The Beat of a Glimpse: Investigating Saccadic Timing in Response to Visual Rhythms

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Abstract

This study investigates the entrainment of saccadic eye movements to visual rhythms, examining whether the mechanisms akin to auditory-motor synchronization are also present for vision and gaze behavior. Through a gaze-contingent task with varying spatial uncertainties, we assessed participants' ability to synchronize saccades with dynamically changing visual stimuli. The results, derived from precise measurements using the EyeLink 1000 system, showed that individuals could entrain saccade timing to visual rhythms, as evidenced by the improved target acquisition and speeded reaction times across trials. The consistency of entrainment across individuals suggests potential applications of rhythmic visual stimuli in cognitive and motor training, particularly beneficial for those with attentional and coordination challenges. The study also explores the use of computational models of saccadic behavior. These findings underscore the importance of visual rhythm entrainment in enhancing visual-motor coordination and open new avenues for research in neural rehabilitation and adaptive learning processes.

Keywords: Saccades; Entrainment; Visual Rhythms

Introduction

Saccadic entrainment to visual rhythms explores the synchronization of rapid eye movements with external visual cues that vary in timing and spatial arrangement. This phenomenon draws from foundational theories in the rhythmic entrainment of motor behaviors, commonly observed in response to auditory stimuli, such as music, and has been shown to influence movements ranging from simple finger taps to complex dance sequences (Large, 2000; Patel & Iversen, 2014). Visual entrainment, however, leverages the temporal properties of visual stimuli to influence the timing and pattern of saccades—the quick, conjugate eye movements that we make between 3 and 4 times each second (Batten & Smith, 2018).While general studies on saccadic movements provide insights into the mechanistic aspects of visual attention and motor responses (Henderson, 2003; Itti & Koch, 2000), recent research has begun to address how these saccades align with dynamic visual sequences, independent of auditory rhythms (Batten & Smith, 2018). The differentiation in saccadic entrainment among populations with neurological differences, such as individuals on the autism spectrum, is intriguing. Studies suggest that autistic individuals and others with neurodevelopmental differences exhibit unique sensory processing patterns that can affect their motor responses to both auditory and visual rhythms (Rohde & Ernst, 2016; Ward, 2018). The variation in entrainment capacity could be linked to broader sensory integration theories, which describe differences in how sensory stimuli are processed and integrated into motor outputs among autistic individuals (Marco, Hinkley, Hill, & Nagarajan, 2011). This study builds on foundational work in rhythmic entrainment and its implications for neurologic music therapy, exploring how these principles apply to visual motor coordination and learning. Our study extends the concept of entrainment to visual saccade timing in dynamic environments, investigating how individuals learn and adapt their gaze behaviors in response to environmental rhythms.

Methods

Participants were engaged in a task designed to assess their ability to entrain saccade timing to dynamic visual stimuli. The task involved identifying targets in a visually dynamic environment where the temporal and spatial properties of stimuli varied. The task involved identifying targets under three conditions of spatial uncertainty, with saccade timing, target acquisition, and reaction times measured via the EyeLink 1000 system.

Results

Saccadic Entrainment and Reaction Time Participants displayed a statistically significant ability to entrain saccade timing to the rhythm of the moving targets across conditions (medium and high uncertainty). This was particularly evident in the condition of high spatial uncertainty, where the targets appeared in pseudorandom locations within a fixed radius of the previous target.

Table 1: Study participants and demographics

Demographics Categories	Frequency
Total participants	20
Gender	
Male	17
Female	3
Age [Mean (SD)]	24 (1.9)
Ethnicity	Asian (20)
Vision [Normal/Corrected to Normal]	20
NIH Toolbox (Fully corrected T score)	
Flanker Task [Mean (SD)]	47.3 (10.88)
Pattern Recognition Task [Mean (SD)]	56.25 (9.63)

Improvement in Target Acquisition We observed improvements in participants' ability to acquire targets with greater accuracy over time, suggesting that they adapted their gaze behavior effectively to the varying temporal demands (figure not shown).

Consistent Learning Patterns Across Conditions Individual and group data analyses revealed consistent patterns of learning and entrainment across participants. We observed that participants demonstrated a significant ability to entrain their saccade timing to the visual rhythm presented in the task. There was a noticeable improvement in target acquisition and reaction time, indicating that participants adapted their gaze behavior effectively to the temporal demands of the environment. These findings were supported by individual and group data analyses, which showed consistent patterns of entrainment and learning across participants

Discussion

The present study provides compelling evidence of entrainment in saccadic eye movement timing to visual rhythms, a finding that aligns with the well-established principles of auditory-motor entrainment, suggesting that similar neurobiological mechanisms may be at play in the visual domain. This capacity for entrainment has profound implications for our understanding of human interaction with dynamic environments and poses potential applications for rhythmic entrainment in rehabilitation programs, especially for individuals with attention and coordination difficulties. Considering models of gaze behavior timing including the SWIFT model (Engbert et al., 2005), the CRISP model (Nuthmann et al., 2010), and the LATEST model (Tatler et al., 2017), we see potential frameworks for understanding the underlying processes in saccadic decision-making and the generation of movements with respect to rhythmic visual stimuli. These models account for factors such as the timing of visual onsets and the inhibition of saccades based on the processing demands of currently fixated visual information.

