An Empirical Assessment of the

Magician’s “Off-beat"

by

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A Dissertation Presented in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Approved June 2013 by the
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ARIZONA STATE UNIVERSITY

August 2013

ABSTRACT

Magicians are informal cognitive scientists who regularly test their hypotheses in the real world. As such, they can provide scientists with novel hypotheses for formal psychological research as well as a real-world context in which to study them. One domain where magic can directly inform science is the deployment of attention in time and across modalities. Both magicians and scientists have an incomplete understanding of how attention operates in time, rather than in space. However, magicians have highlighted a set of variables that can create moments of visual attentional suppression, which they call “off-beats,” and these variables can speak to modern models of temporal attention. The current research examines two of these variables under conditions ranging from artificial laboratory tasks to the (almost) natural viewing of magic tricks. Across three experiments, I show that the detection of subtle dot probes in a noisy visual display and pieces of sleight of hand in magic tricks can be influenced by the seemingly irrelevant rhythmic qualities of auditory stimuli (cross-modal attentional entrainment) and processes of working memory updating (akin to the attentional blink).

DEDICATION

This work is dedicated to my loving wife, Lauren, who has made innumerable sacrifices in order to help me add a few letters to the end of my name. Without her love and support, this would not have been possible.

ACKNOWLEDGMENTS

First and foremost, thanks to my friend and advisor, Steve Goldinger. In his laboratory, I was afforded a host of opportunities that I would not have had elsewhere. His willingness to support student research outside of his domain of expertise and to learn alongside his students is to be commended. Thanks also to my committee members Art Glenberg, Don Homa, and Dan Simons. I have appreciated the support and advice that you have provided as I make this attempt to contribute to the new, strange “science of magic” movement. Finally, thanks to my genius labmates, Michael Hout, Whitney Hansen, Megan Papesh, and Steve Walenchok, for the collegial and supportive environment that they helped to create in the lab.

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Historically, magicians and scientists have always engaged in a discourse. The discourse usually ended with magicians usurping the newest technological innovations for use in deceiving the masses. This was the case with Robert-Houdin’s (1859) early use of electromagnetism to change the weight of a small box at the magicians will. Over the last century, the dynamic has shifted such that scientists are becoming interested in the techniques employed by magicians (Kuhn, Amlani, & Rensink, 2008; Macknik et al., 2008; Macknik & Martinez-Conde, 2010). There is an increasing awareness that magicians are informal cognitive scientists who continually test hypotheses outside of the sterile confines of the laboratory. The knowledge accrued through this informal experimentation can guide formal scientific theories (Raz & Zigman, 2009) as well as translate into fresh methodologies for studying phenomena in the lab (Hergovich, Gröbl, & Carbon, 2011).

Thus far, the most fruitful collaborative effort between these disparate groups has been in the study of attention and inattention (Kuhn & Martinez, 2012). In the context of inattentional blindness, magic provides an ecologically valid means of studying the phenomenon both under well-controlled laboratory conditions (Kuhn, Tatler, Findlay, & Cole, 2008) and under conditions of more natural performance and viewing (Kuhn & Tatler, 2005). Furthermore, the collaboration is a natural fit, as magicians and scientists share many of the same analogies when discussing attention, most commonly speaking of the “spotlight of attention” (de Ascanio, 1964/2005; Kuhn & Martinez, 2012).

Analogies can be useful for guiding research and theory, but they can also constrain thinking in ways that limit theory development. Within psychology and neuroscience, widespread use of the spotlight analogy has led to a conceptualization of attention that is biased toward the visuo-spatial domain at the expense of temporal and internal (decidedly *not* spatial) dimensions (Fernandez-Duque & Johnson, 1999; Levin & Saylor, 2008). On some level, magicians have awareness that attention can be influenced by variables outside of the visuo-spatial domain. They regularly teach that sleight of hand should occur on the “off-beat” to evade detection (Kurtz, 1998). Embedded in this idea are a few assumptions. The first of these is that attention is not a static entity. Timing a sleight to occur at a specific moment in time rather than focusing on diverting attention in space suggests that magicians understand attention to be a dynamic process that waxes and wanes in time. Secondly, framing the momentary attentional suppression as a “beat” implies that the waxing and waning of attention follows a predictable, regular time course, like the beats of a metronome. While these intuitions do not fit comfortably into many popular models of attention (Posner & Rothbart, 2007), they are in line with modern dynamic models of attention which tend to focus on temporal over spatial aspects of attention (Large & Jones, 1999; Olivers & Meeter, 2008).

Visual Attention & Working Memory Updating

Although magicians have some notion of the *variables* that help to create a moment of attentional suppression, they rarely consider the *mechanisms* that drive the suppression of visual attention. Thus, the study of attentional deployment in time provides an ideal springboard for the collaboration between magicians and cognitive scientists. The first variable that magicians use to create moments of attentional suppression is the need for conceptual processing or memory search. Both of these processes are active in the successful perception of humor, and for this reason, magicians frequently use humor in their presentations. Although some have suggested that the experience of mirth is the root cause of humor-induced attentional suppression (Macknik et al., 2008; Macknik & Martinez-Conde, 2010), I contend that, instead, the processes that underlie an appreciation of humor commandeer attentional resources that could otherwise be used externally (Lamont & Wiseman, 1999).

A central component of nearly all formal theories of humor perception is a process of ambiguity detection and resolution (Attardo & Raskin, 1991). Raskin's (1986) script-based semantic theory of humor (SSTH) framed joking as the interplay of opposing semantic scripts. The set-up of a joke strongly activates a single interpretation (or script) in memory. Given the punch-line, the ambiguity of the set-up is appreciated and a shift from one semantic script to another takes place to resolve the newly-discovered ambiguity. In other words, the punch-line of a joke differs from the listener's predicted conceptual resolution, necessitating a search of working (and long-term) memory to access an alternative script that allows for reinterpretation of the joke's setup under the new constraints of the punch-line (Attardo, 1997).

The process of ambiguity detection and resolution places large demands on working memory and executive function (Shammi & Stuss, 2003; Uekermann, Channon, & Daum, 2006), and the computational complexity of the disambiguation process likely necessitates an inward focusing of attention toward the activated cognitive mechanisms. In support of this notion, people are more susceptible to inattentional blindness when they have to manipulate the contents of working memory (as one would need to do when reinterpreting a joke's set-up) than when they simply have to maintain its contents (Fougnie & Marois, 2007). Although this explanation of humor's role in the misdirection of attention is more detailed and mechanistically grounded than that provided by magic theorists, its spirit is captured in the writing of one of the founders of the Spanish school of magic, Arturo de Ascanio (1964/2005):

> Patter, in fact, can generate thoughts in the spectator's mind. As it turns out, when a significant thought goes off in his brain, its light is so blinding—even if only for an instant—that although he might be looking, he won't see a thing. This is because humans do not see with their eyes but rather with their minds, and at that moment the brain is busy absorbing the information, gauging it, and weighing its meaning and relevance (p. 64).

The moment of visual attentional suppression elicited by humor (or conceptual processing in general) has a distinct flavor of the attentional blink (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992): Following the detection of a meaningful stimulus in the environment (the punchline), detection of a subsequent meaningful stimulus (sleight of hand) is briefly hindered. The hallmark of the attentional blink (AB) phenomenon is the finding that, when searching an RSVP stream for a target stimulus (T1), a second target item within a ≈200-500 msec time window (T2) often goes unnoticed. The AB and humor-induced attentional suppression likely share more than a surface similarity. Indeed, many models of the AB share qualities with my conceptualization of the cognitive mechanisms underlying humor perception (Dux & Marois, 2009). In a general sense, most models (Hommel et al., 2006) suggest that the detection of T1 generates an attentional episode to enhance its processing (e.g., episodic registration and working memory consolidation). All of this post-detection processing demands attentional resources, thus depleting them from later stimuli (T2) which, as a consequence, are less apt to be detected and processed.

In their original study of the AB, Raymond, Shapiro, and Arnell (1992) theorized that the attentional blink acted to reduce the odds of erroneous feature binding of separate items in the RSVP stream. Their *gating theory* suggested that an attentional episode occurs with the detection of target features in the stream which briefly opens a gate to higher level perceptual processing. Once T1 has been admitted, the gate is closed until processing is complete, thus disallowing other stimuli occurring during this brief period (including T2) from being processed. This narrow interpretation of the AB was later expanded and generalized to suggest that gating is meant to counteract *any* type of post-target interference with T1 processing (Olivers, van der Stigchel, & Hulleman, 2007). Extending the initial theory was necessary, as AB is not limited to visual perception and can occur cross-modally between audition and vision (Arnell & Jolicœur, 1999) and even between vision and haptics (Soto-Faraco et al., 2002). More recent models of the AB have moved away from the ambiguous “gating” mechanisms to focus on more concrete mechanisms of attentional selection. The delayed-reengagement account of AB (Nieuwenstein & Potter, 2006; Nieuwenstein, Potter, & Theeuwes, 2009) reframed AB as reflecting the difficulty in reengaging attention for T2 following its disengagement as a consequence of post-T1 distractors. In support of this notion, the AB is attenuated when distractor items are replaced with a sequence of targets, removing the need for attentional disengagement (Nieuwenstein, Potter, & Theeuwes, 2009).

Wyble, Bowman, and Nieuwenstein (2009) provided a framework for the attentional blink that concatenated the gating and delayed-reengagement theories. Their connectionist *episodic simultaneous type/serial token* (eSTST) model generates a series of attentional episodes, with the duration of each episode being a consequence of attentional engagement/disengagement a la the delayed-reengagement theory. Items from the RSVP stream are monitored by a task demand node which allows targets to activate their corresponding type nodes while inhibiting activation from distracters that fall outside the attentional set. As targets are detected, an “attentional blaster” enhances the activation elicited by each target, facilitating activation of the type nodes. This activation feeds forward in time to subsequent targets until a distractor is encountered, triggering an immediate reduction in attentional blaster activity, effectively gating the input queue. As type nodes become activated by targets from the input stream, once a threshold is reached, an encoding process is triggered wherein the activated types are bound to the temporal information encoded from the input stream to create a set of tokens in working memory. The encoding process actively inhibits the attentional blaster, producing an AB.

An analogous outcome occurs when participants have to report, in real time, detection of multiple stimuli in a stream. If a second stimulus appears shortly after the first, reaction times to report the second stimulus are slowed substantially. This *psychological refractory period* (PRP) effect is generally attributed to a bottleneck in mechanisms responsible for response selection (Pashler, 1994; Telford, 1931). In support of this notion, when response selection is complicated by increasing the number of potential response alternatives, the PRP is prolonged (Karlin & Kestenbaum, 1968). The primary difference between the AB and the PRP may lie in the methodologies. The method used to study the AB typically does not require online target reporting. Instead, targets are reported after the RSVP stream has concluded. This methodological difference has led to the inference that disparate mechanisms underlie the PRP effect and the AB. However, using a cross-modal PRP task, Marti, Sigman, and Dehaene (2012) supplied evidence that both effects are driven by activity in the frontal cortex, which is, in turn, affected primarily by the duration of T1 processing. Their task elicited both AB trials (where the second target was missed completely) and PRP trials (where the second target was detected, but reporting was slowed). Using MEG, they observed that T2-related activity in the frontal cortex was delayed on PRP trials and absent on AB trials. Furthermore, late-arriving T2-related components generated by frontal regions and correlated with central processing demands were delayed on trials when T1 processing was slower. They took this to mean that both the AB and PRP effects are due to a bottleneck in central processing stages that make content available to consciousness. Therefore, the differences between AB and PRP could depend more upon the quantity than the quality of processing necessary to perform the task.

A similar relationship could exist between the AB and working memory updating in the service of linguistic ambiguity resolution (as exploited by magicians). While both effects could prey on the same central processors, additional factors could influence the size of their behavioral effect. For example, in an RSVP task, task-irrelevant emotional stimuli can capture attention, creating something akin to an attentional blink (McHugo, Olatunji, & Zald, 2013). Furthermore, words with emotional meanings can produce Stroop interference (Williams, Mathews, & Macleod, 1996). That is, a person’s ability to simply name the colors in which words are printed can be hindered by the emotional meaning of a colored word. Taken together, these findings suggest that attention is preferentially diverted toward items of high emotional salience. Thus, the automaticity of language processing combined with the humorous content of the message and the complexity of ambiguity resolution could make jokes a *superstimulus* for creating momentary visual attentional suppression akin to the AB. In support of this notion, it is now well-accepted that as the amount of T1 processing (or the time a participant allots to

T1 processing) increases, so too does the size of the AB (Jolicoeur, 1999; Marti, Sigman, & Dehaene, 2012).

Reviewing the AB literature makes clear that the AB is not the result of a single process or mechanism (Dux & Marois, 2009; Hommel et al., 2006). The AB is more likely to be rooted in a set of interacting processes housed in disparate regions of the brain, all of which could be modulated by additional situational variables. In support of this notion, evidence is beginning to accrue that the AB may result, at least in part, from brain states preceding the start of an RSVP trial. Oscillatory mechanisms implicated in the orchestration of regional interactions (specifically oscillations in the beta band) have been shown to differ before AB and no-AB trials (Kranczioch, Debener, Maye, & Engel, 2007). The role that brain oscillations play in awareness is only beginning to receive attention (Janson & Kranczioch, 2011), but new research is suggesting that they have a more direct relationship to cognitive life than previously believed (Buzsaki, 2006). Rhythms in the brain play a pivotal role in the second type of off-beat magicians regularly exploit.

