NARRATIVE REVIEW
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Effects of Visual, Auditory, and Combined Cues on Human Movement and Brain Regions Involved in Perception Action

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ABSTRACT

Background: Sensory stimuli such as visual and auditory cues are important to perceive our surroundings accurately. The effects of visual, auditory, or combined cues to modulate human movements such as walking are well-reported in the neuroscience literature. To date, no comprehensive report has summarized these findings.

Objective: The primary aim of this narrative review is to synthesize the literature on the interaction of visual, auditory, and combined cues of movement, as well as to present specific brain regions involved in perception-action.

Methods: A comprehensive review of the literature of published scientific work was conducted using PubMed and Google Scholar. Only English language articles that reported on visual, auditory, or combined cues and human movements were selected. Literature that included biofeedback was excluded.

Results: The literature suggests that visual and auditory cues have the potential to induce deviation in human movements. The posterior superior temporal sulcus and mirror neuron networks are shown to be critical in multimodal sensory integration.

Conclusion: This review presents some important theoretical models and outlines the brain regions involved in sensorimotor synchronization in human movement. Individual visual, auditory, or combined cues may have the potential to develop therapeutic interventions in the rehabilitation of movement disorders.

KEYWORDS
Visual cue, Auditory cue, Synchronization, Mirror neuron network

1 | INTRODUCTION

Humans function within a multisensory environment, where sound often accompanies action (clapping, crushing a can, or hammering). The most common sensory stimuli are visual and auditory signals, which, when combined, amplify the perception of surrounding objects and movement.(1) It is well established that the response (or reaction) is optimal with multisensory stimulation instead of individual stimulus(2). Multisensory integration involves complex sensory interactions that help to perceive the environment more accurately.(3) The perceptual system integrates the audiovisual information to provide a comprehensive picture for optimal functioning within multisensory surroundings, evident by a decrease in reaction time to multisensory stimulation.(4, 5) Additionally, multisensory signals provide information about the environment that would be insufficient when obtained from anyone sensory signal in isolation.(6)

The perceptual-motor system has been studied for over half a century. This narrative review will present the interaction of sensory cues and movement as well as brain areas involved in perception-action. The review will also provide an overview of the literature on unintentional synchronization. This comprehensive review is divided into three sections: Section 1 will present the effects of visual, auditory, and combined cues on human movement; Section 2 will highlight brain region activation in response to sensory cues and the mirror neuron network, and Section 3 will discuss unintentional synchronization.

2 | METHODS

Only the English language literature related to sensory cues and human movement was searched in PubMed and Google Scholar. A pragmatic search strategy approach using a saturation matrix typically used in qualitative research was deployed, whereby the search was terminated once the same articles appeared. The aim of this work is not to present a reproducible search but to present the breadth of information on a topic. Literature in the field of biofeedback was excluded.

3 | EFFECT OF INDIVIDUAL SENSORY CUES ON MOVEMENT

3.1 | Visual cue

Visual stimulus is the most dominant and ecologically salient source of information during walking.(7-10) Johansson et al. (1973) conducted a pioneer study to determine the ability of the visual system to recognize biological motion. In his study, the visual stimulus was constructed using a point-light attached to human joints the observers were asked to identify.(11) The study demonstrated the ability to interpret visual signals related to human movements in order to make meaningful inferences using past knowledge. We are constantly exposed to real multisensory stimuli complex scenes , so the perception of envirnonment complex scenes would differ from the relatively simple point-light design in the study. Moreover, it is shown that complex visual scenes result in distributed activations of different brain regions. The ventral temporal cortex (lateral and medial fusiform) is activated in response to video displays as opposed to point-light images.(12) The ventral temporal cortex is also responsive to static and moving human stimuli and objects (such as a saw or hammer) in motion. In contrast, the lateral temporal cortex is specifically responsive to moving complex stimuli such as articulated human motion.(12) This differential neural activation arose from the additional information in video display, such as form, color and texture that was absent in point-light display. Furthermore, the perception of motion is also affected based on the observer's position. It is shown that the perception of motion of the point-light images differs between a static observer posture (standing on a treadmill or sitting on a static bicycle) and dynamic self-motion, such as healthy individuals walking on a treadmill.(13) The perception of point-light images is least accurate when the observer walks than when sitting.(13) In research and clinical practice, visual cues such as laser light and stride length markings on the floor are often used as a strategy to improve walking performance in people with Parkinson's.(14) Recently, a trial studied the use of visual cues such as steppingstones for the rehabilitation of post-stroke walking.(15, 16) The use of steppingstones displays as a visual cue in healthy elderly subjects was reported to positively affect gait parameters.(17) The steppingstone visual display was compared to metronome beats among adults during a treadmill walking task and showed that the visual information resulted in quick gait recovery in response to perturbations compared to auditory beats.(17) Visual cue displayed over the treadmill determines step length (and consequently step frequency within a range of walking speeds) and directs spatial position for foot placement. The disadvantage of visual cues such as steppingstones, flashlights, or stripes on the floor, is that the cues have no ecological meaning.

