruents show a steep increase in negativity. Error bars indicate standard errors across participants.

**Figure 26.** Deviant minus Standard-Before Early-RON Voltage: Imbalance X Congruency Interaction.
The Late-RON in the standard-after minus standard-before follows three separate patterns in terms of the imbalance levels. The voltage in the medium condition follows the same pattern as the Early-RON in the deviant minus standard-before wave. The low and high conditions follow opposite patterns with the high increasing in negativity from filter towards perfect. Error bars indicate standard errors across participants.

**Figure 27. Standard-After minus Standard-Before Late-RON Voltage: Imbalance X Distraction Interaction.**
References


https://doi.org/10.1001/archpsyc.56.11.1007