Attentional Entrainment

Whereas humor-induced attentional suppression and its experimental counterparts (AB and PRP) are endogenous effects upon attentional deployment (if an audience member isn’t actively attending to the humor, the effect should disappear), magicians also exploit automatic, exogenous cues to temporal attention allocation. The second variable that magicians employ to create an attentional off-beat is the instantiation of a visual or auditory rhythm to focus attention at predictable points in time while presumably relaxing attention at moments between beats. Implementation of this strategy may be less active than the use of humor. In many cases, it may be a natural effect of using music or rhythmic patter to accompany the performance of magic, of which magicians are unwittingly taking advantage. One general situation where the strategy is actively employed was described by early magic researcher Max Dessoir (1891). When a magician makes some object disappear, he will often create anticipation for its disappearance by counting to three. In order to evade detection, the method used to vanish the object is usually implemented between beats (or at least before "three" is reached). The audience's attention is optimized in time to coincide with the count of three, when the magical event is expected to take place, and thus they fail to detect the secret method.

Although not meant to fool the entire audience, Slydini used this strategy in his famous "Flight of the Paper Balls" (Ganson, 2001; Slydini, 1975), wherein he repeatedly caused wadded balls of tissue to vanish under the eyes of a spectator by throwing them over the spectator's head. By instantiating a physical rhythm while feigning the placement of each ball into his hand, Slydini automatically created a series of off-beats that coincided with the moment he released the balls to fly over the spectator's head. Perhaps a stronger example was provided by modern magician, David Williamson (Kaufman, 1989). In his "striking vanish," a coin visibly disappears from the open hand when it is struck by a magic wand. The method is quite simple, but the effect is impressive: Before the magic wand strikes it, the coin is thrown from the open palm into the hand holding the magic wand. Although not originally described this way, in practice, the magician typically strikes the coin with the wand twice before its eventual disappearance on the third strike. By virtue of entraining the audience's attention to the rhythmic tapping, the sleight (which occurs during the attentional “trough” between the second and third beats) goes unnoticed.

As already noted, although attention theories tend to be biased toward the visuo-spatial domain, a few theories have attempted to address how attention is deployed in time. The most notable of these is the *dynamic attending model* (Large & Jones, 1999). Large and Jones took as their starting point the idea that internal oscillations (or *attending rhythms*) can be influenced by rhythms ex vivo such that the attending rhythms entrain to these external sources, optimizing attentional resources in anticipation of future events. Attending rhythms are conceptualized as self-sustaining biological oscillations wherein a brief pulse of energy (generated from the external rhythm) can cause a phase shift, aligning one point in the oscillator’s limit cycle with the recurring environmental stimulus. The hallmark of entrainment is the oscillator’s ability to adapt to perturbations in the external rhythm, maintaining a high level of temporal alignment.

In order to computationally model attentional entrainment, Large and Jones (1999) started with the simplest case: an oscillation whose periodicity matches the frequency of the external rhythm. Under these basic conditions, entrainment was a matter of calculating the relative phase of the attending rhythm to the external rhythm. Disparity between the external rhythm’s onset and its expected onset would be used to adjust the phase of the attending rhythm to optimize future predictions. This strategy would work to entrain to a consistent rhythm and even to a rhythm that varies greatly around a mean periodicity by instantiating a weighting or coupling strength term which could disallow over-adjustment in these cases. However, if the external rhythm changes at a regular rate over time, this strategy would consistently predict future beats either too early or too late without appreciating the rate change; it would fail to entrain. To entrain to a consistently changing external rhythm, the attending rhythm's periodicity would need to be malleable in the same way as its phase. Thus, Large and Jones added a periodic state variable that adapts the attending rhythm's periodicity to deviations in the external rhythm's frequency (also weighted based on the consistency of the external rhythm).

The final component Large and Jones (1999) built into the model was a density function that allowed the temporal expectation to fall within a range of times rather than at a single, specific point in time. This addition allowed the model to better align with the entrainment conditions that happen in the real world, where perfectly consistent rhythms are rare. It also allowed for the expectation to adapt under conditions of high or low environmental variability. The kurtosis of the density function changes as a function of synchronization strength to optimize attention at highly specific time points under conditions of high rhythmic consistency and distribute attention more diffusely over time under conditions of low consistency.

Indeed, laboratory examinations of attentional entrainment have produced rather astounding results that fall in line with the dynamic attending model. Mathewson and colleagues (2010) employed a metacontrast masking procedure, asking people to detect a briefly-presented, dot presented at fixation and backward masked with an annulus. On some trials, the target was preceded by a set of rhythmic visual stimuli (identical to the backward mask). The researchers hypothesized that detection of the target would improve if it was presented in phase with the entraining stimuli and suffer if the stimulus presentation was offset from the entraining rhythm in either direction. As predicted, they found that detection rates (and d' values) for targets presented at the expected time point increased as a function of the number of entraining stimuli and that rates of detection were substantially reduced for targets presented out of phase. Thus, attention naturally aligns to environmental rhythms as a means of optimizing perception of future events. While the transient deployment of attention in time can enhance stimulus processing, it also comes with a cost. Stimuli appearing at unpredictable timepoints (such as the tossing of the coin in David Williamson's striking vanish) are less apt to reach awareness.

The neural oscillations that accompany stimulus processing hint at the mechanisms underlying the attentional entrainment. Lakatos and colleagues (2008) presented compelling evidence that oscillations across frequency bands entrain to rhythms in the environment that are predictive of when attention should be deployed to facilitate the perception of a transient stimulus. They presented macaques with auditory and visual streams with complementary, although jittered, relative phases. That is, the onset of an auditory stimulus occurred 180° out of phase with the prior visual stimulus, on average, with each stream having a mean frequency of 1.5 hz (falling within the delta band of 1-4 Hz, believed to interfere with processing). On each trial, the monkeys were required to monitor either the visual or the auditory stimulus stream for an oddball while neural activity in V1 was measured with multielectrode arrays. When the monkeys were attending to the visual stream, delta oscillations entrained to the visual rhythm such that their local minima (i.e., the moment of least processing interference) coincided with the onset of each visual stimulus. The opposite pattern of visual cortex activity was observed when the monkeys attended to the auditory stream. In this condition, phase minima were aligned with auditory, not visual, onsets. Furthermore, the delta activity modulated activation in higher frequency bands, with theta and gamma waves (which have been implicated in attentional selection) showing increased amplitudes in anti-phase with delta waves. Beyond simply aligning in time to external rhythms, the measured oscillations were also predictive of response times to detect oddball stimuli, with stimuli presented coincidentally with the trough of the delta phase eliciting the fastest responses.

Similar results have been observed in experiments focused on the relationship between slow alpha oscillations (in the 8-12 Hz range) and perception. Alpha oscillations appear to be indicative of neural inhibition (Ward, 2003). Over the visual cortex, their amplitude is negatively correlated with the probability of detecting a transient visual stimulus (Mathewson et al., 2011). Rohenkohl and Nobre (2011) examined alpha activity as a consequence of temporal expectancies. Participants in their study tracked a ball that moved across the screen at regular or irregular time steps, thus instantiating an entraining event in the regularly-paced trials. The ball temporarily disappeared behind an occluder, and when it reappeared, participants had to make a perceptual judgment about a new stimulus overlaid on the ball. EEG data collected over the visual cortex revealed robust alpha desynchronization, a reduction in the amplitude of alpha oscillations, immediately prior to the reappearance of the ball on regularly-, but not irregularly-paced trials. Alpha desynchronization was accompanied by faster RTs in the entrained conditions, supporting the idea that entrainment allows for the optimization of attention at expected time points.

Taken together, the preceding experiments and models suggest that perhaps a more apt analogy for attention is that of a *blinking* spotlight (VanRullen, Carlson, & Cavanagh, 2007). These results point to an almost automatic tendency for the brain to entrain to rhythms in the environment when they are available, sampling information from the sensory stream at regular intervals. Automatic processes hold a great appeal for magicians, as they almost always lead to the establishment of faulty assumptions that go unquestioned (Barnhart, 2010). Lamont and Wiseman (1999) noted that action rhythms can create moments of primary and secondary interest (on and off the beat respectively), but few magic scholars explicitly discuss how attention can be influenced by the mere presence of rhythms in the environment. Fitzkee (1975) and Ammar (1980) both addressed the importance that rhythm has in deflecting attention away from sleight of hand, suggesting that if the sleight coincides with the *interruption* of a rhythm, be it visual or auditory, a moment of unwanted attentional capture is likely. Similarly, in his treatise on the psychology of magic, Sharpe (1988) suggested that sleight of hand could evade detection if carried out during a *period of inattention* resulting from attentional fatigue. Ascanio (de Ascanio, 1964/2005) limited his discussion of timing and rhythm to the idea of "in-transit actions," subtle gestures that occur within a greater "final action." If the overarching final action is salient, the in-transit actions (usually sleight of hand) will elude attention.

Although these theories may be useful for magicians, aside from Ascanio's theory, they clearly lack the specificity necessary for integration into psychological theories, and they often fail to consider the relative value or independence of each contributing variable. For instance, Slydini, often regarded by magicians as the modern father of misdirection theory, stressed the role that timing and rhythm play in the misdirection of attention without specifying how they operate independently of other forms of misdirection (e.g., joint attention and physical tension):

> In some instances it is the *timing* which is the strong feature in the means of deception, and in other instances it is mainly the *misdirection* but in all cases the two things are present to some degree…To give the correct *timing* to the actions

> and to create *misdirection* the performer uses coordinated movements of the arms, the hands, the head and the body, and also alters his facial expression in accordance with the impression he wishes to convey (Ganson, 2001, p. 22).

Magicians typically do not concern themselves with the separability of the components of deception. Why would they? Their only concern is in the outcome of a magical effect, not in the unique contribution that each factor makes to the outcome. Oftentimes, the methodological redundancies that magicians build into their effects produce a perceptual outcome that is not amenable to (or that complicates) the reductionism necessary for laboratory experimentation. Binet (1894) noted this complication, saying, “The illusion of each trick is not merely the result of one single cause, but of many, so insignificant that to perceive them would be quite as difficult as to count with the naked eye the grains of sand on the seashore” (p. 558).

Despite Binet’s warning, the experiments described here attempt to empirically assess some of these grains of sand. Specifically, the current experiments examine the variables that magicians manipulate to create a moment of visual attentional suppression. The vague characterization of attentional deployment in time provided by magic theorists allows for psychological science to take the reins. By empirically examining the variables that magicians have highlighted in the manipulation of temporal attention, psychological theories can be updated, and, in turn, “fill in the gaps” of magical theories. These variables were examined across a variety of conditions, ranging from incredibly artificial laboratory tasks to conditions that attempt to emulate the real-world viewing of a magic show.

Experiment 1: Cross-Modal Attentional Entrainment Effects

Although the effects of attentional entrainment within modalities are well-known (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Large & Jones, 1999; Martin et al., 2005; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Rohenkohl, Coull, & Nobre, 2011; Rohenkohl & Nobre, 2011), very little research has assessed the possibility of cross-modal attentional entrainment. Logic dictates that the entrainment of attention should occur across the senses. We live in an inherently rhythmic world. There are large-scale rhythmic regularities in the progression of the seasons and in the rising and setting of the sun (Buzsaki, 2006). At a more fine grained level, there are regular rhythms in our locomotion (whether it be walking or skipping), our eye-movements, and the speech we use to communicate (Schroeder, Lakatos, Chen, Radman, & Barczak, 2009).

In most instances, stimulation falling on one sensory organ is accompanied by similarly-structured stimulation of other sensory organs. For example, when one watches a trotting horse, the visual rhythm is often accompanied by a concurrent auditory rhythm. Sensitivity to these covarying streams of information produces phenomena like the McGurk (MacDonald & McGurk, 1978) and the *ventriloquism* (Jack & Thurlow, 1973) effects. The frequent covariation of visual and auditory rhythms in the environment should naturally lead to conditions of cross-modal entrainment to facilitate perception in situations where information from each modality may be degraded, as in the case of speech perception in a noisy room. Entraining to the rhythm of phoneme and syllable production (both visually and aurally) should optimize processing of visual information when auditory content is degraded, and vice versa (Sumby & Pollack, 1954).

Neuroscientific investigations into multisensory interaction suggest that oscillatory mechanisms should lead to cross-modal attentional entrainment. For example, research with monkeys has shown that a brief electrical pulse to muscles in the wrist (which is processed very quickly) can cause phase-resetting of oscillations over the auditory cortex, facilitating detection of a concurrently presented auditory stimulus, necessarily processed slightly later than the somatosensory input (Lakatos, Chen, Mills, & Schroeder, 2007). Similar modulation of auditory cortex field potentials has been observed with coupled audio-visual stimuli (Kayser, Petkov, & Logothetis, 2008).