3.2 | Auditory cue

Auditory system is a fast-processing sensory system that rapidly captures and extracts meaning from the received signals.(18, 19) Reaction time to auditory cues is faster by 20-50 milliseconds compared to visual or tactile cues.(18, 19) External auditory cues, such as metronome beats and music, are shown to have beneficial effects on walking in various neurological populations such as stroke, Parkinson's, Huntington's conditions.(14, 20-28) Unpredictable changes in auditory cue frequency provided by the metronome are shown to induce perturbation during walking in patients with stroke.(29, 30) This suggests that changes in the frequency of metronome sequences produces direct frequency entrainment capable of triggering instantaneous gait adjustments.

The critical aspect of rhythmic auditory cueing is the underlying rhythmicity or periodicity that enables auditory-motor interaction and also determines the strength of those interactions.(31) The auditory system is sensitive to time information and builds precise, stable time traces that acts as a motor template and helps individuals sync their movements.(31) The rhythmicity of the cue serves as an anticipatory and continuous external frame of reference. If the beats occur at regular intervals, there is a strong tendency to anticipate the next stimulus. This 'anticipation tendency' guides subsequent movement in advance. A stable auditory-motor synchronization is indicated by minimal variability in timing between the movement and the external cue. Steady-state auditory-motor synchronization is shown to occur within 2 to 3 repetitions of exposure to rhythmic metronome beats during finger tapping.(32) This ability of the sensory information from auditory cues helps to establish a stable synchronization pattern rapidly.

Monotonous metronome beats provide periodicity; this is in contrast to musical cues that are rich in other information such as melodicity. Auditory entertainment cues such as musical rhythms during a walking task in healthy young adults(33) and elderly individuals(34) resulted in reduced variability in synchronization compared to a metronome. Acoustic stimuli delivered as rhythmic music resulted in increased stride length and gait velocity compared to no cue stimuli or metronome conditions.(34) There is evidence that music-supported therapy has a beneficial effect in people post-stroke, as it provides an opportunity for the repetitive movement practice.(35)

Auditory-motor synchronization is well reported in the field of musical performance. Musical performance is a complex process that requires fast feedforward and feedback loops to rapidly process auditory, visual, and motor signals while referencing the learned sequence of musical output.(36, 37) Professional musicians are known to display precise auditory-motor synchronization.(36) Imaging studies in skilled musicians show brain activation in response to either auditory stimuli or passive finger movements, suggesting a co-activation phenomenon.(36) Auditory-motor coupling is defined as co-activation of cortical auditory and sensorimotor hand regions in either pure auditory or silent motor tasks.(38) Auditory-motor coupling is suggested to activate similar cortical networks both in trained and naïve musicians within 20 minutes of practice.(39-41) This suggests that music is able to establish a relatively fast coupling effect within a short span of exposure. In addition, professional musicians display involuntary auditory-to-motor (listening to music – purely acoustic) and motor-to-auditory co-activation (silent finger movements – purely motor).(37, 38, 42-46) Similar brain activation is also seen with imagery of sound or music playing motor action (non-acoustic).(47-49) A well-trained pianist showed involuntary, without actual finger movements, activation of the motor cortex (M1)(42), bilateral supplementary motor area (SMA), the primary motor cortex (PMC), anterior cingulate gyrus and parietal cortex(50-52), on listening to piano music, compared to a non-trained musician; this suggests a strong coupling between perception and action. Recent studies showed activation in posterior superior temporal gyrus (pSTS) and ventral premotor cortex during entrainment of motor responses with auditory cues in non-musicians.(53)

