THE EFFECT OF AUDITORY ENTRAINMENT ON THE ALLOCATION OF
VISUAL ATTENTION

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by

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Abstract

by

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Auditory and visual attention to rhythmic environmental stimuli can be thought of as involving periods of maximal and minimal attention such that the distribution of attention is entrained to the rhythm of the environmental input. We examined how entraining auditory attention to a rhythm affects the allocation of visual attention. In Experiments 1 and 2, subjects moved their eyes to a dot whose onset was either in synch or out of synch with an entrained auditory rhythm. Saccade latency was fastest for the in-synch condition, indicating that entraining auditory attention similarly entrains visual attention such that both are maximized concurrently. Experiment 3 tested the effect of auditory entrainment on visual attention in a temporally independent manner by having subjects perform a gap judgment task. Judgments were most accurate when the onset of the square was in-synch with the preceding auditory rhythm, replicating the effect observed in Experiments 1 and 2.
CONTENTS

Figures................................................................................................................................ iv

Acknowledgments..............................................................................................................v

Chapter 1: Introduction ........................................................................................................1
  1.1 Overview ...................................................................................................................1
    1.1.1 Defining Rhythms in Attention .................................................................2
  1.2 Rhythms in Auditory Attention .........................................................................3
    1.2.1 Behavioral Evidence ...........................................................................3
    1.2.2 Neurological Evidence ........................................................................5
    1.2.3 Attentional Model ...............................................................................6
  1.3 Rhythms in Visual Attention .............................................................................6
    1.3.1 Behavioral Evidence ...........................................................................6
    1.3.2 Neurological Evidence ........................................................................7
    1.3.3 Attentional Model ...............................................................................8
  1.4 Rhythms in Crossmodal Attention .....................................................................9
    1.4.1 Links in Crossmodal Attention ...........................................................9
    1.4.2 Competing Predictions ......................................................................10
    1.4.3 Framing Entrainment Accounts Using Kahneman’s (1973) Central Resource Theory ...................................................12
  1.5 The Current Study ............................................................................................17

Chapter 2: Experiment 1 ....................................................................................................19
  2.1 Introduction ......................................................................................................19
  2.2 Method .............................................................................................................21
    2.2.1 Subjects .............................................................................................21
    2.2.2 Stimuli and Design ............................................................................21
    2.2.3 Apparatus ..........................................................................................23
  2.3 Procedure .........................................................................................................23
  2.4 Results ..............................................................................................................24
    2.4.1 Auditory Only Task ..........................................................................24
    2.4.2 Visual Task .......................................................................................25
  2.5 Discussion of Results .......................................................................................26

Chapter 3: Experiment 2 ....................................................................................................28
  3.1 Introduction ......................................................................................................28
  3.2 Method .............................................................................................................30
    3.2.1 Subjects .............................................................................................30
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.2 Stimuli and Design</td>
<td>30</td>
</tr>
<tr>
<td>3.3 Procedure</td>
<td>31</td>
</tr>
<tr>
<td>3.4 Results</td>
<td>31</td>
</tr>
<tr>
<td>3.4.1 Entrainment Sequence</td>
<td>31</td>
</tr>
<tr>
<td>3.4.2 Random Sequence</td>
<td>32</td>
</tr>
<tr>
<td>3.5 Discussion of Results</td>
<td>34</td>
</tr>
<tr>
<td>Chapter 4: Experiment 3</td>
<td>35</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>35</td>
</tr>
<tr>
<td>4.2 Method</td>
<td>37</td>
</tr>
<tr>
<td>4.2.1 Subjects</td>
<td>37</td>
</tr>
<tr>
<td>4.2.2 Stimuli and Design</td>
<td>37</td>
</tr>
<tr>
<td>4.3 Procedure</td>
<td>38</td>
</tr>
<tr>
<td>4.4 Results</td>
<td>39</td>
</tr>
<tr>
<td>4.5 Discussion</td>
<td>40</td>
</tr>
<tr>
<td>Chapter 5: General Discussion</td>
<td>42</td>
</tr>
<tr>
<td>5.1 Review of Results</td>
<td>42</td>
</tr>
<tr>
<td>5.2 Symmetry of Crossmodal Entrainment</td>
<td>45</td>
</tr>
<tr>
<td>5.3 Conclusion</td>
<td>47</td>
</tr>
<tr>
<td>References</td>
<td>48</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1: Schematic of the trial structure from Jones et al. (2002). The standard tone was followed by 8 distractor tones with IOIs of 600ms (except for the critical IOI, which varied and was either 524ms, 579ms, 600ms, 621ms, or 679ms) and a test tone.

Figure 2: A comparison of Kahneman’s flexible central resource account of attention as conceptualized by sustained/vigilant attention (Figure 2a) and entrained attention (Figure 2b).

Figure 3: Shows the possible effect of entrainment in one modality on the allocation of attention in another modality.

Figure 4: The distribution of auditory tones across a trial. The box around the final tone represents that the actual interval between the final two tones varied.

Figure 5: Percent correct tone judgments as a function of test tone onset for the auditory-only task. The * indicates that the in-synch condition was significantly more accurate than the out-of-synch conditions.

Figure 6: Shows the saccade latencies as a function of onset condition for the visual task. The * indicates that saccade latencies in the in-synch condition were significantly shorter than saccade latencies in the out-of-synch conditions.

Figure 7: Shows saccade latencies for the entrainment sequence as a function of onset condition. The * indicates that saccade latencies were significantly shorter for the in-synch condition versus the out-of-synch conditions.

Figure 8: Shows saccade latencies for the random sequence as a function of onset condition.

Figure 9: Shows the sequence of a typical trial in Experiment 3. The square could appear in one of four locations; it is shown in only one here.

Figure 10: Gap judgment accuracy as a function of visual onset in Experiment 3. The * indicates that gap judgments were significantly more accurate for the in-synch condition versus the out-of-synch conditions.
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CHAPTER 1:

INTRODUCTION

1.1 Overview

Imagine you are driving your car down the street listening to your favorite song when you approach a flashing red light. You slow your car down to a stop and wait your turn to continue through the light. In this instance, both the auditory and visual stimuli in your environment are rhythmic (the beat of the music, the steady pulse of the red light). Evidence exists that these types of rhythmic stimuli can entrain both auditory and visual attention such that both become cyclical in nature. In fact, entrainment to rhythmic environmental stimuli has been argued to be inherently biological (Winfree, 2000). For example, biological organisms are automatically entrained to generic environmental rhythms such as light and dark cycles, meals, etc. Furthermore, rhythm is fundamental to many activities including listening to music, dancing, reading, and even typing (Shaffer, 1982). The goal of the current study is to determine how the rhythmic entrainment of attention in audition affects the allocation of attention in vision.

We begin by defining what we mean by the “entrainment of attention.” Next, we review literature that establishes that auditory and visual attention can be entrained to rhythmic stimuli. We then explore the effect of auditory attentional entrainment on the allocation of visual attention in three experiments. Experiments 1 and 2 examine the
effect of auditory attentional entrainment on the allocation of visual attention in an eye-
movement paradigm. Because the dependent variable in this paradigm is a measure of
reaction time (saccade latency), Experiment 3 seeks to replicate the pattern of results
from Experiments 1 and 2 in a temporally-independent perceptual task. Finally, we end
with a general discussion of the implications of crossmodal entrainment on attentional
theories generally as well as a sampling of interesting areas for future research.