To date, only one study has been published examining cross-modal attentional entrainment effects. Miller, Carlson, and McAuley (2013) measured saccadic latencies to a dot probe that was presented either in phase or out of phase with a stream of seemingly irrelevant auditory tones. They observed significantly faster fixation times to dot probes with an onset aligned to the rhythm rather than out of phase with it. In addition, entrainment to the auditory tones facilitated detection of the opening in a Landolt Square that was presented in phase with the tones. Their results support the notion that attentional entrainment is an automatic, exogenous orienting effect, as the rhythmic tones were not actively attended to in any meaningful way (see also Rohenkohl, Coull, & Nobre, 2011).

For the majority of their experiments, Miller, Carlson, and McAuley (2013) employed visual stimuli that easily captured attention. Thus, they were unable to examine differences in dot probe detection accuracy. As a consequence, it becomes difficult to assess whether entrainment in their task facilitated detection of the dot probes or simply the execution of an oculomotor response. Under conditions where visual information is noisy, entrainment should facilitate signal detection (not just motor responses) to stimuli appearing in phase with the rhythm. Experiment 1 was designed to assess whether entrainment to a regular auditory rhythm leads to a concurrent optimization of visual attention at time points coinciding with the auditory beat. Entrainment effects were examined within simple auditory and visual stimulus monitoring tasks wherein the presentation of a *subtle* visual stimulus was either aligned or misaligned in time with the regularly occurring rhythm of an auditory stimulus stream. If entrainment operates across sensory modalities, visual perception should be more sensitive in moments when an auditory stimulus onset is expected than in the “off-beats” between auditory stimulus presentations.

An important, and unanswered, question is whether or not cross-modal entrainment effects are necessarily the result of attending to a rhythm in the environment. If the rhythmic auditory stream did not require attention, would visual attention entrain to the rhythm, or would attention be deployed in a more continuous, vigilant manner? Entrainment experiments in a single modality have shown that performance in time can be biased by the mere presence of entraining stimuli, but they have not actively manipulated whether special attention needs to be paid to the entraining stimuli for this to happen (Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010). In this prior work, since all of the relevant information was gleaned from the one modality, there is no reason to believe that participants were not actively attending to the entraining beats in that modality despite the fact that they were irrelevant to the primary task. However, in a cross-modal task, one could expect it to be much easier to ignore the seemingly task-irrelevant information coming from the entraining modality. Thus, Experiment 1 also actively manipulates (between subjects) whether participants need to attend to the auditory stream (Condition 1) or not (Condition 2). I expect that, when a rhythm is available to one modality, attention will automatically entrain to that signal (regardless of attentional set), with this entrainment spilling over into other modalities. This prediction is in line with the observed tendency for oscillatory mechanisms in the brain to phase lock across cortical regions (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008).

Method

Participants

Participants were recruited from Introductory Psychology courses at Arizona State University. 111 students with normal or corrected-to-normal vision participated (52 in Condition 1; 59 in Condition 2) for partial course credit.

Materials & Stimuli

Experiments were programmed in the E-Prime 1.2 software package (Schneider, Eschman, & Zuccolotto, 2002), and data were collected on Gateway computers. Visual stimuli were presented on 16” flat-screen CRT monitors with refresh rates at 60Hz. Responses were collected using PST serial response boxes. Auditory stimuli were delivered via headphones.

Auditory stimuli consisted of streams of 150-msec tones at 750 or 900Hz. On half of the trials, the 750Hz tones were used as entraining stimuli, while the 900Hz tones were used on the other half. In trials with 750Hz entrainers, the 900Hz tones were oddball stimuli, and vice versa. Entraining tones were presented at one of two rates, manipulated within-subjects. On fast trials, tones were presented every 650 msec (or at roughly 1.5Hz). On slow trials, tones were presented every 1500 msec (or at .67Hz). Visual stimuli consisted of three background images created using Adobe Photoshop. The images were generated at 1024x768 pixels to fill the computer screen. In each image, the color value for every pixel was selected randomly, creating a field of visual noise. Six dot probe stimuli were created in a similar fashion. Each dot probe was a 30x30 pixel square (roughly 3° visual angle), generated using the same random pixel color procedure as the background images. Then, a yellow field with 95% transparency was overlaid upon the probe so that it could be discriminated from the background noise. Background and dot probe stimuli were randomly sampled from this pool on every trial.

Procedure

After obtaining informed consent, participants completed six practice trials (half fast and half slow) followed by 108 experimental trials. On each trial, participants heard a stream of auditory tones while they monitored a visual field of colored noise for the onset of a transient dot probe. Participants in Condition 1 actively monitored the auditory stream for the presence of an oddball stimulus. Participants in Condition 2 experienced the same auditory conditions, but were not directed to monitor the stream for an oddball. Participants pressed the right-most button on the response box to report detection of a dot probe, and those in Condition 1 pressed the left-most response box button upon detecting an auditory oddball.

Each trial lasted for 19.5 seconds (13 tones at the slow rate; 30 tones at the fast rate), but trials were blocked into 36 groups of three (each block at the same entrainment rate) with no explicit boundaries between trials. Thus, participants perceived each trial to last for 58.5 seconds. Within each block they encountered one auditory oddball and three visual dot-probes (one per trial). The position of the auditory oddball trial in each block (trial 1, trial 2, or trial 3) was randomized across blocks. Within the auditory oddball trials, the dissimilar tone could appear at one of two positions within the stream: following the first third or preceding the final third of the entraining tones (also selected randomly).

The primary visual attention task was adapted from Klein (1988). On each trial, dot probes appeared overlaid on the background of colored noise in one of nine randomly-selected positions in a 3X3 grid measuring 624x442 pixels, with a random amount of jitter (up to ±50 pixels) then added about the X and Y axes. Dot probes appeared at one of three temporal positions relative to the entraining tones in each trial (counterbalanced across trials): following the first quarter of entraining tones, at the midpoint of the auditory stream, or before the final quarter of entraining tones. Within each block of three trials, the onset of the dot probe was temporally aligned with the onset of an entraining tone on one trial, offset by 25% of the entraining frequency on one trial, and offset by 50% of the entraining frequency on one trial (with the order randomized across blocks). Dot probes disappeared 500 msec after their onset regardless of whether participants responded with a button-press, and only one dot probe response was accepted on each trial.

Results

Eleven participants were excluded from analyses (8 from Condition 1; 3 from Condition 2). Six were excluded from Condition 1 for average rates of oddball detection more than 2.5 standard deviations below the group mean. Five participants were excluded for detecting dot probes at rates more than 2.5 standard deviations below their group means. Responses falling outside a 1500 msec window following dot probe onset were considered to be erroneous. This criterion led to the exclusion of 31.5% of all trials from reaction time analyses. High error rates in this experiment (and later experiments reported here) precluded analysis via repeated-measures analyses of variance, as many participants had at least one empty cell, and thus would be excluded. Consequently, all analyses reported in this document were carried out through linear mixed effects modeling (LMM) in SPSS using the MIXED procedure. LMM is built upon maximum likelihood methods, allowing for estimation across incomplete datasets with unbalanced designs.

Dot-probe responses collected during auditory oddball trials were excluded from analyses, as the need to program two motor responses in close succession could create interference (or a PRP effect). Indeed, a paired-sample t-test upon dot probe detection accuracy showed that accuracy was reduced on trials with an auditory oddball, as compared to trials without an oddball, $t(99) = 1.97$, $p = .05$, $d = .14$.

Reaction Times

I examined only reaction times (RTs) for trials where a response was elicited within 1500 msec of the dot probe onset. These RTs were log transformed prior to analysis. I began my analyses with a LMM with between-subjects factor Condition (1, 2) and within-subject factors Rate (fast, slow) and Phase (on beat, off 25%, off 50%). There was a significant main effect of Condition, $F(1, 100) = 15.41$, $p < .001$, $pseudo\text{-}r^2 = .15$, with reaction times 85 msec faster in Condition 2, where participants were not required to listen for auditory oddballs, compared to Condition 1. Reaction times differed significantly as a consequence of entrainment Rate, $F(1, 500) = 17.67$, $p <.001$, $pseudo\text{-}r^2 = .03$. Participants were 33 msec faster to respond to dot probes in the fast entrainment condition than the slow condition. There was also a reliable main effect of Phase, F(2,

500) = 3.37, $p = .04$, $pseudo\text{-}r^2 = .01$, with reaction times slowed for dot probes presented out of phase with the entraining rhythm. Post-hoc analyses showed that RTs to dot probes presented on the beat were significantly faster than to those presented 25% off the beat ($p = .02$, $d = .04$) and those presented 50% off the beat ($p = .03$, $d = .04$). RTs for dot probes presented 25% off the beat did not differ from those presented 50% off the beat. The latter two main effects were qualified by a Rate by Phase interaction, $F(2, 500) = 3.29$, $p = .04$, $pseudo\text{-}r^2 = .06$, wherein the phase effect was only evident for entrainers presented at the slow rate (see Figure 1). Importantly, none of the effects interacted with Condition.

To assess whether entrainment effects increase with prolonged exposure to an auditory rhythm, I ran another LMM analysis with factors Condition (1, 2), Phase (on beat, off 25%, off 50%), and within-block Trial (1, 2, 3). This analysis produced only a main effect of Condition, $F(1, 100.08) = 14.53$, $p < .001$, $pseudo\text{-}r^2 = .14$, in the same direction as the prior analysis.

Probe Detection Accuracy

The same series of analyses was carried out upon accuracy rates across conditions. Again, I began with a LMM with factors Condition (1, 2), Rate (fast, slow), and Phase (on beat, off 25%, off 50%). I observed a significant Rate effect, $F(1, 500) = 877.51$, $p < .001$, $pseudo\text{-}r^2 = .64$, wherein participants were more accurate to detect the dot probe in the fast condition (M = .84) than in the slow condition (M = .54). The only other effect was a reliable Phase effect, $F(2, 500) = 3.31$, $p = .04$, $pseudo\text{-}r^2 < .01$ (see Figure 2). Post hoc analyses showed that accuracy to detect dot probes presented on the beat (M = .70) was significantly higher than accuracy detecting probes 25% off the beat

(M = .67, *p* = .01, *d* = .07), but neither were significantly different from dot probe detection 50% off the beat (M = .69).

Next, I carried out a LMM with factors Condition (1, 2), Phase (on beat, off 25%, off 50%), and within-block Trial (1, 2, 3). This analysis produced a significant Phase effect, *F*(2, 800) = 3.07, *p* = .05, *pseuro*-r^2 = .01. Post-hoc comparisons again showed that accuracy was higher for dot probes presented on the beat than 25% off the beat (*p* = .04, *d* = .06). However, in this analysis, accuracy was also significantly better for dot probes presented 50% off the beat than for those presented 25% off the beat (*p* = .03, *d* = .07). Accuracy did not differ for dot probes presented on the beat and off the beat by 50%. There was also a significant Condition by Trial interaction, *F*(2, 800) = 3.52, *p* = .03, *pseudo*-r^2 = .01, which was likely due to fatigue in Condition 1, as accuracy decreased in later trials within a block. This pattern was not present in Condition 2.

Discussion

Experiment 1 produced clear evidence of cross-modal attentional entrainment effects both on dot probe detection accuracy and on reaction times to report the onset of a dot probe. Participants responded to dot probe onsets faster and with greater accuracy when dot probe onset was aligned in time with the onset of an auditory stimulus in the rhythmic tone stream than when its onset was shifted away from the beat. Although participants were faster to detect and report dot probes in the fast entrainer condition, the effects of attentional entrainment were most prominent when the entraining rhythm was slow. Lakatos and colleagues (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Lakatos et al., 2005) have suggested that the mechanisms underlying attentional entrainment should flexibly adapt to almost any rhythmic stimulus, as entrained neural oscillators modulate both the phase and amplitude of those in higher and lower frequency bands. However, it could also be the case that the fast entraining rhythm elicits a more vigilant mode of attending, whereas slow rhythms encourage periodic attentional optimization (Schroeder & Lakatos, 2008). Future research should examine the dynamics of attentional entrainment across rhythmic frequencies.

An important outcome from Experiment 1 is the observation that entrainment effects did not differ as a consequence of attentional set. That is, entrainment effects were still observed when the auditory stimuli required no attention at all (in Condition 2). This suggests an almost automatic tendency to integrate information, however irrelevant, across sensory systems to generate predictions for perceptual optimization. Generally, this result supports Kahneman's (1973) capacity theory of attention, suggesting that resources from a central pool may be allocated flexibly across all modalities. This notion is also supported by the finding that RTs were generally slowed in Condition 1, when attention had to be divided between sensory modalities. Many theories of attention pre-suppose isolated attentional resources for disparate sensory systems, and would not predict this outcome (Allport, Antonis, & Reynolds, 1972; Arrighi, Lunardi, & Burr, 2011; Larsen, McIlhagga, Baert, & Bundesen, 2003; Shiffrin & Grantham, 1974).