The entrainment observed in our study suggests a predictive component in saccade generation that are described in some of these models. For instance, the SWIFT model, with its dynamic programming of saccades and inhibition mech-

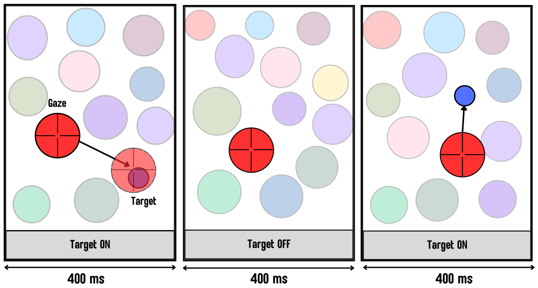

Figure 1: Gaze-contingent task. Target (blue circle) is the smallest circle amidst a field of distractors. Participants are instructed to align gaze (red circle, not visible to participants) with the target as soon as it is detected. A reinforcing tone occurs for correct hits; an error buzz sounds for distractor hits or early target arrival.

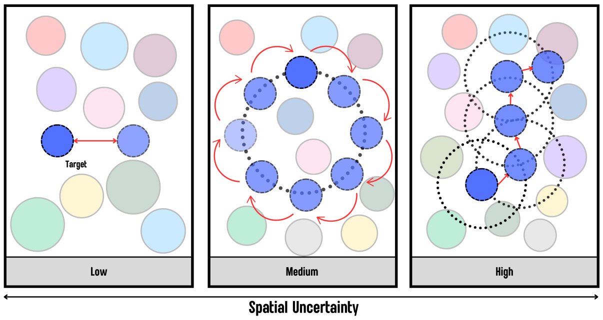

Figure 2: Representation of the 3 conditions of the gaze-contingent task. The low spatial uncertainty condition is where the target (blue circle) oscillates between left and right positions; medium spatial uncertainty is where the targets go around the screen in a circular fashion; and the high spatial uncertainty is where the target positions are pseudorandom where the next target appears within a fixed radius from the previous one.

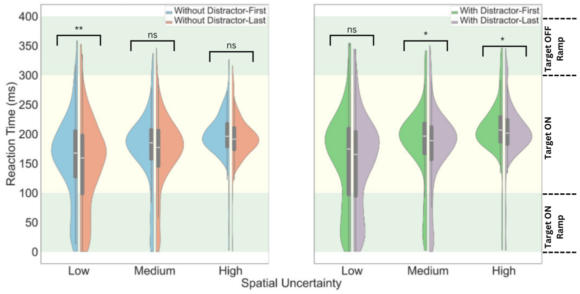

Figure 3: Reaction Times. Distribution of reaction times for the first and last 35 targets across participants and conditions.

anisms, could explain the participants' ability to adapt their saccadic rhythms to the varying spatial and temporal properties of the stimuli. Similarly, the CRISP model's concept of an automatic saccade timer, modulated by cognitive and visual factors, aligns with the entrainment and learning effects we observed. Furthermore, the LATEST model, which incorporates elements of the other two while focusing on temporal expectations in eye movement control, could offer insights into the predictive nature of saccadic responses to rhythmic visual stimuli. We plan to explore how these models can account for the enhanced saccadic coordination and learning shown by participants in the face of dynamic visual rhythms, particularly considering the implications for designing targeted interventions. In summary, saccadic entrainment to dynamic visual stimuli the not only contributes to the broader understanding of sensorimotor synchronization but also signals a promising interdisciplinary research trajectory, bridging cognitive neuroscience and potential future therapies. Future research could leverage these models to further dissect the intricacies of saccadic behavior and to harness the potential of visual rhythm entrainment in supportive interventions for neurodivergent populations.

References

Batten, J. P., & Smith, T. J. (2018). Saccades predict and synchronize to visual rhythms irrespective of musical beats. *Visual Cognition*, 26(9), 695–718. https://doi.org/10.1080/13506285.2018.1544181

Engbert, R., Nuthmann, A., Richter, E. M., & Kliegl, R. (2005). Swift: A dynamical model of saccade generation during reading. *Psychological Review*, 112(4), 777–813. https://doi.org/10.1037/0033295x.112.4.777

Henderson, J. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences*, 7(11), 498–504. https://doi.org/10.1016/j.tics.2003.09.006

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, 40(10–12), 1489–1506. https://doi.org/10.1016/s0042-6989(99)00163-7

Large, E. W. (2000). On synchronizing movements to music. *Human Movement Science*, 19(4), 527–566. https://doi.org/10.1016/s0167-9457(00)00026-9

Marco, E. J., Hinkley, L. B. N., Hill, S. S., & Nagarajan, S. S. (2011). Sensory processing in autism: A review of neurophysiologic findings. *Pediatric Research*, 69(5 Part 2). https://doi.org/10.1203/pdr.0b013e3182130c54

Nuthmann, A., Smith, T. J., Engbert, R., & Henderson, J. M. (2010). CRISP: A computational model of fixation durations in scene viewing. *Psychological Review*, 117(2), 382–405. https://doi.org/10.1037/a0018924

Patel, A. D., & Iversen, J. R. (2014). The Evolutionary Neuroscience of musical beat perception: The action simulation for Auditory prediction (ASAP) hypothesis. *Frontiers in Systems Neuroscience*, 8. https://doi.org/10.3389/fnsys.2014.00057

Rohde, M., & Ernst, M. O. (2016). Time, agency, and sensory feedback delays during action. *Current Opinion in Behavioral Sciences*, 8, 193–199. https://doi.org/10.1016/j.cobeha.2016.02.029

Tatler, B. W., Brockmole, J. R., & Carpenter, R. H. (2017). Latest: A model of saccadic decisions in space and time. *Psychological Review*, 124(3), 267–300. https://doi.org/10.1037/rev0000054

Ward, J. (2018). Individual differences in sensory sensitivity: A synthesizing framework and evidence from normal variation and developmental conditions. *Cognitive Neuroscience*, 10(3), 139–157. https://doi.org/10.1080/17588928.2018.1557131