1.1.1 Defining Rhythms in Attention

When referring to attention being “entrained” to an environmental rhythm, we
mean that the allocation of attention is synchronized with the occurrence of an
environmental stimulus such that attention is maximized when the stimulus is expected to
occur. This creates a series of attentional peaks and troughs that is often referred to as an
“expectancy profile” (Large & Jones, 1999; Jones, Moynihan, MacKenzie, & Puente,
2002). For example, if visual attention is entrained to a light flashing every 500ms,
attention will peak every 500ms, based on the expectation that the light will continue to
appear at that regular interval. Conversely, if the light occurs at an unexpected interval
(e.g. 420ms), less attention will be devoted because it has not yet peaked. As such, we
will refer to instances in which stimulus occurrence is expected as occurring “on-peak”
and instances in which stimulus occurrence is unexpected as occurring “off-peak.”

One helpful way to conceptualize entrainment is to think of attention as having to
pass through a screen door that is controlled by the expectation of stimulus occurrence.
That is, the door is opened when a stimulus is expected to occur, and closed during
intervals when the stimulus is not expected to occur. When the door is opened, maximal
attention is let through, corresponding to an attentional peak. When the door is not opened, attention can still be allocated by sliding through the holes in the screen, although less efficiently than if the door was completely open. This is an important caveat, because entrainment suggests that attention is less efficiently allocated, versus not allocated at all.

The effect of entrainment on the allocation of attention is reflected behaviorally by an improvement in performance for a variety of tasks when judgments occur at an expected point in the rhythm versus at an unexpected point in the rhythm (Jones et al., 2002; Large & Jones, 1999; Barnes & Jones, 2002). Neurologically, oscillations in the brain are theorized to be of primary functional importance for attending to rhythmic stimuli (Lakatos, 2005; Lakatos et al., 2007; Schroder & Lakatos, 2009; Schroder et al., 2009). That is, the expectancy derived from an environmental stimulus might entrain neural oscillations to the frequency of the rhythm of the stimulus. Having established a schematic of how attention might be entrained, we review specific empirical evidence that demonstrates that both auditory and visual attention can be entrained.

1.2 Rhythms in Auditory Attention

1.2.1 Behavioral Evidence

One of the most common forms of rhythmic auditory stimuli is musical beat. In fact, it has been argued that entrainment is largely responsible for our ability to perceive temporal regularities that occur in music (Large & Kolen, 1994; Large, 2000; Large & Palmer, 2002). For example, Large & Kolen (1994) proposed a connectionist network that is capable of phase-setting attention to rhythmic patterns, which results in an
attentional expectancy for a stimulus to occur on a particular beat. They also argued that this network is dynamic and can adjust to a new stimulus rhythm, indicating that attention may be quite sensitive to environmental changes in rhythm.

A striking demonstration of the capability of auditory attention to be cyclical comes from Jones, et al. (2002). In their experiments, subjects were entrained to rhythmic sequences of tones with the task of comparing the pitch of a test tone at the end of the sequence to a standard tone at the beginning of the sequence. The inter-stimulus onset interval (IOI) for the sequence of tones was held constant at 600ms, but was manipulated for the last IOI such that the interval between the penultimate tone and the test tone could occur either in-synch with the preceding tones (600 ms), very early (524 ms), early (579 ms), late (621 ms), or very late (676 ms) as shown in Figure 1. Subjects’ judgments of pitch of the test tone were more accurate when the test tone occurred in rhythm with the sequence versus out of sequence. Interestingly, subjects were told to ignore the sequence of tones between the standard tone and test tone; however, this sequence still created an expectancy profile that resulted in increased accuracy of pitch judgments when the tone occurred on rhythm. When the sequence of tones consisted of irregular IOIs that still resulted in the same mean IOI as in the original experiment, the effect was eliminated, confirming that the expectancy profile was established from the isochronous pattern of the tones rather than a general total mean of the IOIs. This is a particularly powerful example of the effect of entrainment on auditory attention because pitch judgment was independent of tone occurrence. That is, entrainment affected attentional processing in a way that was completely dissociated from response time such that temporal expectancy
actually influenced the ability to perceive the pitch of the tone accurately. We will adopt a task in Experiment 3 that employs a similar dissociation.

Figure 1. Schematic of the trial structure from Jones et al. (2002). The standard tone was followed by 8 distractor tones with IOIs of 600ms (except for the critical IOI, which varied and was either 524ms, 579ms, 600ms, 621ms, or 679ms) and a test tone. Subjects’ task was to judge if the pitch of the test tone was the same as the pitch of the standard tone.

1.2.2 Neurological Evidence

Neurological evidence also exists that suggests that auditory attention can be entrained to environmental rhythms. For example, Luo (2007) showed that theta band oscillations in the brain could modulate their phase structure to fit the rhythms of speech patterns. In particular, the phase structure of theta oscillations has been linked to the intelligibility of spoken sentences, such that when the rate of a spoken sentence corresponds to the phase structure of the theta oscillation, intelligibility is increased. This is consistent with research that has shown that the auditory cortex will often structure its temporal activity pattern to optimize the processing of rhythmic inputs (Lakatos, 2005).

Additionally, Will and Berg (2007) demonstrated that the temporal structure of an auditory stimulus could reset delta phase oscillations in the brain, which can in turn phase
lock other oscillations hierarchically. In other words, waves with lower frequencies such as delta waves may phase lock to the rhythm of the auditory sequence. In turn, waves with higher frequencies, such as theta and gamma waves, may phase lock to the pattern structure of delta waves, which was established by the auditory stimulus. This is important because it may reflect a fundamental role for rhythm in neural processing.

1.2.3 Attentional Model

One way of considering how auditory attention and rhythmic auditory stimuli are related is through the theoretical framework of dynamic attending theory (DAT). DAT is a unique approach to modeling auditory attention because it focuses on rhythmic aspects of attending (Jones & Boltz, 1989; Jones, Johnston, & Puente, 2006; Large & Jones, 1999; McAuley, 1995; McAuley & Jones, 2003). DAT argues that auditory attention can set its phase structure to be synchronized with an expectancy profile derived from an environmental rhythm, such that auditory attention is maximized at the occurrence of the stimuli. For example, Barnes and Jones (2000) found that the accuracy of duration judgments relative to a standard duration decreased as the test IOI deviated from an isochronous context rate.

1.3 Rhythms in Visual Attention

1.3.1 Behavioral Evidence

Some aspects of visual attention may also be rhythmic in nature such that visual attention can be entrained to environmental stimuli. Evidence from general theories of visual attention provides support for the idea that environmental rhythms might affect the
distribution of attention over time. For example, visual attention follows a pattern of engagement and disengagement (Posner & Cohen, 1984; Posner & Peterson, 1990) such that the distribution of visual attention is dynamic over time rather than static. In fact, evidence exists that top-down control of visual attention may act to predict an expected stimulus (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008). Furthermore, temporal and spatial expectation has been shown to enhance visual attention (Doherty, Rao, Mesulam, & Nobre, 2005). Still, behavioral research on rhythm in visual attention is relatively new and as such has not been widely examined. However, there is a significant amount of neurological evidence that suggests that rhythm may fundamentally affect visual attention.