Although Experiment 1 generally supported an attentional entrainment account, one result was unexpected. I predicted that detection accuracy would be lowest (and reaction times slowest) at moments exactly in between auditory beats. However, the accuracy results showed a rebounding of attention at the 50% offset (which will be replicated in a later experiment). Perhaps the current predictions depended on an overly-simplistic interpretation of oscillatory processes and entrainment. Although I designed the experiment to assess the exogenous temporal entrainment of attention, endogenous factors were also at play across conditions. Endogenous and exogenous attentional effects are dissociable both behaviorally and physiologically (Coull & Nobre, 2007; Lawrence & Klein, 2013; Rohenkohl, Coull, & Nobre, 2011). Consequently, endogenous attentional factors may have independently acted to boost attention (or arousal) when oscillations elicited by exogenous entrainment were in the trough of their limit cycle, producing a rebound between beats. Alternatively, multiple oscillatory cycles could have entrained to the rhythm such that there was a reduced, but stable entrainment to moments half way between auditory beats as well as entrainment to the beats, themselves. These alternatives will be explored further in the General Discussion.

Although magicians are likely to be unwittingly exploiting attentional entrainment, as we saw in David Williamson's "striking vanish" (Kaufman, 1989), they may not appreciate the opportunities afforded by this automatic tendency. If magicians selected music to accompany their performances that had a clear, constant rhythm (at an optimal frequency) and complemented this entrainment with more standard techniques of misdirection, they could greatly increase susceptibility to inattentional blindness with little effort.

The picture developing from this set of experiments highlights the importance of expectation in the manipulation of attention. By setting up an expectation for when an important event is going to occur (either consciously or unconsciously), one can dupe perception by presenting an unexpected event at the wrong time or by shifting the onset of the expected event. However, entrainment is an instance of a rather low-level predictive mechanism. As discussed earlier, there are other, more high-level, tools in the magician’s arsenal that can be used to cause a momentary suppression of visual attention. Many such strategies call upon the cognitive processes underlying the disambiguation of language and the predictive processes that attempt to lighten the cognitive load of language interpretation.

Experiment 2: Cross-Modal Temporal & Conceptual Entrainment to Speech

Experiment 1 used pure tones as auditory entrainers. However, these were not likely to be the types of stimuli that the auditory cortex evolved to handle, as they do not appear in the natural world. Luo and Poeppel (2007) showed that neural oscillations play an important role in the parsing of speech sounds. Slow theta rhythms entrain to the syllable structure of words to maximize processing efficiency. Furthermore, the theta phase modulation is not driven primarily by acoustic properties. Rather, it is an instantiation of top-down optimization of neural function. Given that speech is likely to be the most regularly-occurring environmental rhythm we encounter, it also seems likely that the neural architecture has calibrated itself to efficiently entrain to these complex rhythms, making them an optimal source of the effects currently being studied. In addition, speech allows for concurrent examination of attentional effects elicited by temporal entrainment (Experiment 1) and conceptual processing.

While attending to speech, people attempt to predict upcoming words and concepts (Van Berkum, Brown, Zwitserlood, Kooijman, & Hagoort, 2005). Informally, we see this occurring every day when people complete others' sentences. Prediction of subsequent linguistic elements is likely useful in lightening the load on online conceptual processing mechanisms by reducing the amount of content that needs to be held active in working memory and speeding lexical access through semantic priming (Peleg & Eviatar, 2008). Prediction also influences how attention is deployed during language processing. Usually, when confronted with an unpredictable word, people focus attention at its onset (which is typically more useful in identifying a word than its rime), but Astheimer and Sanders (2011) showed that when a word is highly predictable based on its context, this attentional focus is dissipated. Predictive deployment of attention in this case can be considered a concept-based attentional entrainment effect. However, unlike the type of entrainment examined in the previous experiment, information is sampled from the environment at moments when the content is least predictable rather than most predictable. What happens, though, when an unexpected word appears within a context of high predictability? This situation is analogous to the processing demands of garden path sentences such as *"The government plans to raise taxes were defeated."* When an incorrect syntactic interpretation of the initial clause in a sentence sets up an incorrect syntactic expectation for the final clause, a reinterpretation of the entire sentence is necessary upon detection of the incongruity between expectation and reality.

When reading garden path sentences, eye movements show that people make a substantial number of regressions following the detection of the final clause ambiguity (Meseguer, Carreiras, & Clifton Jr., 2002). However, in speech perception, relevant information is no longer available in the environment, thus requiring regressions into memory. In light of Astheimer and Sanders' (2011) findings, the strong expectation elicited by the initial clause in a garden path sentence probably reduces the amount of attention deployed to the final clause, thereby complicating disambiguation. Furthermore, after detecting the ambiguity, attention will need to be diverted to memory stores to resolve the ambiguity.

In a sense, interpretation of garden path sentences imposes the same cognitive demands as the interpretation of jokes. The set-up of a joke creates an expectation that is disconfirmed by the punchline, requiring a recursion into memory to reinterpret the set-up under the new constraints of the punchline. As already noted, these processes bear a high similarity to the processes thought to produce the attentional blink. Experiment 2 examined a simplified, but analogous instance of conceptual entrainment using linguistic stimuli. Participants in Experiment 2 heard strings of spoken numbers, presented at a regular rate of .5Hz while taking part in the dot probe detection task from Experiment 1. In Condition 1, participants monitored the auditory stream for instances where three odd numbers appear in a row. Participants in Condition 2 were exposed to the same stimuli but were not instructed to listen for strings of odd digits. Thus, all participants should show evidence of exogenous attentional entrainment (at .5Hz), as reflected in slowed RTs (and reduced accuracy) for dot probes presented off the beat.

While the entrainment phenomenon examined in Experiment 1 was expected to be an automatic tendency, conceptual entrainment most likely requires active attention to the auditory stream. At a magic show, one strategy that audience members could adopt to avoid being deceived would be to ignore the story that the magician is presenting, focusing solely on the magician's actions. This resistance to conceptual entrainment would presumably free attentional resources that could be deployed to detect the magician's methods. Thus, only those participants listening for odd digits strings (Condition 1) should show evidence of endogenous conceptual entrainment effects upon attention, reflected in rates of detection for dot probes presented concurrent with the third odd digit in a string (when content is being encoded into working memory).

Method

Participants

Participants included 118 Arizona State University students (61 in Condition 1; 57 in Condition 2). All participants were native English speakers who reported normal or corrected-to-normal vision.

Materials & Stimuli

Testing conditions were identical to those of Experiment 1. The auditory entrainment procedure was adapted from Jacoby, Woloshyn, and Kelley (1989). Auditory stimuli consisted of artificial speech recordings of the numbers one through ten presented at .5Hz. For each trial, a list of 40 numbers (four instances of each number from one to ten) was randomized online such that there were no instances where three odd digits appeared in a row. On sequence-present trials, a randomized 5-digit string (three odd numbers surrounded by an even number on each side) replaced five numbers at one of four randomly-selected positions within the central 30 numbers of the stream: either the beginning or end of the stream or in either of two positions evenly-spaced between the endpoints. The visual stimuli were identical to those in the previous experiment.

Procedure

Following the collection of informed consent, participants completed three practice trials followed by 30 experimental trials. Participants in Condition 1 were told to monitor the auditory stream for instances of three odd digits appearing in a sequence. They reported the presence or absence of an odd digit string at the end of every trial. Participants in Condition 2 were told that the auditory stimuli were irrelevant to their primary task and that they need not attend to them. Of the 30 experimental trials, 25 of them were sequence-present trials (i.e., trials containing a sequence of three odd digits).

Concurrent with the auditory stream, participants performed the visual dot probe detection task from Experiment 1, reporting dot probe onsets by pressing the right-most response box button as quickly as possible. Each trial contained only one dot probe. On 60% of sequence-present trials, the onset of the dot probe was aligned with the odd digit string. Dot probes could appear with the first, second, or third digit in the string (counterbalanced across trials). On the other 40% of trials, the dot probe appeared at a randomly-selected position not aligned with the odd digit string. The onset of dot probes was manipulated relative to the entraining rhythm such that 25% of probes appeared with the entraining beat, 25% appeared 500 msec off the beat, 25% 1000 msec off the beat (exactly in between beats), and 25% 1500 msec off the beat (also selected randomly).

Results

Six participants were excluded from analyses (four in Condition 1; two in Condition 2). One participant was excluded from Condition 1 for odd digit sequence detection rates more than 2.5 standard deviations below the group mean. Three participants were excluded due to average RTs more than 2.5 standard deviations slower than the mean. Finally, two participants were excluded as a consequence of having no accurate dot probe detections. As in the prior experiment, responses falling outside a 1500 msec window following dot probe onset were considered to be erroneous, leading to the exclusion of 38% of trials in RT analyses. For ease of interpretation, trials with dot probes appearing 75% off the beat were collapsed with trials containing a dot probe presented 25% off the beat. In the context of the attentional entrainment literature, these conditions should yield identical results.

Reaction Times

RT data were log transformed prior to statistical analyses. Participants in Condition 1 performed the odd digit sequence detection task with high accuracy (M = 83.5%). For all analyses, Condition 1 trials with unsuccessful digit sequence responses were excluded. I began by assessing attentional entrainment effects through a LMM with between-subjects factor Condition (1, 2) and within-subject factor Phase (on beat, 25/75% off beat, 50% off beat). This analysis produced only a significant main effect of Condition, $F(1, 110.86) = 8.88$, $p = .004$, *pseudo*-$r^2 = .09$. Participants responded to dot probes 83 msec faster in Condition 2 where they were not required to dual-task.

Next, I assessed conceptual entrainment effects in a LMM with between-subjects factor Condition (1, 2) and within-subject factors sequence Alignment to dot probe (aligned, not aligned) and dot probe Position within the digit string (digit 1, digit 2, digit 3). For trials where the dot probe was not aligned with the digit sequence, Position becomes a meaningless variable, and RTs should not differ as a consequence of the position that was randomly assigned to not-aligned trials. Again, there was a reliable effect of Condition, $F(1, 108.83) = 9.09$, $p = .003$, *pseudo*-$r^2 = .09$, with faster responses in Condition 2. A significant Position effect, $F(2, 478.22) = 3.21$, $p = .04$, *pseudo*-$r^2 = .01$, reflected a general slowing of response times later in the odd digit string, as cognitive load increased. Finally, there was a reliable Condition by Alignment by Position interaction, $F(2, 482.11) = 4.31$, $p = .01$, *pseudo*-$r^2 = .02$ (see Figure 3). In Condition 1, the pattern of RTs reflected interference from cognitive load when dot probes were aligned with the odd digit sequence. That is, RTs were slowed when dot probes were presented with the third odd digit on sequence-aligned trials. When the digit stream was not attended to in Condition 2, the RT patterns had no apparent relationship with Alignment or Position.

To explore the relationship between attentional entrainment and conceptual entrainment effects, I ran a LMM with between-subjects factor Condition (1, 2) and within-subject factors Position (digit 1, digit 2, digit 3) and Phase (on beat, 25% off beat, 50% off beat) on trials where the dot probe was aligned with the odd digit sequence. This analysis produced only a main effect of Condition, $F(1, 106.77) = 8.34$, $p = .005$, *pseudo*-$r^2 = .10$. As before, reaction times were slower in the dual-task condition.

Finally, although performance on the digit sequence detection task was near ceiling in Condition 1, I examined dot probe RT as a function of sequence detection on sequence-present trials where the sequence was aligned with dot probe onset using a LMM with factor Sequence Detection (correct, incorrect). This analysis did not reveal any significant effects.

Probe Detection Accuracy

The same set of analyses was carried out upon dot probe detection accuracy, excluding Condition 1 trials where participants incorrectly reported the presence/absence of an odd digit sequence. Again, I began with a LMM with factors Condition (1, 2) and Phase (on beat, 25% off beat, 50% off beat) to assess temporal entrainment effects. This analysis yielded a main effect of Condition, $F(1, 112) = 4.50$, $p = .04$, *pseudo*-$r^2 = .04$, with higher dot probe detection accuracy in Condition 1 (M = .68) than Condition 2 (M = .58). There was also a significant Phase effect, $F(2, 224) = 4.03$, $p = .02$, *pseudo*-$r^2 = .03$. Post-hoc analyses showed that dot probes presented on the beat were detected with significantly greater accuracy than those presented 25% off the beat ($p = .005$, $d = .10$), however accuracy did not differ between those presented on the beat and those presented 50% off the beat or between probes presented 25% off the beat and 50% off the beat (see Figure 4). The main effect of Phase was qualified by a marginal Condition by Phase interaction, *F*(2, 224) = 2.99, *p* = .05, *pseudo-*r^2 = .06. The Phase effect was more pronounced in Condition 2 than Condition 1 (see Figure 5).

Next, I assessed conceptual entrainment effects with a LMM with factors Condition (1, 2), sequence Alignment with probe onset (aligned, not aligned), and dot probe Position with digit sequence (digit 1, digit 2, digit 3). This analysis produced only a reliable effect of Condition, *F*(1, 112.12) = 4.91, *p* = .03, *pseudo-*r^2 = .05, with greater accuracy in Condition 1 than in Condition 2.

I also assessed temporal-conceptual entrainment interaction effects in a LMM with factors Condition (1, 2), Position (digit 1, digit 2, digit 3), and Phase (on beat, 25% off beat, 50% off beat). However, as was the case with RT analyses, this analysis revealed only a main effect of Condition, *F*(1, 111.73), *p* = .05, *pseudo-*r^2 = .05, with accuracy reduced in Condition 2.

