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Time to make multisensory research mobile

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Abstract

Over the past decade, there has been a growing trend in investigating sensory processing during human locomotion. However, questions related to multisensory processing while walking remain numerous and not yet well explored. In this theoretical research, we provide a general review of the progress made in human walking-related cognition research based on the development of Mobile EEG, while highlight the lack of focus on multisensory processing. Additionally, we present some interesting findings from animal models related to multisensory processing during locomotion, which contributes to the motivation of a systematic investigation into multisensory processing. Finally, we propose several research questions that future studies should address to gain a better understanding of human cognition.

Full Text

Time to Make Multisensory Research Mobile

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Cognition Is Embodied and Walking Is a Crucial Body Movement

For over a century, the investigation of human cognition has been conducted primarily through experiments with highly controlled sensory input in stationary states, where body movement is maximally suppressed. Such carefully designed experiments have played a crucial role in revealing fundamental cognitive processes and underlying mechanisms by controlling confounding variables and acquiring high signal-to-noise ratio neural data. However, as suggested by embodied cognition, human cognitive processes are intricately linked with interactions between the body and the environment (Byrge, Sporns, & Smith, 2014; Chiel & Beer, 1997; Wilson, 2002). Body movement represents a vital way humans interact with their environment, yet laboratory settings may fail to capture these interactions, causing the role of body movement in cognition to be largely overlooked.

Among the numerous body movements, walking has historically played a crucial role in validating mobile brain/body imaging (MoBI) techniques. These techniques were developed to address the challenges of recording EEG data during movement and have served as tests for signal processing approaches to correct noise in EEG data recorded while subjects walked on a treadmill (Debener, Minow, Emkes, Gandras, & De Vos, 2012; Gramann, Gwin, Bigdely-Shamlo, Ferris, & Makeig, 2010). More importantly, walking is pervasive, complex, and highly functional. Failures in walking can have dire consequences, such as increased hospitalization risks for aging populations and navigation difficulties for patients with locomotor disorders. As a fundamental activity integral to daily living, understanding cognition during walking can provide insights into broader aspects of human cognition and brain function.

Progress in Walking-Related Research

One major area of research has focused on how the processing of visual and auditory cues influences kinematics—such as gait, stride, postural adjustments, and head-related patterns—during walking (Burtan et al., 2021; Graci, Elliott, & Buckley, 2009; Hiraoka, Kunimura, Oda, Kawasaki, & Sawaguchi, 2020; Jahn, Strupp, Schneider, Dieterich, & Brandt, 2001; Kao & Pierro, 2021). Some studies have also examined how auditory and visual information processing affects cognitive processes during walking, such as obstacle avoidance, self-motion reproduction, speed estimation, and other navigation-related functions (Jetzschke, Ernst, Froehlich, & Boeddeker, 2017; Kolarik, Scarfe, Moore, & Pardhan, 2016; Muroi & Higuchi, 2017; Silva, Aravind, Sangani, & Lamontagne, 2018; Zanchi, Cuturi, Sandini, Gori, & Ferre, 2023). Although this research did not directly measure the influence of walking on cognitive tasks, it provided hints about how certain types of information are processed or changed by walking. For instance, findings showing that subjects exhibit more cautious behavior with decreased walking speed and step length when peripheral vision is occluded using protective goggles suggest the importance of peripheral processing during walking (Graci, Elliott et al. 2009).

Another line of study, which has drawn increasing attention over the past 10 years, has assessed the influence of body movement on cognitive processing (for reviews, see Schmidt-Kassow & Kaiser, 2023; Stangl, Maoz, & Suthana, 2023). These studies typically employed a classic EEG dual-task methodology, comparing EEG responses between movement and static conditions. This research has revealed several important findings. First, walking is associated with decreased amplitude of both visual and auditory P300 compared to standing (Bradford, Lukos, Passaro, Ries, & Ferris, 2019; Chen, Cao, & Haendel, 2022; Gramann et al., 2010; Ladouce, Donaldson, Dudchenko, & Ietswaart, 2019). Traditionally, increased P300 amplitude may indicate enhanced attention or cognitive processing resources allocated to a task, while decreased amplitude may suggest reduced attention or cognitive load. The reduced P300 amplitude was therefore considered a neural marker of reduced attention due to cognitive-motor interference. Another widely reported finding is that walking leads to reduced ongoing parietal-occipital alpha power compared to standing, an effect that has been repeatedly reported independent of task features and stimulus modalities (Cao, Chen, & Haendel, 2020; Cao & Handel, 2019; Chen et al., 2022; Delaux et al., 2021; Ehinger et al., 2014; Lin, Wang, & Jung, 2014). Alpha power has been well-documented as a reflection of inhibition, with low alpha activity considered a signature of functional regions engaged in active neuronal processing, whereas strong alpha oscillations reflect the inhibition and disengagement of task-irrelevant cortical areas (Jensen & Mazaheri, 2010; Klimesch, 2012). The reduction of alpha power during walking therefore might indicate a changed attentional state. Some researchers have also demonstrated that specific phases of walking can differentially influence neural and behavioral responses, as well as eye movement patterns (Davidson, Verstraten, & Alais, 2024; Hollands, Marple-Horvat, Henkes, & Rowan, 1995; Lajoie, Teasdale, Bard, & Fleury, 1993; Patla & Vickers, 2003). Overall, these findings reveal significant effects of walking on cognitive processing with considerable consistency across modalities, highlighting the importance of considering walking as a behavioral state to fully understand human cognition.