1.3.2 Neurological Evidence

Most of the neurological evidence linking rhythm to visual attention has used methods similar to those employed when examining auditory attention and has focused on neural oscillations. For example, work in selective visual attention has revealed an increase in the synchronization of gamma oscillations when monkeys attend to relevant visual stimuli (Fries, Reynolds, Rorie, and Desimone, 2001; Fries, Womelsdorf, Oostenveld, and Desimone, 2008). These results are important because they point to a functional role for neural oscillations in visual attention such that such oscillations are not merely incidental. If neural oscillations can subserve visual attention generally, it is reasonable to predict that they may play a role in processing rhythmic stimuli. In fact, delta oscillations in V1 have been shown to entrain to the rhythm of a stream of visual information if that information is rhythmic (Lakatos, Karmos, & Mehta, 2008). This
process suppresses inputs that are inconsistent with the attended stream and consequently removes irrelevant information. Furthermore, Gross et al (2004) demonstrated that beta-band oscillations correspond to an increase in visual processing, and that these bands can strongly influence attentional control.

1.3.3 Attentional Model

There is not a specific model of visual attention that deals primarily with visual attention to rhythmic stimuli. However, nearly all theories of attention underscore the fundamental cognitive truth of limitation. That is, we cannot possibly attend to every stimulus in our environment at any given point in time. For example, filter theories of attention (Broadbent, 1958; Deustch & Duetsch, 1963; Keele, 1973; Triesman, 1964) theorize that information is filtered out from further processing at early, middle, or late points in processing. This differs from resource accounts, which propose that there is a limited availability of resources that can process information (Allport, 1980; Baddeley & Hitch, 1974; Kahneman, 1973; Wickens, 1980). However, both theoretical perspectives assume that attention is limited such that certain stimuli, or aspects of stimuli, receive attention while others do not. Given that attention is a limited resource, it is reasonable to predict that the attentional system may act on an opportunity to optimize the allocation of attention across time. This is consistent with the idea that rhythms may entrain visual attention such that it is maximized at the regular occurrence of a stimulus. In so doing, the attentional system increases the efficient use of a limited resource.

Still, these models are typically concerned with either what attention is allocated to or where attention is allocated. The current research is focused on when attention is
allocated, and the existing models say little in this regard. In fact, the dynamic allocation of attention to rhythmic stimuli may reflect a fundamentally different operational mode of attention, as has been suggested in the neural oscillation literature (Schroeder et al., 2009). Specifically, entrainment modes of attention may critically differ from vigilant modes of attention (Schroeder and Lakatos, 2009). That is, in vigilant attention, timing is unpredictable. Attention is deployed to a stimulus when it appears, and this appearance is random. As such, when compared to the peaks and troughs of entrained attention, vigilant attention may be in a sustained state of high excitability. This is relevant to the current research because an effect of auditory entrainment on visual attention may reflect a shift of visual attention from vigilance to entrainment as a function of the auditory stimulus.

Furthermore, despite being developed primarily in the auditory domain, DAT is theoretically consistent with the idea that visual attention can entrain to environmental rhythms (Barnes & Jones, 2002). In fact, principally, DAT is assumed to be a general account of the dynamic allocation of attention over time rather than a modality-specific one. As such, one can also apply the logic of DAT described in the auditory domain to the visual domain.

1.4 Rhythms in Crossmodal Attention

1.4.1 Links in Crossmodal Attention

Given that DAT is assumed to be a modality-independent account of the allocation of attention to rhythmic stimuli over time, an interesting question is whether crossmodal links exist. Specifically, is the entrainment of attention to rhythmic stimuli a general attentive consequence of entrainment such that crossmodal effects can be
observed, or is it limited to the presently entrained modality? For example, does entraining auditory attention have any effect on visual attention?

General links between auditory and visual attention are extensive and have been demonstrated in the domains of spatial attention (Driver & Spence, 1998a, 1998b, 2004; Howard & Templeton, 1966; Spence & Driver, 1997; McDonald & Ward, 2003, Rorden & Driver, 1999), perceptual processing (O’Leary & Rhodes, 1984; for review see Vroomen & De Gelder, 2004), and saccadic eye movements (Colonius & Arndt, 2001; Frens, Van Opstel, & Van der Willigen, 1995; Corneil, Van Wonrooij, Munoz, & Van Opstel, 2002). Much of this research has focused on the spatial aspects of crossmodal attention rather than the temporal aspects that are studied here. However, it has been suggested that sound can alter temporal aspects of vision such as perceived duration and rate (Shipley, 1964; Walker & Scott, 1981). For example, Fendrich and Corballis (2001) found that when a visual flash and an auditory click are presented in close temporal proximity, subjects’ judgment of stimulus onset is biased towards aligning the two stimuli temporally. Furthermore, neurological research has shown that oscillations in the brain may be linked to early integrative multisensory processing (Senkowski, 2007; Sakovitz, Quiroga, Schurmann, & Basar 2001) and that low frequency delta oscillations can entrain multiple sensory systems (Lakatos, Chen, O’Connell, Mills, & Schroeder, 2007; Schroeder & Lakatos, 2009).

1.4.2 Competing Predictions

Generally, past research links auditory and visual attention in a way that suggests that visual and auditory attention may be aligned when possible (Driver & Spence,
1998a, 1998b, 2004; Fendrich & Corballis, 2001; McDonald & Ward, 2003; Lakatos et al., 2007; Rorden & Driver, 1999; Senkowski, 2007). For example, cross-modal cuing effects have been repeatedly demonstrated with many modality pairings (for review see Spence and Driver, 2004) and may reveal the operation of a supramodal attentional system (Farah, Wong, Monheit, & Morrow, 1989). Therefore, it is reasonable to predict that entrainment in one modality may similarly entrain another modality such that attentional peaks are synchronized between the two modalities. We will refer to this as the correspondence account of attentional entrainment.

However, it is possible that entrainment operates on attention in a very different way than predicted by demonstrations of alignment of crossmodal attention in space (as in work by Driver & Spence, 1998a, 1998b, 2004; Howard & Templeton; Spence & Driver, 1997). As such, we discuss two possible alternative accounts of attentional entrainment: conflict and independent effect. The conflict account predicts that attentional entrainment in one modality will suppress attention in another modality such that when attention is at its peak in the entrained modality, attention is minimized in the second modality. One could make this prediction based on the idea that attention draws from a limited pool of resources. As such, maximization in one modality may exhaust attention resources, impairing processing in other modalities. The independent account predicts attentional entrainment in one modality will not affect the allocation of attention in a second modality. In this account, the unentrained modality remains in a sustained state that more closely mirrors vigilant attention. Importantly, both the correspondence and conflict accounts predict a general link between auditory and visual entrainment (with the
links differing in phase), while the *independent* account assumes no effect of entrainment in one modality on the allocation of attention in another.

1.4.3 *Framing Entrainment Account using Kahneman’s (1973) Central Resource Theory*

One way of understanding how attentional entrainment might affect the allocation of attention across time and modality is to conceptualize such effects in terms of Kahneman’s (1973) central resource theory, which provides a straightforward context to compare competing accounts of crossmodal entrainment (see also multiple resource accounts Allport, 1980; Wickens, 1980; or action-selection accounts, Allport, 1987; Neuman, 1996).

Central resource theory acknowledges that we can only process a certain amount of information at any given point in time. Thus, attention must be allocated to relevant stimuli that demand more detailed processing. It posits that the mechanism for distributing attention to optimize performance is a central processer that is influenced by a number of factors including evaluations of demands on capacity, momentary intentions and enduring dispositions (Figure 2a). Arousal affects capacity such that higher levels of arousal result in greater capacity. Evaluation of demands can be defined as a check on the demands placed on the allocation of attention. That is, evaluation of demands influences the central processer by determining what is achievable given limited resources. Furthermore, evaluation of demands also affects arousal such that more demanding tasks result in greater arousal. Momentary intentions essentially represent top-down control on the allocation of attention such as choosing to look at a stoplight while driving, or
directing your attention to the field while watching a sporting event. Enduring dispositions can be thought of as the most bottom-up influence in the model and consist of stimuli that quickly capture attention, such as hearing your name or seeing the onset of a new stimulus. These would generally be considered difficult to ignore and attention directed towards them is assumed to be largely involuntary. Specifically, Kahneman argues that each one of these factors can influence how the central processor differentially allocates attention.