Finally, I examined Condition 1 accuracy as a function of sequence detection performance on sequence-present, dot probe-aligned trials in a LMM with factor Sequence Detection (correct, incorrect). There was a reliable effect of Sequence Detection, *F*(1, 107) = 4.95, *p* = .03, *pseudo-*r^2 = .13. Participants detected the dot probe with greater accuracy on trials where they also successfully detected the odd digit sequence (M = .67) than on trials where they failed to detect the odd digit sequence (M = .54).

Discussion

Experiment 2 was designed to move one step closer to the conditions under which magicians operate, where audience members must constantly deploy attention across multiple modalities while also performing rather complex cognitive tasks. In a replication of Experiment 1, dot probe detection accuracy was reduced when probe onset occurred between auditory beats. In addition, there was also a slight rebound half way between auditory stimuli. Unlike the results of Experiment 1, entrainment effects on detection accuracy differed across conditions, with entrainment being most evident when attention was not actively deployed to the auditory modality (in Condition 2). In Condition 1, the demands of attending to the semantic content of the auditory stream rather than its timing may have acted to dampen entrainment effects. In Condition 2, semantic processing of the auditory stream was reduced, allowing more subtle processing tendencies related to the temporal deployment of attention to become apparent.

Experiment 2 extended the findings of Experiment 1 by adding computational complexity to the auditory processing task in order to emulate the conditions of a magic show. Reaction times showed evidence of a cross-modal PRP effect. When the dot probe’s onset aligned with the third odd digit in a sequence, RTs to detect the dot probe were slowed in Condition 1 as compared to Condition 2. That is, working memory encoding seemed to usurp attentional resources from the visual modality, delaying report of the dot probe. Furthermore, all reaction times to detect the dot probe in Condition 1 were slower than those in Condition 2, suggesting that dual-tasking required the subdivision of attentional resources between modalities. There was some evidence of a speed-accuracy trade-off, however, as accuracy to detect dot probes was higher in Condition 1 than in Condition 2. There was also evidence of differential engagement with the primary conceptual task in Condition 1. Performance on the auditory task was positively correlated with performance on the visual task.

Unfortunately, there was no evidence that temporal and conceptual entrainment effects combined to produce a large attentional blink in the moments following onset of the third odd digit in a sequence. Given the high error rate (and variability) in performance of the visual task, there simply may not have been enough statistical power to detect additive effects of conceptual and temporal entrainment. Although the digit sequence detection task was meant to emulate the cognitive complexity of humor perception, it is admittedly a much simpler task, requiring no disambiguation or mental time-travel. The amount of attention required to update working memory may have been too slight for effects to manifest themselves. With a more difficult conceptual task, the PRP effect observed in this experiment could increase to become an attentional blink (Marti, Sigman, & Dehaene, 2012). Future research should manipulate the complexity of the primary conceptual task.

As already noted, magicians often employ rudimentary additive factors logic in designing their methods. This experiment marks the first attempt at testing their logic empirically, albeit in a rather artificial, unmagical context. Furthermore, this was the first experiment to directly assess Ascanio's (1964/2005) intuition that language processing can blind one to visual stimulation. By combining exogenous and endogenous cues to manipulate the deployment of attention in time, magicians hope to create "super-stimuli" that effectively blind viewers to moments in time that are aligned with the performance of deceptive actions underlying the method of their magic. Experiment 2 set the stage for the culminating experiment of the sequence, examining both forms of entrainment within the context of (almost) real-world viewing of magic tricks.

Experiment 3: Cross-modal entrainment during (almost) real-world viewing of magic tricks

This set of experiments has attempted to examine aspects of attentional deployment in time across a set of conditions, steadily moving toward natural, real-world viewing. Thus far, only the auditory stimuli have traversed the artificial-to-natural continuum. In the culminating experiment, the natural auditory entraining task from Experiment 2 was embedded in a more natural visual task: the viewing of magic tricks. As noted by Binet (1894), magicians combine a host of methods to gain control over the audience's attention. Although Experiment 3 included a selection of different magic tricks, all having different methods and layers of deception, there were some commonalities across the selected effects. First, they all used social cues (e.g., joint attention) to drive attention away from a location in space. Second, the method used to accomplish each magic trick happened in full view, at one very specific moment in time. It was this second commonality that made this selection of magic tricks useful for the current experiment. Although spatial attention is likely to have been diverted at the moment that the magical method takes place, on the whole, temporal attention has not been manipulated. Thus, I could assess the effect that attentional entrainment in the auditory modality had on subsequent perception of the magic trick in the visual modality. Similarly, I could examine whether performance on the conceptual entrainment component of the task affected visual perception.

Although the use of magic in the laboratory provides a high level of ecological validity to the study of attentional deployment and perception, one complication is the selection of dependent measures. In most cases, it is difficult to assess how effectively a participant has been deceived. Self-report measures are problematic, because participants can often guess the method behind a magic trick even if they have not directly perceived the method during viewing. This problem was also identified in Mack and Rock's (1998) work on inattentional blindness, where, when queried, about 1/4 to 1/3 of participants were apt to report having seen something new in the display even when there was no inattentional blindness stimulus present (pp. 239-240). Thus, in the current experiment, a variety of dependent measures were used to assess *when* a participant has detected that a magic trick has occurred as well as *where* participants were attending at a few important time points within each trial. In addition, self-report measures were used to assess whether each participant was deceived by the method of each magic trick.

It was expected that, when participants have entrained to an auditory rhythm, transient mechanics that are the true cause of a magical effect may be more apt to go unnoticed if they are aligned with the attentional trough between beats. Similarly, these events may be more apt to evade detection when they are accompanied by an internal shift of attention to encode items into or manipulate the items in working memory. By manipulating the alignment between video of magic tricks being performed and the auditory entraining beats and conceptually-entraining number sequences, the relative contribution of each variety of misdirection can be evaluated empirically.

Method

Participants

Ninety-four Arizona State University students participated for partial course credit (67 in Condition 1; 27 in Condition 2). All participants had normal or corrected-to-normal vision and were native English speakers.

Materials & Stimuli

Data were collected using the same hardware as previous experiments. However, Experiment 3 was programmed in E-Prime 2.0, which allows for the presentation of video stimuli. Visual stimuli consisted of eight videos of magic performances where the method to accomplish the effect happened at a relatively distinct point in time (the "magical moment") and happened in full view. Table 1 describes each magic trick and its method. Three videos of "sham" magic tricks were also created. These videos were designed to simulate stereotypical action patterns of magic tricks without actually containing magic tricks.

The auditory stimuli were identical to those from Experiment 2, consisting of a stream of 40 spoken numbers presented at .5Hz. However, auditory streams were not generated online. Instead, multiple versions of each video stimulus were created, with auditory stimuli embedded as audio tracks to insure appropriate timing between audio and video content. As with the online procedure used in Experiment 2, a pseudo-randomized digit stream was used for sequence-absent trials, and odd-digit sequences were added in one of four internal positions to create sequence-present trials. Nine videos were generated for each visual stimulus: three sequence-absent trials, three sequence-present trials where the "magical moment" was aligned to the third odd digit of the sequence, and three sequence-present trials where the magical moment was not aligned to the odd digit sequence. Within each of these triads, the onset of the magical moment was shifted relative to the entraining stimuli such that it aligned with the beat in one video, was shifted 25% off the beat in one video, and was shifted 50% off the beat in one video.

Since the audio stream was of a longer duration than each video, the screen went to black before and after the video played (while digits were still being spoken).

Procedure

Following the collection of informed consent, participants completed one practice trial followed by 11 experimental trials. Participants were told that they would be watching a series of videos, some of which contained the performance of a magic trick. Their primary task was to press the right-most response box button as soon as they perceived that a magic trick had occurred. They were also informed that they should try to discover how each magic trick is accomplished. Participants in Condition 1 were told to actively attend to the auditory stream for instances where three odd numbers are presented in a sequence. As in Experiment 2, the presence or absence of an odd digit sequence was reported after each trial ended. Participants in Condition 2 were told that the auditory stimuli were irrelevant to their primary task, and that they need not attend to them. Six of the eight experimental trials were sequence-present trials. On sequence-present trials, the magical moment aligned with the third odd digit of the sequence on 50% of trials. Otherwise, it was aligned with a digit outside of the odd digit sequence. The magic moment was also shifted relative to the entraining rhythm such that 1/3 of experimental trials placed the magic moment in phase with the rhythm, 1/3 shifted it 25% off the beat, and 1/3 shifted it 50% off the beat.

On trials containing magic tricks, after participants reported the presence or absence of an odd digit string, they were asked whether they observed how the magic trick was accomplished. An affirmative response was followed first by a prompt asking them to describe in their own words how the trick was accomplished. Next, they were presented with a multiple-choice list of potential methods. If they chose the correct method from this list, the trial terminated. If they were incorrect (or respond negatively to the initial query), they were asked to re-watch the video (with entraining stimuli) until they detected the method or had viewed the video three times.

Results

Button presses elicited within 10 seconds of the magical moment in each experimental video were counted as accurate RTs. Application of this criterion led to the exclusion of 51% of first-viewing responses from RT analyses. Four participants were excluded from analyses (all in Condition 1). One participant's digit sequence detection rate was more than 2.5 standard deviations below the group mean. The other three participants registered no accurate magic trick detection responses.

Magic Trick Detection Reaction Times

I examined magic trick detection RTs elicited during the first viewing of each magic trick. Only accurate RTs on trials with a successful digit sequence response (for Condition 1) were analyzed. First, I looked for evidence of attentional entrainment effects on magic trick detection in a LMM with factors Condition (1, 2) and Phase (on beat, 25% off beat, 50% off beat). This analysis produced no reliable effects.

Next, the influence of conceptual entrainment upon magic trick detection was examined in a LMM on sequence-present trials with factors Condition (1, 2) and sequence Alignment with magic moment (aligned, not aligned). This analysis produced a marginal Condition by Alignment interaction, $F(1, 73.90) = 3.68$, $p = .06$, $pseudo\text{-}r^2 = .04$. However, the interaction was driven primarily by responding in Condition 2, where RTs were substantially slowed to magic moments aligned with the odd digit sequence as compared to those not aligned with the digit sequence. This pattern was not evident in Condition 1 RTs, where it should have appeared (see Figure 6).

Finally, I examined for interactions of conceptual and temporal entrainment in a LMM on sequence-present trials with factors Condition (1, 2), Alignment (aligned, not aligned), and Phase (on beat, 25% off beat, 50% off beat). This analysis produced no significant effects.

Magic Trick Method Detection Accuracy

Magic method detection responses following the first viewing of each magic trick were examined for evidence of temporal and conceptual entrainment. Accuracy was assessed via self-report and method selection in the multiple choice test. First, I ran a LMM with factors Condition (1, 2) and Phase (on beat, 25% off beat, 50% off beat). This analysis revealed no significant effects. However, there was a trend for increased method detection accuracy when the magic moment was aligned with the entraining rhythm (see Figure 7).

Next, I examined accuracy as a function of conceptual entrainment with a LMM on sequence-present trials with factors Condition (1, 2) and Alignment (aligned, not aligned). Again, this analysis produced no reliable effects, but there was a trend for accuracy to be reduced in Condition 1 when the digit sequence was aligned with the magic moment (see Figure 8).

Finally, conceptual-temporal entrainment interaction effects were explored in a LMM on sequence-present trials with factors Condition (1, 2), Alignment (aligned, not aligned), and Phase (on beat, 25% off beat, 50% off beat). No significant effects were observed.

Magic Trick Viewing Repetitions

The number of magic trick viewings required for successful detection of the magic method was assessed in a series of LMMs. First, I examined temporal entrainment in a LMM with factors Condition (1, 2) and Phase (on beat, 25% off beat, 50% off beat). There were no significant effects, but there was a trend for videos with the magic moment aligned to auditory stimulus onset to require fewer viewings (see Figure 9).

Next, conceptual entrainment effects were assessed in a LMM on sequence-present trials with factors Condition (1, 2) and sequence Alignment (aligned, not aligned). Again, there were not significant effects, but a trend for a greater number of viewings in Condition 1 when the magic moment aligned with the odd digit sequence and fewer viewings in Condition 2 overall, relative to Condition 1(see Figure 10).

Finally, a LMM was run on sequence-present trials with factors Condition (1, 2), sequence Alignment (aligned, not aligned), and Phase (on beat, 25% off beat, 50% off beat). This analysis produced no significant results.

Discussion

Few concrete conclusions can be drawn from the results of Experiment 3. Although many analyses produced suggestive trends, few outcomes were statistically significant. I expected that conceptual and temporal entrainment could be used to delay (or eliminate) detection of the magical moment in each of the magic effects, however reaction times to report detection of magic moments did not appear to be influenced by these factors. As a whole, reaction times were highly variable, with roughly half of all observations falling outside of a 10-second window following the onset of the magic moment. This variability may have made the detection of relatively subtle effects impossible. Participants may have required further coaching (and more than one practice trial) to elicit fast responses to these rather complex events.