3.3 | Combined visual and auditory cues

Human visual and auditory systems are tele-receptive senses. This can be defined as a sensory system that receives and processes information from near and distant external environments and defines the origin of these sensations.(54)-(55) Perception of a scene depends on the concordance between the visual and auditory stimuli and should be temporally congruent in order to have a coherent percept, known as the Unity assumption. In other words, the more different sensory signals arise from a single source, the greater likelihood that the inputs would be combined to provide a coherent percept. For instance, women walkers produce a the sound of footsteps that suggest a feminine gender.(56-60) At the single neuron level, multisensory integration is defined as a statistically significant difference between the number of impulses evoked by a cross-modal combination of stimuli and the number evoked by the most effective of these stimuli individually.(61) The temporal congruency of visual and auditory stimuli is necessary for neural potentiation and is reflected in the magnitude of synaptic potential for congruent stimuli.(62) Thus, auditory and visual signals need to be meaningfully linked to each other and be temporally congruent for a coherent perception.

Sound signals can influence the perception of visual stimuli. A study presented variation in footstep sounds to young adults, resulting in an alternation of visual depth-perception of the point-light walker. The study showed that looming sounds paired with orthographic (facing the viewer) point-light walkers appear more looming, and similarly point-light walkers appear more receding (facing away from the viewer) when paired with receding sounds, compared to no-sound and stationary sound conditions.(55) Another study demonstrated decreased reaction time to the presence of a coherent point-light walker when auditory motion travelled in the same direction as the walker and increased reaction time when auditory and point-light walker motions travelled in the opposite direction.(59) Another group of researchers designed a task in which observers had to decide whether a periodically moving point-light walker had the same temporal frequency as a series of auditory beeps, which in some cases coincided with the footsteps of the walker. Performance in this task was consistently better for upright point-light walkers compared to inverted or scrambled walkers.(63) This suggests that individual auditory or visual stimuli can influence the the other stimulus's perception and that combined stimuli improve perception.

Among the various meaningful sounds in the environment, the sound of footsteps has a clear acoustic signal. Walking involves two distinct phases; a stance and swing phase, which are repeated periodically. The stance phase, which consists of heel strike and foot flat events has a distinct acoustic signal, while the swing phase has no acoustic signal.(64, 65) Human bipedal locomotion generates a stable regular footstep rhythm and a periodic motion of arms, trunk, and lower limb during normal gait.(66, 67) Besides, the sound of human footsteps carries a rich pattern of social information such as source - gender(68, 69), emotional state(68) and posture of the walker(70), walking surface(71), sole of footwear(68) as well as the temporal and spatial origin of sounds.(72) Also, footstep sound provides information about a dynamic human group, such as people walking in synchrony or one leading the other in pairs.(73) Given these qualities, the sound of footsteps is termed as footsteps' acoustic signature in the literature.