Multisensory Processing During Walking Is Not Well-Explored

Despite the fruitful research directly or indirectly reflecting cognitive processing during walking, both lines of studies have focused exclusively on single modalities, with tasks including only visual or auditory stimuli. Relatively little work has explored how multisensory processes are integrated during walking. Even among studies that have attempted to investigate multisensory processing during walking, the focus has been on whether one sensory modality is more important than another in affecting walking-related activities. Vision has been found to be influential in avoiding obstacles and collisions, as well as alleviating split-belt locomotor adaptation effects—referring to the continuous adjustment of limb timing and coordination by the nervous system (Eikema et al., 2016; Kolarik et al., 2016; Silva et al., 2018). Bodily sensations including vestibular, somatosensory, and proprioceptive inputs also play crucial roles and can interact with visual processing to influence overall locomotor function (Cano Porras et al., 2020; Frissen, Campos, Souman, & Ernst, 2011). In some cases, these sensations can dominate cognitive processes during walking. Similarly, for audition and tactile sensation, studies have focused on how integrating auditory and tactile stimuli influences walking-related patterns (Dollack, Perusquia-Hernandez, Kadone, & Suzuki, 2019; Eikema et al., 2016; Gupta, Kelty-Stephen, Mangalam, McKindles, & Stirling, 2023; Jetzschke et al., 2017; Pitman, Sutherland, & Vallis, 2021). However, the majority of studies still make interpretations based on how sensory processing changes walking-related patterns, while direct evidence of how humans process sensory input across modalities during walking remains lacking.

Sensory Processing Between Modalities Might Work in an Integrated Way as Shown in Animal Models

Research based on animal models has raised important questions regarding multisensory processing during locomotion. Animal studies show that, unlike the facilitatory effect of locomotion on visual cortical responses (Niell and Stryker, 2010), the activity of auditory cortical neurons is suppressed (Schneider, Nelson, & Mooney, 2014; Schneider, Sundararajan, & Mooney, 2018; Yavorska & Wehr, 2021). This suppression has been observed in studies examining both auditory cortical neurons and simultaneous recordings of auditory and visual thalamus (Williamson, Hancock, Shinn-Cunningham, & Polley, 2015). Such suppression is not simply inhibition of external sound or self-generated sound from footfalls, but rather reflects a shift in neural resource allocation from auditory to visual regions (Schneider et al., 2014; Zhou et al., 2014) and a tradeoff with the emergence of explicit and reliable coding of locomotion velocity (Vivaldo, Lee, Shorkey, Keerthy, & Rothschild, 2023). One review has also suggested that suppression in auditory information processing could be associated with reallocation of processing resources away from acoustic input toward somatosensory or visual cues when individuals actively explore their environment (Lohse, Zimmer-Harwood, Dahmen, & King, 2022). This animal work generally suggests that during locomotion, sensory processing across different modalities may work in an integrated way to aid perception, possibly due to limited resources. More broadly, how an individual's sensory processing is influenced by locomotion likely results from multiple factors being modulated and weighted together. While recent studies suggest similar findings in humans, conclusive evidence remains lacking compared to animal studies, highlighting the need for systematic investigation into multisensory processing.

Real-World Implications and Future Directions

In real-world scenarios, humans rarely walk while detecting stimuli on a complete two-dimensional panel (e.g., a screen in front) or processing auditory information attached to the ears from left or right. Instead, a common condition involves actively noticing, reaching for, or exploring something while walking, where multiple external sensory information sources interact with walking-generated visual, auditory, and other body-related sensory inputs. From a fundamental science perspective, it is worth investigating whether walking negatively affects auditory behavioral task performance and neural responses to visual stimuli, as observed in animal studies. This question is closely related to how attention is allocated during walking. Practically, this is also relevant to real-world scenarios such as crossing streets or avoiding people and obstacles. To answer these questions, it is crucial to understand how walking influences attention allocation dynamics and associated neural patterns, an area that holds significant interest for future studies.

In summary, recent research has made significant progress in understanding how walking influences sensory processing in individual modalities. However, questions related to multisensory processing during walking remain numerous and are not yet well explored in humans. Future research should aim to investigate how multisensory information is integrated during walking, as this line of inquiry is essential for advancing our understanding of human cognition in real-world scenarios.

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