On a promising note, higher order measures of magical deception were suggestive of both temporal and conceptual entrainment effects, although none were statistically significant. Participants detected the method underlying a magic trick more effectively on the first viewing if its onset was temporally aligned with the onset of an auditory entrainer, suggesting that visual attention was optimized in the same moments as auditory attention. Furthermore, participants required fewer viewings to detect the method when the magical moment was temporally aligned with the entraining rhythm. Similarly, participants were more successful at detecting the method on the first viewing and required fewer viewings to detect the method if the magical moment was not aligned with an odd digit string. As was the case in Experiments 1 and 2, the second condition appeared to allow for enhanced attentional deployment in the visual modality by the elimination of dual tasking. Participants tended to require fewer viewings in Condition 2 than in Condition 1 to detect the method underlying the magic. Moving forward, it would be advantageous to increase the sample size (especially in Condition 2) in order to increase statistical power. In addition, participants should be provided with more training such that they fully understand what constitutes a “magical moment,” and the complexity of the conceptual task should be increased to provide more interference with performance of the visual task.

Experiment 3 in this series was the first of its kind in many ways. First, on a conceptual level, it was the first to bring together theories from magic with theories from psychology under a unique methodology of real-world viewing. It allowed for magic to inform psychology (by providing a real-world context in which cross-modal attentional entrainment effects are likely to manifest themselves) and for psychology to inform magic (by providing a quantitative assessment of the conditions under which these variables provide the most value to deception).

Second, the experiment stepped away from the now-standard model of using one magic trick to study one psychological phenomenon (Cui, Otero-Millan, Macknik, King, & Martinez-Conde, 2011; Demacheva, Ladouceur, Steinberg, Pogassova, & Raz, 2012; Hergovich, Gröbl, & Carbon, 2011; Kuhn & Land, 2006; Kuhn, Tatler, Findlay, & Cole, 2008; Otero-Millan, Macknik, Robbins, & Martinez-Conde, 2011). The current experiment adds power to the empirical study of the psychological mechanisms underlying magical deception by employing a selection of disparate magic tricks that, although using different methods, can be strengthened or weakened based on differences in attentional deployment in time. Until now, only one study has used a similar model (Parris, Kuhn, Mizon, Benattayallah, & Hodgson, 2009).

Third, some have argued that neuroscience provides the appropriate level of analysis for understanding the science of magic (Macknik & Martinez-Conde, 2009). While I fundamentally disagree with this notion, as do others (Lamont & Henderson, 2009), the current experiment sets the stage for an efficient interface between psychology and neuroscience within this domain. Psychology has provided a set of theoretical mechanisms and models to explain and predict the myriad influences on the deployment of attention in time within these magical effects. Given the set of outcomes and trends reported here, now there is adequate motivation and grounding to study these phenomena from a neuroscientific perspective, to elucidate the neural mechanisms that underlie the phenomena using EEG (and possibly fMRI) methodologies.

Finally, and perhaps most importantly, the current experiment was among the first to study cross-modal attentional entrainment and to do so under conditions similar to real-world viewing. To date, most experiments have only examined attentional entrainment within a single modality (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Large & Jones, 1999; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Rohenkohl & Nobre, 2011; but see Miller, Carlson, and McAuley, 2013), and no studies have examined entrainment to natural stimuli, with the exception of Luo and Poeppel's (2007) study of entrainment to spoken sentences. Therefore, this experiment may set the stage for a more naturalistic examination of attentional deployment in time and across modalities.

General Discussion

The results of the experiments reported here were expected to emulate the long-held intuitions of magicians regarding the additive roles of rhythm and patter in the misdirection of attention. Although misdirection is typically conceptualized as the control of attentional deployment in space (Kuhn & Martinez, 2012), magicians also manipulate the deployment of attention in time through the creation of "off-beats" where attention should naturally be suppressed (Kurtz, 1998). Although magicians' theories in the domain of temporal attention are under-specified (see Ganson, 2001), they do speak to dynamic theories of attentional deployment from the psychological literature (Large & Jones, 1999; Wyble, Bowman, & Nieuwenstein, 2009) which predict that attention should naturally entrain to consistent environmental rhythms and oscillate between sensory and cognitive systems based on ongoing shifts in computational demands.

However, as was noted in the motivation of Experiment 2, there is no requirement that spectators at a magic show engage with the narrative content of the magic show. It is quite possible that ignoring the words the magician uses could eliminate the off-beats created through conceptual processing, thereby weakening the perception of magic. Indeed, across the first two experiments, RTs tended to be slower and accuracy reduced when participants were required to attend to the auditory stimuli. Furthermore, in Experiment 2, RTs to detect dot probes were slowed as odd digits were added to the sequence and cognitive load was increased. This effect was not apparent in Condition 2, when participants were not listening for odd digit strings.

While these endogenous attentional sets are volitional, and can thus be "turned off" through disengagement with the auditory stream, the off-beats created through attentional entrainment seem to survive this disengagement. The Phase effects observed in Experiment 1 failed to interact with Condition. However, Experiment 2 provided evidence that attention to the content of the rhythmic stimuli may even hinder attentional entrainment, as Phase effects were most prominent in Condition 2, when participants did not need to attend to the auditory content.

Across this set of experiments, I presented evidence that attention can entrain cross-modally from audition to vision to facilitate the detection of stimuli appearing in phase with the entraining rhythm. Although previous research had shown that motor responses can be facilitated by entrainment (Miller, Carlson, & McAuley, 2013), the current research shows that cross-modal entrainment elicits both a readiness for action (faster button-presses to report dot probes presented on the beat) and a readiness for perception (enhanced detection of stimuli presented on the beat). The present work has also begun to highlight the limits of attentional entrainment. In Experiment 1, entrainment effects were evident when tones were presented at a slow rate (.67Hz), but not when they were presented at a fast rate (1.5Hz). In terms of neural oscillators, both of these rates fall within the delta band. Lakatos and colleagues (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008) showed that oscillators in this band are adept at entrainment to external rhythms, thus it is unclear why entrainment was evident in one frequency, but not the other. Future research should attempt to glean the source of this difference.

Both Experiments 1 and 2 produced a surprising outcome wherein dot probe detection accuracy rebounded for probes presented exactly between beats. Although this outcome was unpredicted, the rebound effect could be attributed to a few different sources. It could reflect the interplay of endogenous and exogenous influences on attentional deployment. Although attention should naturally entrain to the auditory rhythm, endogenous attentional control mechanisms could fight this tendency, attempting to enhance attention at moments when entrainment would push it to its lower limit. However, this hypothesis is relatively intractable, from an experimental standpoint. Perhaps a better explanation is provided by an experiment conducted by Gomez-Ramirez et al. (2011). They replicated and extended the work of Lakatos and colleagues (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008) by examining entrainment to one channel of an audio-visual stream at a rate of .67Hz, on the lower-end of the delta band. While they observed significant entrainment to the rhythm, as evidenced by EEG amplitude peaks of a .67Hz component, they observed peaks of a much higher power at the second harmonic, 1.33Hz. Experiment 2, reported here, used .67Hz entrainers, so a substantial second harmonic would fall exactly in between beats, and could have produced the observed rebound effect.

The explanation that Gomez-Ramirez et al. (2011) provide for this unusual phenomenon relies on a disagreement in the EEG literature. The lower boundary of the delta band has been widely debated, with original classifications placing it at 1Hz (Hari, Parkkonen, & Nangini, 2010). More recent assessments place it at .5Hz or anywhere below 3.5-4Hz (Shaker, 2007). Gomez-Ramirez et al. accept a lower boundary of 1Hz. Consequently, they suggest that entrainment effects, in general, may be traced back to the delta band, and that the second harmonic of a .67Hz oscillator would be the first to fall within this boundary, thus producing this surprising outcome. At any rate, the hierarchical nature of neural oscillators likely underpins the rebound effect reported in the current experiments.

Future Directions

Although the current research was inspired by oscillatory mechanisms underlying attentional deployment, the experiments described here did not fully test predictions from the attentional entrainment literature. Entrainment in these experiments was of the simplest kind, to an unchanging rhythmic stimulus. However, the hallmark of attentional entrainment is the predictive deployment of attention to a shifting, imprecise external rhythm. Thus, future research should examine entrainment with stimuli that have a constant rate of change. This would also allow researchers to examine the limits of attentional deployment as a rhythm changes its rate across frequency bands.

Future research should also explore the automaticity of attentional entrainment. One unique way to do so would be through an auditory manipulation similar to that used by Lawrence and Klein (2013). In their experiment, participants were exposed to an auditory stream of diotic white noise (the same pattern of white noise delivered to each ear). However, the stream was occasionally punctuated by bursts of dichotic white noise, where the white noise pattern differed between ears). Thus, the intrusions were not explicitly capturing attention, as there was no change in overall intensity during these moments. A manipulation of this kind could introduce a subtle attentional entrainment effect, presumably in the absence of awareness.

As already noted, future work should manipulate the complexity of the auditory task. Magicians rely not on psychological refractory periods that simply delay responding; they count on attentional blinks that blind conscious awareness. Thus, it might be advisable for experiments to manipulate natural language processing in the same way that magicians do, using humor or language that requires complex, online disambiguation via memory search. Garden path sentences could provide the type of computational complexity required without necessitating the generation of humorous stimuli, which inevitably fail in the lab.

Finally, the set of experiments described here naturally open the door to a neuroscientific investigation of attentional dynamics. Each of these experiments could easily be adapted to study the neural oscillations underlying temporal attention. As oscillatory activity measured over sensory cortices reliably reflects the presence of rhythmic stimuli falling upon their sensory apparatus, the same oscillatory signal observed over cortices *not* receiving rhythmic stimulation serves as direct evidence of cross-modal interaction. Thus, in Experiment 1, oscillatory dynamics measured over temporal regions should reflect auditory attentional entrainment to the .67Hz rhythm, reflected in increased synchronization (or amplitude) of oscillations in the delta band. Furthermore, if entrainment in the auditory modality influences attention in the visual modality, as was suggested here, reaction times to detect the dot probe should have a direct relationship to synchronization of delta oscillations over occipital regions. Increased delta power should coincide with fast reaction times for in-phase dot probes and slow RTs for out-of-phase dot probes. On trials where delta oscillations are desynchronized over occipital regions, reaction times should not differ as a consequence of dot-probe timing relative to the entraining rhythms.

In the context of language processing and humor-induced attentional suppression, the shift of attention toward linguistic resolution mechanisms should also be apparent in oscillatory signatures in the EEG data. Alpha oscillations, slow oscillations in the 8-12 Hz range, appear to be indicative of neural inhibition (Ward, 2003). Over the visual cortex, their amplitude is negatively correlated with the probability of detecting a transient visual stimulus (Mathewson et al., 2011). Therefore, an inward shift of attention to aid in ambiguity resolution should produce an increase in the amplitude of alpha oscillations over posterior cortical regions, and possibly some amount of alpha desychronization over temporal and frontal regions active in language processing. Furthermore, ERPs should reflect the amount of attentional suppression that linguistic ambiguity resolution produces. When participants read sentences that do not end as predicted, oftentimes an N400 ERP is observed (Block & Baldwin, 2010). Holcomb (1993) suggested that the magnitude of the N400 ERP reflects the relative difficulty of integrating new information into a continually developing mental representation. Thus, the magnitude of the N400 response should have a direct, positive relationship to the amount of visual attentional suppression elicited by conceptual processing.

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Table 1

Experiment 3: Magic Tricks & Explanations

Effect	Audience Experience	Explanation
Card Under Glass	A selected card vanishes from the deck, reappearing beneath a glass that has been visible from the start.	The card is palmed from the deck and placed beneath the glass as the cards are being spread on the table to reveal the vanish.
Card To Mouth	A selected card vanishes from the deck, reappearing between the magician's teeth.	The magician places the card in his mouth while feigning the placement of the card into the center of the deck.
Vanishing Ball a la Kuhn & Land (2006)	After throwing a ball in the air twice, it vanishes on the third throw.	Instead of throwing the ball the third time, it is palmed in the hand while the throw is simulated.
Color-Changing Coin	A silver coin changes into a copper coin when it is tapped with a pen.	The coin is switched while the magician searches his pockets for a pen.
There & Back	A coin, placed beneath a napkin, disappears from its location, only to reappear beneath a second napkin.	The coin is on a conveyor belt-like mechanism that moves it from one location to another while attention is misdirected.
Vanishing Coin Trick	A coin vanishes when tapped with a pen.	The coin is thrown into the hand holding the pen just before the pen strikes the hand.
Multiplying Balls	The magician holds three white balls in the fingers of his right hand. The central ball falls. He catches it, only to find that it has already been replaced by a fourth ball.	The dropping ball provides misdirection for the magician to steal the extra ball from a secret location.
Vanishing Cigarette Lighter a la Kuhn et al. (2008)	The magician feigns removing the flame from a lighter with his hand. Upon opening his hand, it's revealed that the lighter has vanished.	The lighter is visibly dropped in the magician's lap while feigning the removal of the flame.