Sensorimotor synchronization is a referential behaviour in which a motor action is performed in sync with an external predictable stimulus or event known as the 'referent'.(74) There are two possible aspects to external cueing; first, the external stimuli are isochronous in time (fixed interstimulus interval) and therefore stable and predictable; second, the interstimulus interval is altered (progressive up or down ramp-like changes or random) and therefore unpredictable. In the variable frequency beats, there is an increase in synchronization error, and thus a deliberate and conscious action on the part of the individual is necessary in order to sustain a stable synchronization state.(75) Synchronized state is said to occur when the response sequence of movement has the same time interval as the external stimulation with no phase deviation.(75) However, during a sensory-motor synchronization, there exists variability in movement performance which necessitates a continuous adjustment to an external rhythm. The error-correction can be brought about by modulating movement in-phase and period duration.(75) Rhythmic auditory stimulation provides an effective timing mechanism, based on individuals' ability to focus on the rhythm, detect time interval of external rhythm, process time information and consciously integrate it in ongoing movement sequence. It also involves the ability to detect errors during synchronization and take corrective measures.(76) For example, walking to a fixed-paced metronome, which is isochronous, involves the ability to predict the subsequent beat, plan movement in anticipation of the beat, and closely match movement to external beat pace. In case of asynchrony or an error, a correction of the next movement is consciously considered in the subsequent movements. Furthermore, sensorimotor synchronization is also dependent on the motor effector. For instance, finger or foot tapping involves muscle force, movement amplitude, and degrees of freedom that are small and limited. In contrast, walking involves large muscle activity with many degrees of freedom that need to be constrained with additional postural and balance demands to match the external rhythm.

4 | BRAIN ACTIVATION IN RESPONSE TO SENSORY STIMULI

The effect of the visual and auditory cue on movement is supported by neuroimaging research that has identified activation of certain brain regions in response to sensory stimulation.(77-89)

4.1 | Supra-spinal regions

Multisensory neurons, specifically in the superior colliculus and cerebral cortex, have a receptive field that needs the stimuli to be congruent and in a close time frame in order to have an accentuated or super-additive effect (non-linear enhancement) that is, stronger than the sum of unimodal response.(3) Perception of congruent audio-visual biological motion (point-light walker and sound of footsteps) stimuli is reflected as activation in the posterior extend of the posterior superior temporal sulcus (pSTS), inferior parietal sulcus (IPS), (77-83) and premotor cortex. (84, 85) A study by Wuerger et al. (2012) demonstrated the role of ventral premotor cortex activation for congruent (same motion direction in auditory and visual modalities) than incongruent (different motion direction) biological auditory (footsteps sound) and visual motion (point-light walker).(86) Alaerts et al. (2009) in healthy adults using auditory (crushing of plastic bottle) and visual (action of crushing) cues, using transcranial magnetic stimulation, showed an increase in motor evoked potentials in the primary motor cortex to congruent audio-visual stimuli compared to unimodal and incongruent actions.(87) In addition to these regions, neurons in the superior colliculus also display a super-additive effect for simultaneous visual and auditory stimuli in animals.(2, 88) There appears to be a continuum in pSTS regions where neurons that respond to vision, auditory, and combined sensory signals(89) are activated in response to action versus non-action related stimulus.(90) Area pSTS is delineated as a robust structure in the perception of biological motion across most human(83) and primate studies.(91) The super-additive effect is also seen for social context and complex visual and auditory signals.(92) This may indicate its role in deriving meaning from the biologically relevant events. The role of pSTS and premotor cortex in biological motion perception is also supported by a study in people with chronic unilateral stroke, which showed that lesions in superior temporal and inferior frontal (premotor) regions play a causal role in biological motion perception (walking, jogging, throwing activities) compared to age-matched controls.(77) The response in the premotor and parietal cortex is enhanced when the observer intends to perform the movement compared to passive observation.(93) There is yet another brain region that could explain the effect of sensory cues on movement: the mirror neuron network.

4.2 | Mirror Neuron Network (MNN)