The rhythmic nature of a stimulus is a property of the dynamic distribution of the stimulus itself and serves initially as a bottom-up influence on the allocation of attention. This is most akin to the influence of enduring dispositions as defined in Kahneman’s model. However, the actual expectation of stimulus occurrence can be considered, at least in part, as a top-down influence on the allocation of attention. This is most similar to the influence of momentary intentions as defined in Kahneman’s model. Considering demonstrations of the effects of auditory stimulus rhythm on the allocation of auditory attention (Jones et al., 2002; Large & Jones, 1999; Barnes and Jones, 2002), we can simply express the influence of stimulus rhythm on the allocation of attention. That is, the rhythm of the stimulus entrains the central processor such that an attentional pulse is generated at expected stimulus intervals. In Figure 2b, the stimulus rhythm occurs at the between enduring dispositions and momentary intentions, reflecting the interactive relationship between stimulus rhythm, which originates in the environment, and expectation, which originates in the person. The rhythm of the stimulus phases locks the central processor such that attention is allocated by the central processor at expected
intervals (represented by the peaks of the lines). As such, more attention is allocated when the event is expected to occur versus when the event is not expected to occur.

Figure 2a

![Figure 2a](image)

Figure 2b

![Figure 2b](image)

Figure 2. A comparison of Kahneman’s flexible central resource account of attention as conceptualized by sustained/vigilant attention (Figure 2a) and entrained attention (Figure 2b).
Thus, Figures 2a and 2b represent two fundamentally different modes of attention. Figure 2a shows attention in an unentrained state, closely tied to vigilant attention. Figure 2b shows attention in an entrained state, where the allocation of attention is driven in part by environmental rhythm. This reflects the idea that attention to rhythmic stimuli and attention to stimuli without rhythm may reflect fundamentally different modes of attentional processing (Schroeder & Lakatos, 2009). Given this distinction, we can examine how each of the competing accounts of attentional entrainment would be expressed by the entrainment model in Figure 2b.

A model of correspondence is presented in Figure 3a. If entrainment in one modality similarly entrains another modality, then the influence of stimulus rhythm on the central executor should be general such that the allocation of attention is phase locked across multiple modalities. For example, auditory entrainment phase locks the central executor to the auditory rhythm such that attention is deployed to both auditory and visual modalities at the same time. This is represented in the model by the rhythm of the auditory stimulus (black line) phase locking both auditory and visual attention (black line).

A model of conflict is presented in Figure 3b. If entrainment in one modality oppositely entrains another modality, then the influence of stimulus rhythm on the central executor should also be general. However, in a conflict account, when resources from the central executor are deployed to the entrained modality, attention in the competing modality is minimized. For example, auditory entrainment generates an auditory attentional pulse via the central executor during which visual attention is suppressed. This
Figure 3. Shows the possible effect of entrainment in one modality on the allocation of attention in another modality. *Figure 3a.* Shows a correspondence account. Auditory entrainment similarly entrains visual attention. *Figure 3b.* Shows a conflict account. Auditory entrainment oppositely entrains visual attention. *Figure 3c.* Shows an independent effect account. Auditory entrainment has no effect on visual attention.
is represented in the model by the rhythm of the auditory stimulus (black line) phase locking auditory attention (black line) but oppositely entraining visual attention (red line) such that the peaks of the black line correspond to the troughs of the red line.

Finally, a model of independent effects is presented in Figure 3c. If entrainment in one modality has no effect on another modality, then the influence of the central executor should be specific such that entrainment in one modality generates an attention spike for that modality and does not affect other modalities. For example, auditory entrainment generates an auditory attentional pulse via the central executor that only affects auditory attention, leaving visual attention in a vigilant mode. This is represented in the model by the rhythm of the auditory stimulus (black line) phase locking auditory attention (black line), but having no effect on how the central executor deploys attention to the visual modality (arrow).

1.5 The Current Study

Three experiments examined these three accounts of crossmodal entrainment (correspondence, conflict, independent effects) by investigating the influence of entrainment in one modality on the allocation of attention in another modality. Experiments 1 and 2 explored whether auditory entrainment affects the allocation of visual attention by examining saccade latencies. Specifically, subjects moved their eyes from a control fixation to a test dot with an onset that varied with respect to auditory entrainment. Experiment 3 examined how auditory entrainment affects performance on a visual task that is not temporally dependent. Specifically, subjects performed a gap-judgment task with the onset of the visual stimulus varying as a function of auditory...
entrainment. A correspondence account predicts facilitation in these tasks (shorter saccade latencies in Experiments 1 and 2, improved accuracy in Experiment 3) when the visual onset is in-synch with auditory entrainment relative to being out-of-synch. A conflict account predicts impairment in these tasks (longer saccade latencies in Experiments 1 and 2, reduced accuracy in Experiment 3) when the visual onset is in-synch with auditory entrainment relative to being out-of-synch. Finally, an independent effects account predicts no difference in performance across the tasks because auditory entrainment will not influence the allocation of visual attention.
CHAPTER 2:

EXPERIMENT 1

2.1 Introduction

Experiment 1 examines the effect of auditory attentional entrainment on visual attention. In order to assess this influence, we adopted a saccadic, crossmodal version of the Jones et al. (2002) paradigm. Subjects were asked to focus on a fixation dot at the beginning of each trial until a test dot appeared in one of the four corners of the screen. When the dot appeared, subjects were instructed to move their eyes to the dot. Coincident with the onset of the fixation dot, a sequence of tones began with one tone occurring every 600ms and lasting for 60ms. Subjects listened to a sequence of 10 tones (Figure 4). Across trials, the onset of the test dot varied such that it occurred in-synch; very early; early; late; or very late, relative to the final auditory tone. The dependent measure was saccade latency from the onset of the dot to the time it took to initiate the saccade.

Generally, visual attention is considered to be tied to gaze position and precedes the actual movement of the eyes to a new location (Duebel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). Thus, faster saccade latencies would be indicative of enhanced visual attention at the onset of the dot. Subjects also performed a replication of the original Jones (2002) auditory-only paradigm in order to assure that subjects were indeed entrained to the auditory sequence. This task was
always performed after the visual task to avoid drawing subjects’ attention to the tone sequence. All task manipulations are summarized in Table 1.