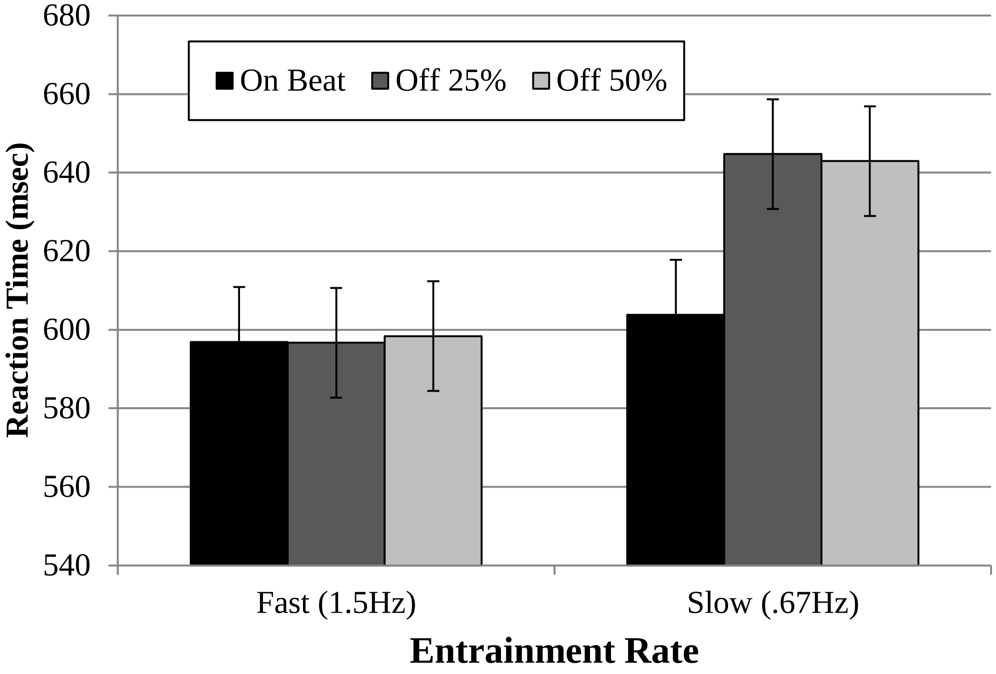


Figure 1. Experiment 1 dot probe reaction times as a function of entrainment rate and phase of dot onset relative to entraining rhythm.

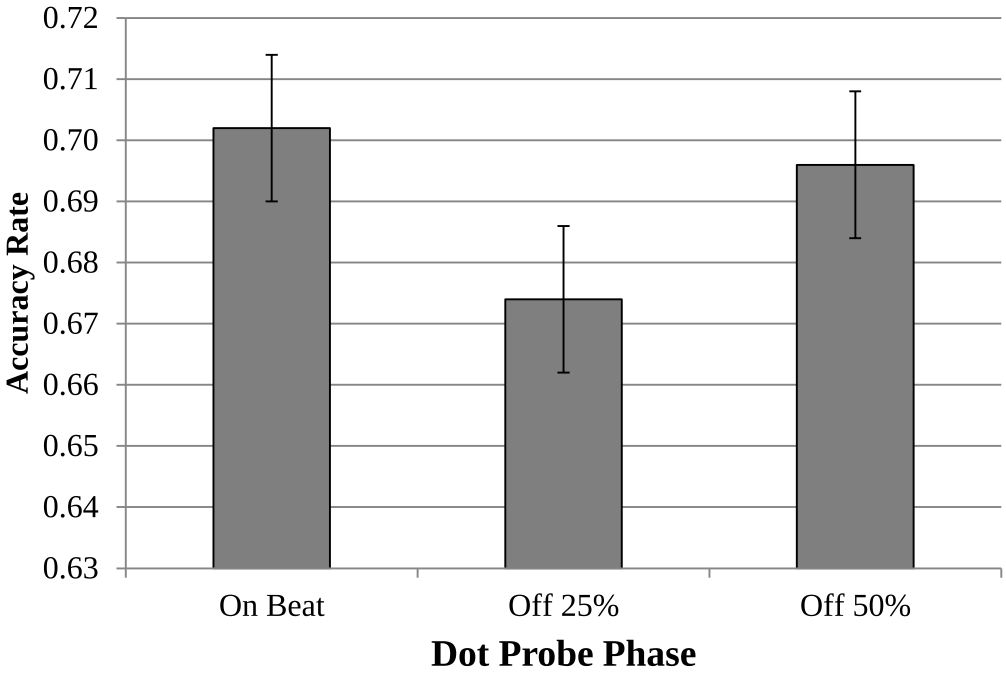


Figure 2. Experiment 1 dot probe detection accuracy as a function of dot probe phase relative to entraining rhythm.

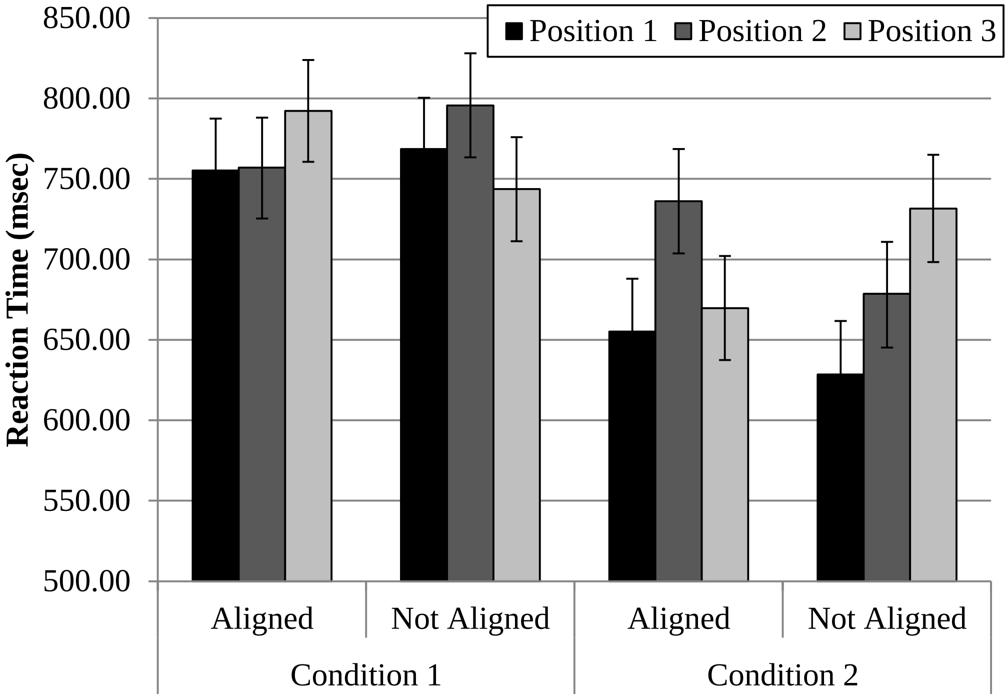


Figure 3. Experiment 2 dot probe reaction times as a function of Condition, dot probe Alignment with odd digit sequence, and Position of dot probe within digit sequence.

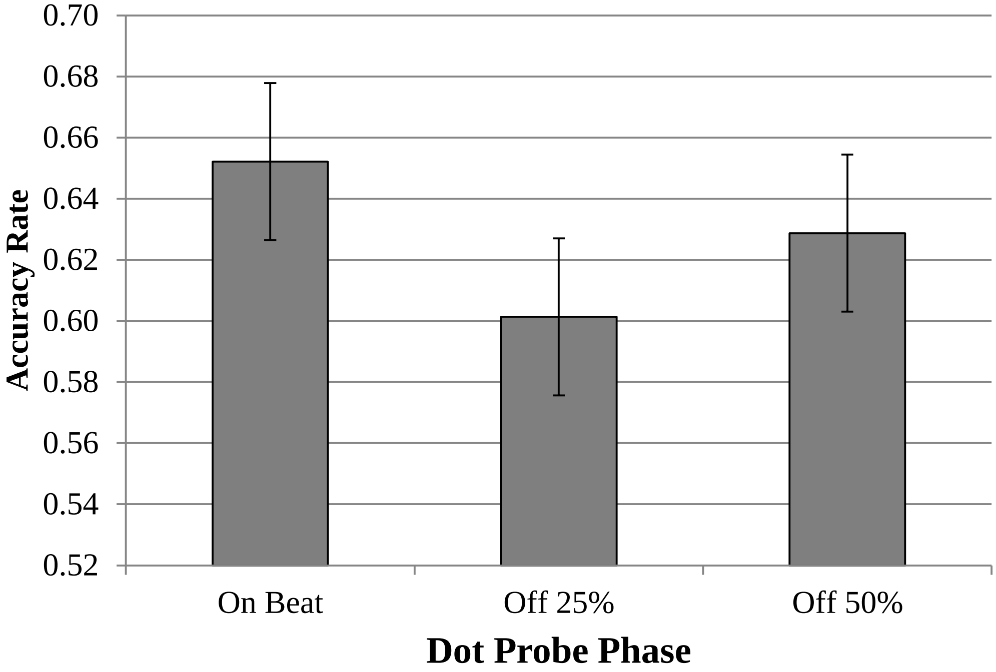


Figure 4. Experiment 2 dot probe detection accuracy as a function of onset phase relative to entraining rhythm.

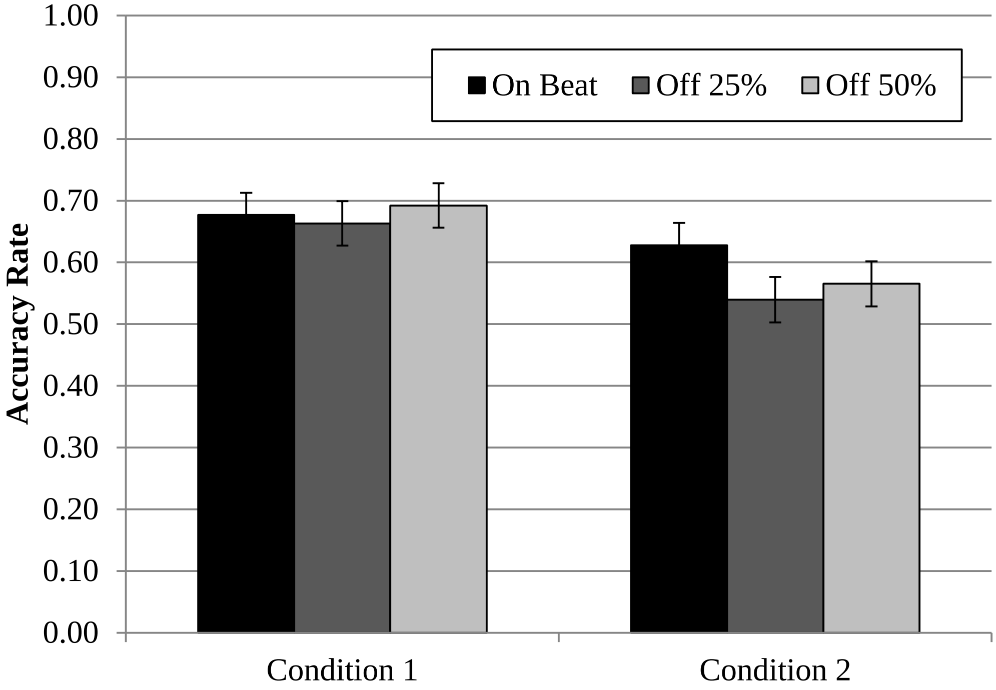


Figure 5. Experiment 2 dot probe detection accuracy as a function of Condition and dot probe Phase relative to entraining rhythm.

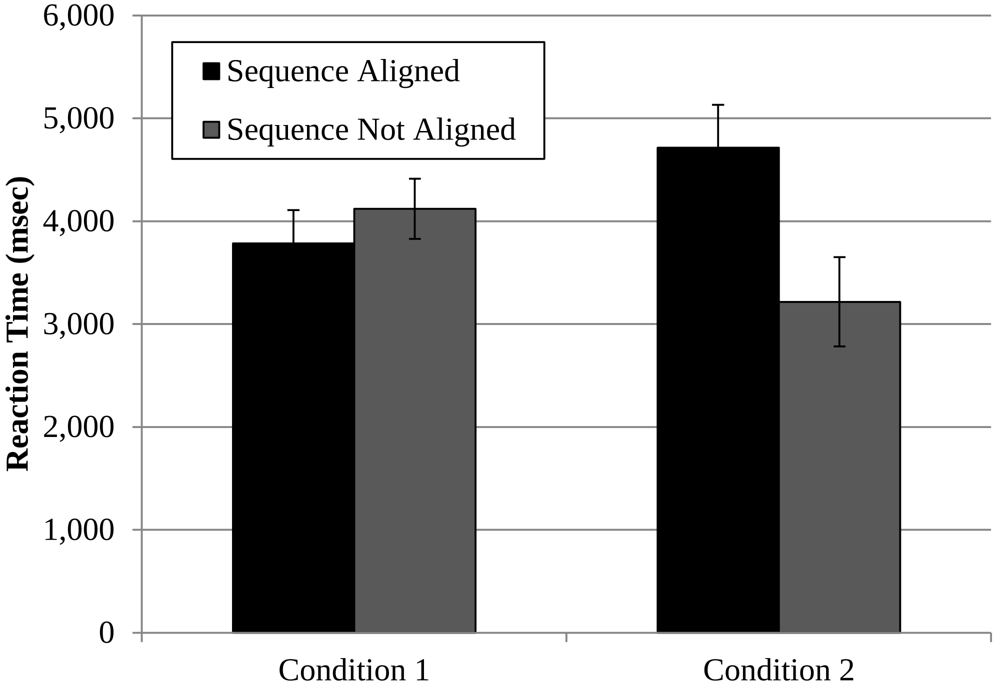


Figure 6. Experiment 3 magic detection reaction times as a function of Condition and sequence Alignment with the magical moment.