Table 1: Summary of Task Manipulations Across Experiments

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<tr>
<td>Exp 1 Auditory Only</td>
<td>Y</td>
<td>N/A</td>
<td>ACC</td>
<td>Y</td>
</tr>
<tr>
<td>Crossmodal</td>
<td>Y</td>
<td>Y</td>
<td>RT</td>
<td>Y</td>
</tr>
<tr>
<td>Exp 2 Crossmodal</td>
<td>Y</td>
<td>N</td>
<td>RT</td>
<td>Y</td>
</tr>
<tr>
<td>Random</td>
<td>N</td>
<td>N</td>
<td>RT</td>
<td>N</td>
</tr>
<tr>
<td>Exp 3 Crossmodal</td>
<td>Y</td>
<td>N</td>
<td>ACC</td>
<td>Y</td>
</tr>
</tbody>
</table>

If saccade latencies were fastest for the in-synch presentation of the dot, and slowest when it was out-of-synch, it would serve as evidence that auditory entrainment also entrains visual attention such that visual attention is maximized when auditory attention is maximized. This would be consistent with a correspondence account of
auditory entrainment on visual attention. Alternatively, if saccade latencies were slowest for the in-synch presentation of the dot and fastest when it was out-of-synch, it would serve as evidence that visual attention is minimized when auditory attention is at its rhythmic peak. This would be consistent with a *conflict* account of auditory entrainment on visual attention. Finally, if there were no difference between saccade latencies, it would demonstrate that visual attention is relatively resistant to auditory entrainment of rhythmic stimuli. This would be consistent with an *independent* account of auditory entrainment on visual attention.

2.2 Method

2.2.1 Subjects

Twenty undergraduates from the University of Notre Dame with normal or corrected-to-normal vision participated in this experiment. All participants gave informed consent and were treated in accordance with APA ethical guidelines.

2.2.2 Stimuli and Design

The visual stimuli were dots displayed on a 19-inch computer monitor at a resolution of 1,024 by 768 pixels. Viewing distance was 56cm from the center of the screen, with the total display subtending approximately 34° by 27° and the fixation dots subtending 0.6° by 0.6°. The test dots appeared in one of four corners of the screen and were equally spaced relative to the fixation dot, with a distance from the fixation dot held constant at 19.8°.
A sequence of auditory tones was played during the visual task that consisted of either a series of regularly-occurring high or low semitones (High - 544.4 Hz, 659 Hz, and 789 Hz; Low - 370 Hz, 440 Hz, and 523.3 Hz). This tone manipulation was used for consistency with the auditory-only task and was not expected to influence the results of the crossmodal task. Each tone lasted 60ms and IOI was always 600ms. High tone trials occurred as frequently as low tone trials.

The onset of the test dot varied such that it occurred a) in-synch with the final tone; b) very early to the final tone (-76ms); c) early to the final tone (-21ms); d) late to the final tone (+21ms); or very late to the final tone (+76ms). Saccade latency was measured as the time from stimulus onset to the initiation of the initial saccade towards the test dot. A saccade was judged to have begun when the eye position moved from fixation in the same direction at a velocity greater than 0.05 deg/msec for at least 3 milliseconds.

For the auditory-only task, the same sequence of tones was used, except that the first tone was replaced with a standard tone that was either 415 Hz or 466 Hz for the high tone sequence and either 622 Hz or 698 Hz for the low tone sequence. Note that a low standard tone was paired with a high tone sequence and a high standard tone was paired with a low tone sequence. This was done in order to ensure that the standard tone was distinct from the distractor tones that followed, consistent with Jones et al (2002). Furthermore, the standard tones lasted 150ms. Therefore, the standard tones were distinct both on the basis of pitch and length. The test tone that occurred at the end of the sequence was either the same as the standard tone or one semitone higher or lower than the standard tone. Stimulus IOIs were 600ms except for the final test tone, which varied
and occurred a) in sequence with the preceding tones; b) very early relative to the sequence of preceding tones (-76ms); c) early relative to the sequence of the preceding tones (-21ms); d) late relative to the sequence of the preceding tones (+21ms); or very late relative to the sequence of the preceding tones to the final tone (+76ms). Consequently, the final IOI varied from 524ms to 676ms (see Figure 4).

2.2.3 Apparatus

Eye movements were recorded using a SR Research Eyelink II tracker that was head mounted and recorded pupil position from the left eye with a sampling rate of 500 Hz. Subjects were positioned in stationary chairs to maintain viewing distance. Subjects listened to sounds through two mono speakers such that the sound was spatially centered.

2.3 Procedure

After calibration, subjects were given instructions on the computer screen. They were told that they would be completing a simple visual task where they were to fixate on a central dot and move their eyes to a test dot when it appeared. A drift correction preceded each trial to ensure that subjects were centrally focused at the start of each trial. Participants were not warned of the occurrence of the auditory tones and were given no explanation for their presence. At the end of each trial, subjects were told to press a button on a video game controller to begin the next trial. Subjects completed ten practice trials and then 40 test trials with the onset of the test dot occurring eight times in each condition (very early, early, synch, late, very late). The order of the trials was randomized.
When subjects completed the crossmodal task, they removed the eyetracker and were given a five-minute break followed by instructions for the auditory-only task. They were instructed to listen to a sequence of auditory tones and to determine whether the pitch of a test tone was the “same as” or “different than” a standard tone. Subjects responded by pressing corresponding buttons on a video game controller. After completing ten practice trials, subjects began the experiment, which consisted of 40 test trials with the onset of the test tone occurring eight times in each condition (very early, early, synch, late, very late). The sequences were presented randomly.

2.4 Results

In order to examine the effects of auditory entrainment on visual attention, it must be established that auditory attention was indeed entrained. Consequently, a discussion of the results for the auditory-only task precedes the primary discussion regarding the influence of auditory entrainment on saccade latency.

2.4.1 Auditory-Only Task

Figure 5 summarizes subjects’ accuracy in determining whether the test tone was the same pitch as the standard tone as a function of test tone onset. There was a significant difference in the judgment of pitch as a function of the timing of the test tone, $F(4,76) = 2.97, p < .05$. When the onset of the test tone was in-synch with the preceding rhythm, pitch judgments were significantly more accurate ($M = 70.0, SE = 2.78$) than when the onset of the test tone was out-of-synch with the preceding rhythm ($M = 60.29, SE = 2.58$), $F(1,19) = 9.87, p < .05$. In fact, accuracy of pitch judgment was higher when
the test tone occurred in sequence with the preceding tones than the very early ($M = 61.8$, $SE = 4.00$), early ($M = 61.87$, $SE = 2.31$), late ($M = 60.00$, $SE = 3.34$), and very late ($M = 57.5$, $SE = 3.99$) conditions individually, $ps < .0125$ (bonferroni correction). This replicates Jones et al (2002) and verifies that subjects’ auditory attention was indeed entrained to the sequence of tones used for the experiment.

![Percent Correct as a Functional of Test Tone Onset](image)

Figure 5. Percent correct tone judgments as a function of test tone onset for the auditory-only task. The * indicates that the in-synch condition was significantly more accurate than the out-of-synch conditions.

### 2.4.2 Visual Task

Figure 6 summarizes subjects’ saccade latency as a function of the test dot onset. There was a significant difference in saccade latency across conditions, $F(4,76) = 2.68$, $p < .05$. When the test dot onset was in-synch with the preceding rhythm, saccade latencies
were significantly faster ($M = 215.30, SE = 6.2$) than when the test dot onset was out-of-
synch with the preceding rhythm ($M = 230.30, SE = 7.5$), $F(1,19) = 37.18, p < .05$. In
fact, saccade latencies were significantly faster when the dot appeared in-synch with the
auditory sequence versus the very early ($M = 231.82, SE = 8.46$), early ($M = 233.53, SE$
$= 6.98$), late ($M = 228.73, SE = 8.96$), or very late ($M = 227.11, SE = 6.7$) conditions
individually, $ps < .0125$ (bonferroni correction).

Figure 6. Shows the saccade latencies as a function of onset condition for the visual task.
The * indicates that saccade latencies in the in-synch condition were significantly
shorter than saccade latencies in the out-of-synch conditions.

2.5 Discussion of Results

These results are consistent with the prediction that entrainment to an auditory
stimulus also entrains visual attention to the same rhythm such that both are maximized
concurrently. That is, auditory entrainment not only phase locks auditory attention but also visual attention. It also serves as another demonstration of a link between sensory modalities and suggests that a supramodal attentional system might control attention to rhythmic stimuli. As such, it favors the *correspondence* account of auditory entrainment of visual attention (see Figure 3a).
CHAPTER 3:

EXPERIMENT 2

3.1 Introduction

In Experiment 1, the test dot onset varied not only with respect to the preceding rhythm but also with respect to the actual occurrence of the tenth tone. That is, if the onset of the test dot was synchronized with the preceding rhythm, it was also synchronized with the final tone; if it was out-of-synch with the preceding rhythm, it was not synchronized with the final tone. The simultaneous presentation of visual and auditory stimuli has been shown to improve both visual target identification and reaction time (Bernstein, Clark, & Edelstein, 1969; McDonald, Teder-Salejarvi, & Hillyard, 2000; Vroomen & De Gelder, 2000; Wallace, Wilkinson, & Stein, 1996). Thus, it is possible that the effects observed in Experiment 1 were not a direct result of entrainment, but an artifact of the simultaneous presentation of crossmodal stimuli (dot and tone).

Furthermore, Experiment 1 did not have a control condition that presented subjects with irregularly-occurring tones in the same task. However, it is important to rule out general properties of the visual task as accounting for the effect observed in Experiment 1. For example, the in-synch condition also represents the mean onset of the visual stimulus (i.e. the visual onset occurred as often across five conditions: very early, early, synch, late, very late, thereby making the in-synch condition the mean onset). It is
possible that the attentional focus of subjects was centered on this mean, which would result in an attentional peak for the in-synch condition that would predict the pattern of results observed in Experiment 1, independent of entrainment.

Experiment 2 examines both of these issues (see Table 1). In one block of trials, subjects performed the same task as in Experiment 1, except that the tenth tone was eliminated. Consequently, the presentation of the test dot was never synchronized with any tone. If the effects observed in Experiment 1 were due to entrainment, and not the synchronous presentation of crossmodal stimuli, then the pattern of results should be replicated in Experiment 2.

Additionally, in a separate block of trials, subjects performed the same task as in Experiment 1, except with random tones instead of an entrainment sequence. The average IOI between tones was the same as Experiment 1, maintaining the absolute duration of the trial as well as relative onset of the test dot (thereby keeping the in-synch condition as mean onset). However, the test tones occurred randomly, at unpredictable time intervals. If the effects observed in Experiment 1 were in fact due to entrainment, there should be no difference in saccade latencies across conditions when the tones occur irregularly. However, if the effects observed in Experiment 1 were confounded by any general properties of the visual task itself, the pattern of results should be replicated, even with randomly occurring tones.

We tested both of these predictions as a within-subjects variable with the order of blocks counterbalanced. This allows the added benefit of observing the nature of the effect across the same group of subjects in different entrainment conditions. If we can...
both replicate and eliminate the effect in the same group of subjects, it would serve as a particularly powerful demonstration of the effect of entrainment on visual attention.

3.2 Method

3.2.1 Subjects

Forty undergraduates from the University of Notre Dame with normal or corrected-to-normal vision participated in this experiment. All participants gave informed consent and were treated in accordance with APA ethical guidelines.

3.2.2 Stimuli and Design

The visual stimuli were as in Experiment 1. The sequence of auditory tones that was played during the visual task remained the same, except for the elimination of the final tone. The random tones consisted of a randomly-occurring sequence of high or low semitones (High - 544.4 Hz, 659 Hz, and 789 Hz; Low - 370 Hz, 440 Hz, and 523.3 Hz). This tone manipulation was used for consistency with Experiment 1 and was not expected to influence the results of the crossmodal task. Each tone lasted for a random period with an average of 600ms. The onset of the final tone was controlled such that the interval between the final tone and the test dot onset was the same as in Experiment 1, maintaining the very early, early, late, and very late distinction. As such, the interval between the final tone and the test dot onset was the same in both blocks of Experiment 2; only the preceding tone sequence varied. The order of the entrainment sequence (block 1 vs. block 2) was counterbalanced.
3.3 Procedure

The procedure in Experiment 2 was the same as in Experiment 1 with one exception. Rather than completing the auditory-only task, as in Experiment 1, subjects completed two blocks of the same visual task, which was as in Experiment 1. The only difference between the two blocks was the nature of the tone sequence. In one block of trials, the tones were as in Experiment 1, except for the elimination of the final tone. In the other block of trials, the tones were randomly occurring, eliminating entrainment. The order of the trials was randomized. Within a block, subjects only received the entrainment sequence of tones, or the random sequence of tones.

3.4 Results

Two subjects were eliminated from the analysis for not following directions by producing erroneous movements, or not staying centrally fixated on over 20% of trials. Erroneous movements were categorized as initial saccades that were not made in the direction of the test dot. Another subject was eliminated for producing saccade latencies that were more than five standard deviations above the mean. The removal of these subjects did not change the pattern of the results. There was a significant difference between saccade latencies for the random sequence blocks and the entrainment blocks, $F(1,36) = 10.41, p < .01$. As such, the two blocks are analyzed separately.

3.4.1 Entrainment Sequence

Figure 7 summarizes subjects’ saccade latency as a function of the test dot onset for the entrainment trials. There was a significant difference in saccade latency across
onset conditions in the entrainment trials, $F(4,140) = 4.52, p < .05$. When the test dot onset was in-synch with the preceding rhythm, saccade latencies were significantly faster ($M = 209.40, SE = 4.79$) than when the test dot onset was out-of-synch with the preceding rhythm ($M = 219.27, SE = 4.01$), $F(1,36) = 8.87, p < .05$, replicating Experiment 1. In fact, saccade latencies were significantly faster when the dot appeared in-synch with the auditory sequence versus the very early ($M = 225.27, SE = 4.77$), early ($M = 219.17, SE = 4.42$), and late ($M = 220.30, SE = 5.09$) conditions individually, $ps < .0125$ (bonferroni correction). The difference between in-synch onset and very late ($M = 212.25, SE = 5.05$) was not significant, $p > .0125$. This is not entirely surprising, given that the interval between the final tone and visual onset creates a foreperiod that might affect reaction time. Specifically, reaction times are often shorter for longer foreperiods (Drazin, 1961; Niemi & Naatanen, 1981).

3.4.2 Random Sequence

Figure 8 summarizes subjects’ saccade latency as a function of test dot onset for the random sequence. There was no effect of onset condition on saccade latency $F(4,140) = .93, p > .05$. This indicates that the effect demonstrated in both Experiments 1 and 2 is not sufficiently explained by a general entrainment to the length of the trial.
Figure 7. Shows saccade latencies for the entrainment sequence as a function of onset condition. The * indicates that saccade latencies were significantly shorter for the in-sync condition versus the out-of-sync conditions.