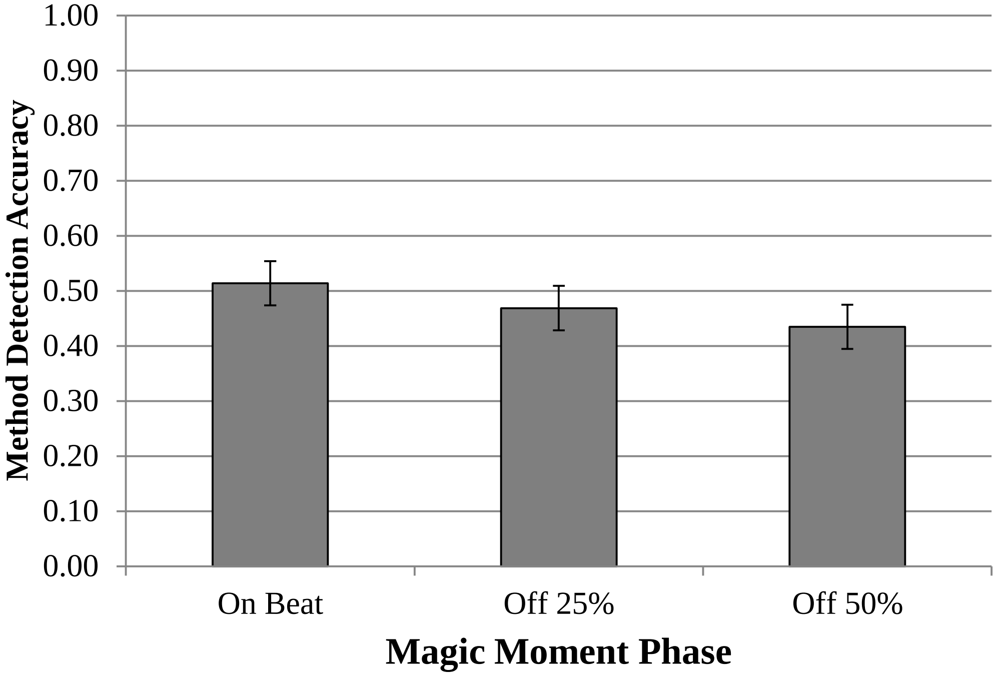


Figure 7. Experiment 3 magic method detection accuracy as a function of magic moment phase relative to entraining rhythm.

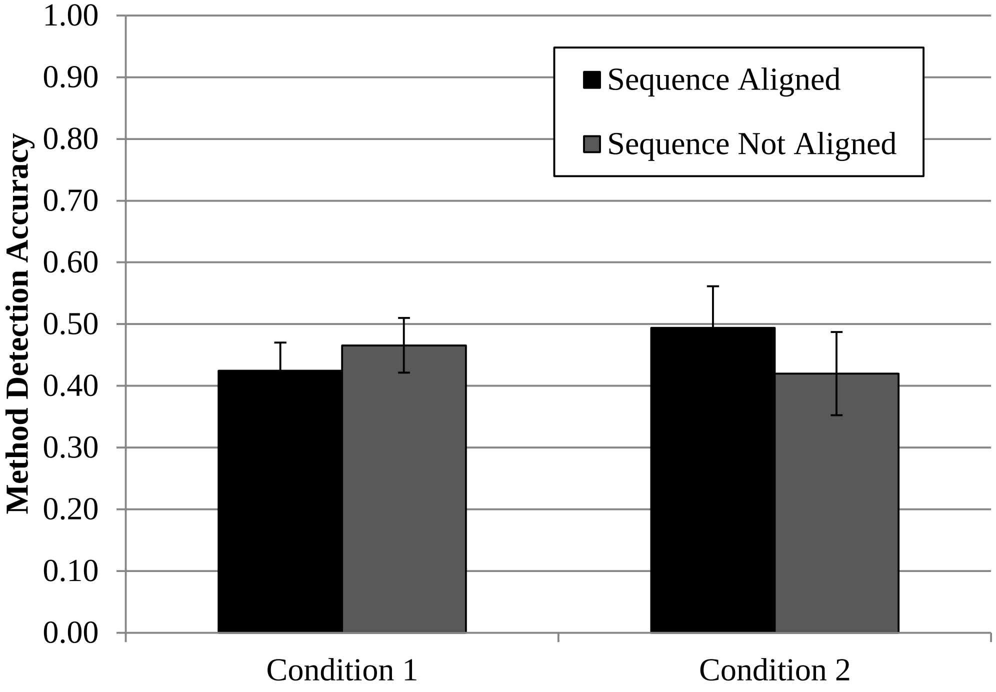


Figure 8. Experiment 3 magic method detection accuracy as a function of Condition and sequence Alignment with magic moment.

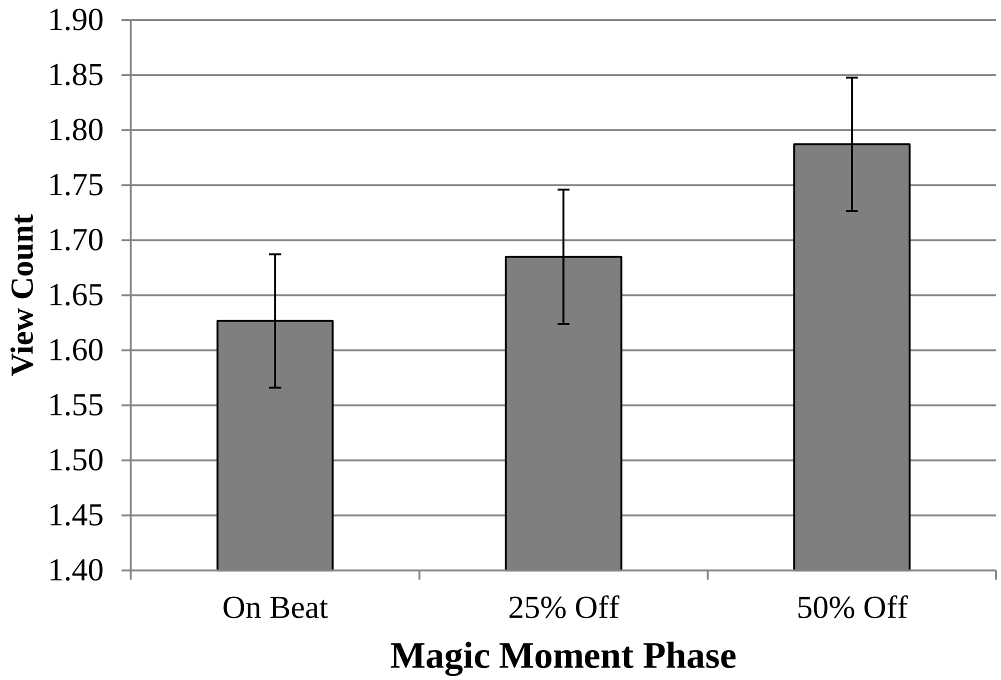


Figure 9. Experiment 3 magic video view count as a function of magic moment Phase relative to entraining rhythm.

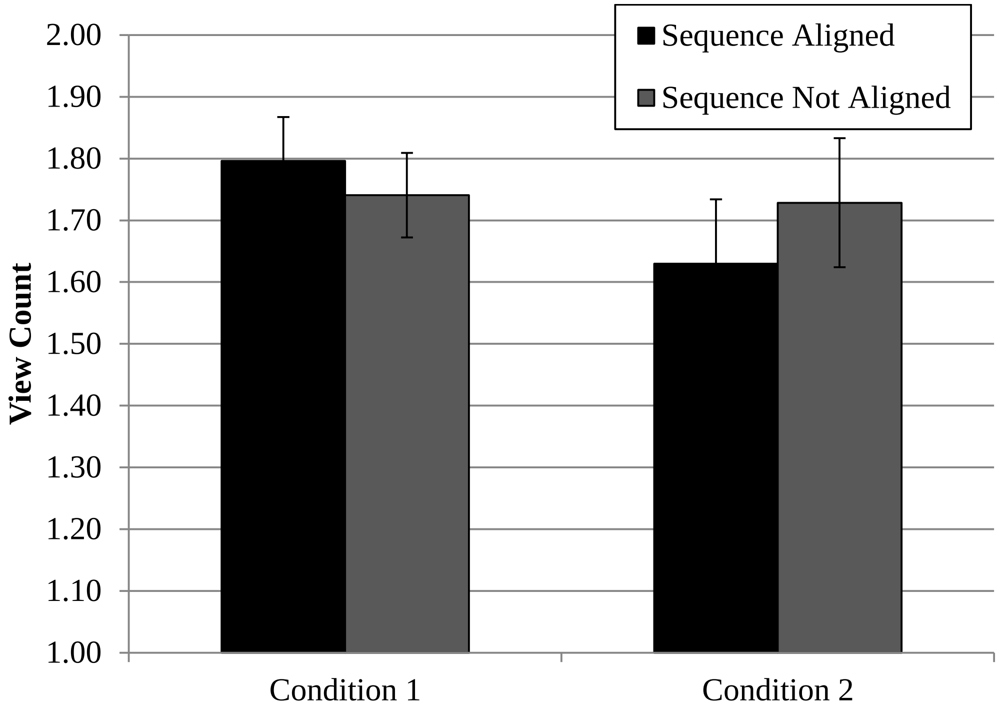
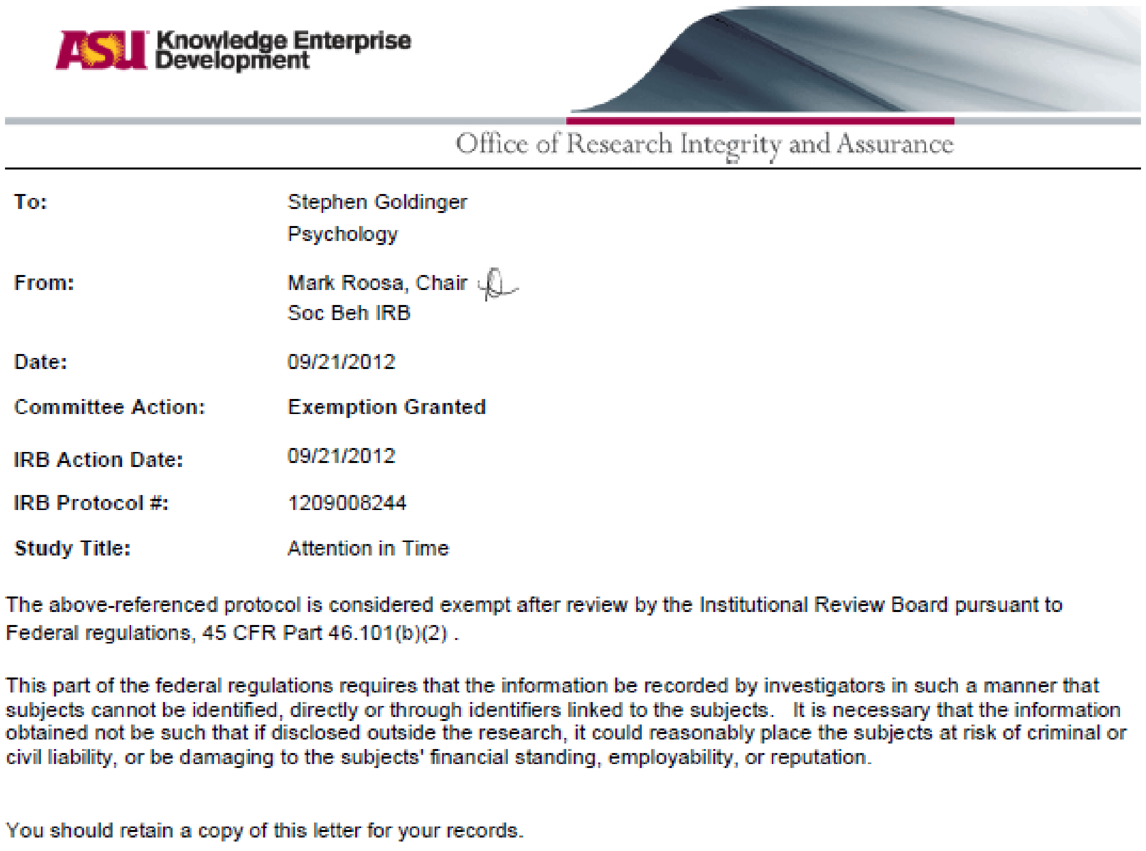


Figure 10. Experiment 3 magic video view count as a function of Condition and sequence Alignment with the magic moment.

APPENDIX A

ASU INSTITUTIONAL REVIEW BOARD HUMAN SUBJECTS RESEARCH APPROVAL



ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Stephen Goldinger Psychology
From:	Mark Roosa, Chair Soc Beh IRB
Date:	09/21/2012
Committee Action:	**Exemption Granted**
IRB Action Date:	09/21/2012
IRB Protocol #:	1209008244
Study Title:	Attention in Time

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.