Figure 8. Shows saccade latencies for the random sequence as a function of onset condition.
3.5 Discussion of Results

These data strongly replicate Experiment 1 and suggest that the synchronous presentation of auditory and visual stimuli is Experiment 1 cannot sufficiently explain the observed pattern of results. Furthermore, the lack of an effect in the random sequence trials suggests that entrainment is necessary to observe the pattern of results from Experiments 1 and 2 and is not a consequence of any general property of the visual task. Overall, these results are consistent with Experiment 1 and the prediction that entraining attention to an auditory stimulus also entrains visual attention such that both are maximized concurrently. As such, Experiment 2 provides further support for the correspondence account of crossmodal entrainment.
CHAPTER 4:

EXPERIMENT 3

4.1 Introduction

Experiments 1 and 2 show an effect of auditory entrainment such that saccade latencies to a visual onset are significantly shorter when that onset is in-synch with the preceding rhythm versus out-of-synch. Recall that in the paradigm used by Jones et al. (2002), subjects judged the pitch of a test tone to the pitch of an initial standard tone. Their critical manipulation was the onset of the test tone, which varied such that it occurred either in-synch with the preceding rhythm (established by distractor tones), or out-of-synch with the preceding rhythm. This type of paradigm is beneficial because it is not temporally dependent, like a reaction time measure, and thus may not be as susceptible to possible temporal confounds. As such, in Experiment 3, we sought to replicate the effect observed in Experiments 1 and 2 using a paradigm that is more directly analogous to the paradigm used by Jones et al. (2002).

In order to achieve this, we used a classic gap-detection task embedded in a Landolt-square. In this type of task, subjects are briefly presented with a square that has a small gap in one side. Their task is to determine in which side of the square the gap occurred. Accuracy is the dependent measure in this task, and as such, the critical effect is temporally independent (see Table 1). Importantly, attention has been shown to
increase spatial resolution (Cameron, Tai, Carrasco, 2002; Yeshurun & Carrasco, 1999) and covert attention specifically has been shown to enhance gap detection in a Landolt-square (Carrasco, Williams, & Yeshurun, 2002). Thus, if auditory entrainment also entrains visual attention, gap-detection should be more accurate when the onset of the square is in-synch with the preceding rhythm versus out-of-synch.

Additionally, one potential ambiguity of the Jones et al. (2002) paradigm is overcome in the current task. Specifically, it is unclear in Jones et al. (2002) whether the effect is directly tied to enhanced processing of the test tone or enhanced retrieval of the standard tone, because of a memory load necessitated by the task. In the current experiment, there is no memory load, so improved accuracy should be indicative of enhanced processing of the stimulus itself.

Finally, because the square is shown only very briefly (100ms in the current task) before it is subjected to a visual mask, it should be impossible for subjects to move their eyes to the stimulus because average saccade latencies are somewhere in the range of 200-250ms (Saslow, 1967; Westheimer, 1954). Even when visual onsets are preceded by a warning cue, like the entrainment sequence, they rarely drop below 150ms (Lansing, Schwartz, & Lindsley, 1959). This is consistent with our findings from Experiments 1 and 2, which never showed an average saccade latency below 200ms, even when the visual onset was perfectly predictable. Given this, Experiment 3 is a test of covert attention, which is nicely analogous to the work done in spatial attention that shows definitive crossmodal interactions that affect the allocation of covert spatial attention (Driver & Spence, 1998a, 1998b, 2004; Howard & Templeton; Spence & Driver, 1997; McDonald & Ward, 2003, Rorden & Driver, 1999).
4.2 Method

4.2.1 Subjects

Sixteen undergraduates from the University of Notre Dame with normal or corrected-to-normal vision participated in this experiment. All participants gave informed consent and were treated in accordance with APA ethical guidelines.

4.2.2 Stimuli and Design

The visual stimuli were displayed on a 19-inch computer monitor at a resolution of 1,024 by 768 pixels. Viewing distance was 66cm from the center of the screen, with the total display subtending approximately 34° by 27°. The stimuli were white on a black background. A fixation dot was presented during each trial and subtended .3° by .3°. We used a typical Landolt-square, which subtended 1° by 1°. The square could occur in one of four locations on the screen, directly above or below the fixation dot, and directly to the left or right of the fixation dot. The center of the square was aligned along the vertical and horizontal axes, respectively. The square was always 3° from the fixation dot. A gap occurred in either the left or right side of the square (counterbalanced across conditions) and subtended approximately .11°. The gap was always vertically centered in the side in which it occurred. A postmask covered the Landolt-square after 100ms and was 1.5° by 1.5°. The auditory stimuli consisted of a series of seven tones of 440hz, all with an IOI of 600ms. Each tone lasted 60ms. The auditory stimuli were played through mono speakers, which were centered to avoid spatial biases.
The onset of the Landolt-square varied such that it occurred a) in-synch with the preceding tones; b) very early relative to the preceding tones (-76ms); c) early relative to the preceding tones (-21ms); d) late relative to the preceding tones (+21ms); or very late relative to the preceding tone (+76ms).

4.3 Procedure

Before the experiment, subjects were given detailed instructions explaining the task and were shown a figure that showed the relative size of the Landolt-square as well as the size of the gap. This was done to prevent task confusion as pilot work revealed difficulty in understanding the task without the presentation of this figure. Each participant completed two blocks of 80 trials each. An example of a typical trial is presented in Figure 9 (not to scale). During a trial, subjects were told to focus on a fixation dot in the middle of the screen until the square appeared. Subjects indicated which side of the square they thought the gap occurred by pressing “1” for left and “0” for right. The square was presented for 100ms and was followed by a mask that was present until response. The onset of the square varied such it occurred very early, early, in-synch, late, or very late, relative to the preceding tones. As in Experiments 1 and 2, participants were not warned of the occurrence on the auditory tones and were given no explanation for their presence. Before completing the two test blocks, subjects completed 20 practice trials to familiarize themselves with the task. During the practice trials, there was no entrainment sequence and the onset of the square was random and between 1500 and 5000ms from the beginning of the trial.
4.4 Results

Accuracy across onset condition is summarized in Figure 10. There was a significant difference in accuracy across visual onset condition, $F(4,60) = 3.86, p < .05$. When the onset of the square was in-sync with the preceding rhythm, gap judgment accuracy was significantly higher ($M = 91.3, SE = 2.0$) than when the onset of the square was out-of-sync with the preceding rhythm ($M = 88.7, SE = 2.2$), $F(1,15) = 7.52, p < .05$. Furthermore, in-sync trials were significantly more accurate than the very early ($M = 86.7, SE = 2.4$) and late ($M = 86.5, SE = 3.1$) conditions individually, $p_s < .0125$ (Bonferroni correction). The difference between the in-sync condition and the early ($M = 89.1, SE = 2.2$) and the very late ($M = 92.4, SE = 2.3$) was not significant, $p_s > .0125$.

Again, the lack of an effect between the in-sync condition and the very late condition is somewhat unsurprising, given the probable influence of foreperiod effects, and replicates the pattern observed in Experiment 2. The lack of a difference between in-sync and early conditions is more surprising; however, in the Jones et al. (2002) task, there was not a significant difference between early and in-sync conditions and, overall, in-sync
trials were significantly more accurate than out-of-synch trials, replicating Experiments 1 and 2.

![Figure 10. Gap judgment accuracy as a function of visual onset in Experiment 3. The * indicates that gap judgments were significantly more accurate for the in-synch condition versus the out-of-synch conditions.](image)

4.5 Discussion of Results

The results from Experiment 3 show that the effect observed in Experiments 1 and 2 can be extended to a perceptual task that is not temporally dependent. Furthermore, Experiment 3 shows that the effect can act on covert attention, since subjects did not have time to move their eyes to the stimulus, which mirrors demonstrations of crossmodal spatial cuing (Driver & Spence, 1998, 2004; Howard & Templeton; Spence & Driver, 1997; McDonald & Ward, 2003, Rorden & Driver, 1999). Finally, these results show that
entrainment is acting on the visual processing of the target itself, rather than enhancing the memory of a previously-stored stimulus, as could be argued in a task with a memory load. Overall, Experiment 3 strongly supports the same hypothesis posited by Experiments 1 and 2; auditory entrainment entrains both auditory and visual attention such that both are maximized concurrently.
CHAPTER 5:

GENERAL DISCUSSION

5.1 Review of Results

Three experiments examined the role of auditory attentional entrainment on the allocation of visual attention. Experiments 1 and 2 demonstrated that entraining auditory attention facilitates saccade latency to a visual onset that is in-synch with a preceding rhythm. Experiment 3 demonstrated that entraining auditory attention facilitates performance on a gap-judgment task such that performance is increased when the visual onset is in-synch with a preceding rhythm.

One way of examining the effect of auditory entrainment on the allocation of visual attention across all three experiments is to examine the performance profiles from each task, as summarized in Table 2, and compare them to the expectancy profiles described by Jones et al. (2002). The Jones et al. (2002) expectancy profile had two critical components. First, performance for in-synch trials was routinely superior to performance for out-of-synch trials. Second, there was a decrease in performance both when the stimulus occurred too early and too late relative to expectation. Across all three experiments, performance was maximized on the in-synch trials (improved accuracy/reduction in saccade latencies) as shown by the dotted line in Table 2. Additionally, there is a significant decrease across all three experiments both when the
stimulus occurs before and after expectation. As such, the current work strongly replicates Jones et al. (2002) in a crossmodal setting.

TABLE 2
SCHEMATIZED PERFORMANCE PROFILES BY EXPERIMENT AND TASK

Our results largely support the idea that attention can be entrained to an environmental rhythm (Large & Jones, 1999; Lakatos et al., 2007; Schroder et al., 2009) and that entrainment in one modality has crossmodal consequences (Lakatos, 2008). This does not support theories that propose that auditory and visual attention are processed in a distinctly separate manner (Shiffrin & Grantham, 1974; Bonnel & Hafter, 1998) and
favors an account that links crossmodal attentional control (Calvert et al., 1997; Farah et al., 1989; Shomstein & Yantis, 2004; Driver & Spence, 2004). Thus, our study supports a correspondence account of auditory attentional entrainment on the allocation of visual attention, which predicts that when auditory attention is entrained, visual attention is also entrained such that they both attentionally peak when a stimulus is expected to occur.

In fact, Schroeder et al. (2009) argue that the attentional system can switch between rhythmic operating modes such that at one pole is “continuous attention” and at the other pole is “rhythmic attention.” Because rhythmic processing is generally thought to use low-frequency oscillations (e.g. delta waves) with relatively long periods of low excitability, these oscillations are suppressed during the continuous mode of attention. Schroeder and Lakatos (2009) even suggest that the rhythmic processing mode may be the preferred condition of the attentional system. This claim underscores the importance of acknowledging that the way in which attention is structured with respect to rhythmic stimuli may fundamentally differ from how attention is structured with respect to non-rhythmic stimuli as reflected by the two different models in Figure 2.

Interestingly, DAT (Jones & Boltz, 1989; Large & Jones, 1999; Barnes & Jones, 2002) differs from the oscillation literature (Lakatos, 2008; Schroeder et al., 2009) with respect to the processing of stimuli occurring off-rhythm. DAT argues that there is no suppression of off-rhythm stimuli such that less attentional resources are devoted to their processing than would be in a non-entrained mode. However, one of the tenets of the rhythmic processing mode hypothesized in the oscillations literature (Schroeder & Lakatos, 2009) is that stimuli that are not part of an attended stream are automatically suppressed. That is, the attentional benefit for the in-synch onset of rhythmic stimuli in
our data could be attributable to several factors. First, it may be caused by an increase in the attentional resources dedicated to processing stimuli on rhythm, with no suppression of attentional resources for off-rhythm periods. Second, it may be caused by a suppression of attentional resources during off-rhythm periods, with no facilitative effect. Finally, it may be attributable to a combination of both suppression and facilitation. Our data suggest that the second explanation of suppression only is extremely unlikely, given that overall out-of-synch saccade latencies were significantly faster in the entrainment condition of Experiment 2 compared to the random condition, indicating facilitation. This is particularly powerful because this comparison was within subjects with order counterbalanced. Future research should aim to determine if suppression during off-peak periods is also occurring. For example, if suppression is occurring during off-peak periods, one might predict that detection of a stimulus that occurs during such a period will be worse than detection of a similar stimulus, at a similar time interval, when no entrainment is present.

5.2 Symmetry of Crossmodal Entrainment

One obvious area for future research on crossmodal entrainment concerns the symmetry of the effect. That is, can visual entrainment affect the allocation of auditory attention in the way that auditory attention affects the allocation of visual attention? The modality appropriateness hypothesis proposes that the modality that is most finely tuned with respect to a given task will dominate processing during that task (Welch & Warren, 1986). Audition has a more acute temporal resolution than vision and dominates temporal tasks, while vision has a higher spatial resolution and dominates spatial tasks (Glenberg...
Given this, one might predict that auditory entrainment is more likely to affect the allocation of visual attention than vice versa because of the preferential encoding of temporal information in the auditory modality.

Conversely, some evidence suggests that visual rhythms can impose their rhythm on auditory attention. Schroeder and Lakatos (2008) found that non-auditory inputs, such as visual signals, could modulate auditory processing such that auditory attention is synchronized with the visual rhythm. They point to the enhanced comprehension of vocal communication when viewing a speaker’s face as an example. Specifically, they argue that auditory oscillations are phase locked by visual attention such that they are in their high excitability state when auditory information arrives. Furthermore, it has been argued that visual rhythms automatically receive auditory encoding (Guttmann et al., 2005). This recoding might cause auditory attention to be entrained to the rhythm of the visual stimulus. However, McAuley and Henry (2010) demonstrated that while this transfer can occur, it is not obligatory.

Implicitly nested within the question of symmetry is the assumption that visual attention can be entrained to visual stimuli in a way that is similar to unimodal demonstrations of auditory entrainment. There has been little research done with respect to this unimodal question, although pilot work in the lab suggests the exciting possibility that visual attention may indeed be entrained to visual stimuli. Subjects were exposed to a series of regularly-occurring flashes on the screen analogous to the tone sequence used in auditory entrainment. At the end of the sequence, a square appeared on either the left or right of the screen. Subjects were instructed to indicate as quickly as possible on which side of the screen the square occurred. Initial data showed that subjects’ response times
were faster when the square onset was in-synch with the preceding rhythm of the flashes ($M = 315\text{ms}, SE = 8.4\text{ms}$) versus out-of-synch ($M = 342\text{ms}, SE = 9.1\text{ms}$). If this pattern persists, it will provide a useful paradigm in which the symmetry of crossmodal entrainment can be examined.

5.3 Conclusion

In all, three experiments examined the effect of auditory entrainment on the allocation of visual attention. Experiments 1 and 2 found a reduction in saccade latency when a visual onset was presented in-synch with the preceding auditory rhythm versus when the visual onset was out-of-synch. Similarly, Experiment 3 found an increase in accuracy for a gap-judgment task when the visual onset was in-synch with the preceding auditory rhythm versus when the visual onset was out-of-synch. All three experiments support a correspondence account of crossmodal entrainment, which argues that auditory entrainment similarly entrains visual attention such that they both share an attentional peak that corresponds to an expectation of stimulus occurrence.
REFERENCES