A group of visuomotor neurons in the primate ventral premotor cortex (f5) and inferior frontal cortex, called mirror neurons, are activated on observation and execution of goal-directed hand actions like grasping objects as well as listening to action-related sound.(94, 95) In humans, MNN is shown to be present in the ventral premotor cortex, precentral gyrus, posterior part of inferior frontal gyrus, Broca's area, and intraparietal area, which activates in response to action observation and sound related to actions such as crushing of plastic bottle or ripping of paper.(79, 85, 96-100) This led to the hypothesis that perception-induced activation of movements may obey a 'whole-or-nothing' principle(96). For example, the perception of tearing paper evokes the action irrespective of whether it is heard, seen, or both, and is modality-independent(96). An alternate hypothesis is the shared 'modality-dependent' action representations, where the mechanism of perception-induced action retrieval is based on the simultaneous input of vision and sound describing the same movement.(101) Neuroimaging suggests that seeing actions activates the frontoparietal neural network, which is also active when performing those same actions(102, 103). There is evidence of motor cortex activation (increased motor evoked potentials) in the observer when viewing an action execution (for example, grasping an object) compared to seeing the object alone or movement alone.(104) The MNN activity occurs in response to action-associated sound, and this area is more likely to respond to ecological stimuli, such as the sound of footsteps than the metronome. The MNN is also hypothesized to be the site for self-agency, defined as a feeling of being in control and being the author of one's movement.(105) The network is implicated in its ability to differentiate voluntary induced self-motion from external action in environment.(105),(106) Lastly, observing someone's actions allows one to predict the possible movement pattern that one would have to generate in order to achieve a similar end outcome, which in other words, provides a first-person grasp of the motor goals(106). From the ideomotor perspective, the neural representation of action generated through observation is similar to that required to execute the same action.(107, 108) Moreover, mirror neurons and observation of gait share a similar neural substrate as motor execution, including the premotor cortex, SMA, basal ganglia, and cerebellum.(109-111) This suggests that sensorimotor tasks based on action observation, imitation, or execution involve complex activation patterns and goes beyond the activation of the cortex and subcortical structures. Therefore, by a mere act of observing an action, it is possible to bring about compatible effects in subsequent action execution.

The cerebellum plays an important role in motion detection and has been recently highlighted in neuroimaging studies. The rhythmic motor synchronization of finger tapping to progressively increased external rhythm shows activation in cerebellar regions (anterior cerebellar lobe, thalamus, cingulate area) and cerebral (intraparietal sulcus, lateral prefrontal, and bilateral dorsolateral prefrontal) regions in a positron emission tomography (PET) study(112). Also, finger tapping to random sequence rhythmic cues showed activation in parieto-thalamic and premotor activity.(112) This suggests that these cerebro-cerebellar connections play a possible role during rhythmic motor synchronization. Lastly, the cerebellum also has a connection to pSTS and possibly plays a role in motion perception.(113)

5 | UNINTENTIONAL SYNCHRONIZATION (SPONTANEOUS OR UNINSTRUCTED)

The studies that used external rhythmic auditory cueing strategy during walking tasks asked the participants to match their heel-strike to auditory cues as precisely as they could, thereby consciously engaging them to synchronize movement to the auditory stimuli.(21, 28, 30) As opposed to this conscious synchronization, there is literature supporting unintentional imitation in humans that is exhibited in daily life and thought to be necessary for social interaction and interpersonal communication.(114, 115) The unintentional imitation, mimicry or a sense of similarity occurs automatically without any intention or awareness.(116, 117) During an unintentional imitation of an action, the consequence of execution or feedback is not registered. Studies have shown that it is possible to influence the task performance during an unintentionally synchronized movement (finger tapping) by changing external rhythm (auditory cue that was modulated at 3%, 7%, and 20% of the interstimulus interval from baseline).(118, 119) In order for unintentional synchronization to remain below the level of conscious perception, the modulation of the external rhythm needs to be subtle and progressive, or else the modulated stimulus reaches a conscious level when the motor adaptations switch to the active response mode.(118) Neuroimaging using PET showed a switch in the activation areas from the ventral medial prefrontal cortex at 3% and dorsolateral prefrontal cortex at 20% modulation (when conscious perception occurs).(118) Similarly, a study by Oullier et al. (2008) involving spontaneous synchronization between partners during rhythmic finger movements showed that the movements become unintentionally coupled as soon as the visual information is available and that the synchronization persists when the visual input of the other's movements is occluded.(120) Thus, subtle modulation in external sensory cues not only influences the ongoing task, but the effect continues even after the external cue is removed. Similarly, several other studies have demonstrated subconscious modulation in motor sequence. A visual-motor conflict study presented participants with their own full-body real-time images as an avatar. The avatar was programmed to deviate during a goal-directed locomotion task. This manipulation showed that the individuals induce compensatory correction without conscious perception when the deviation was within 10-15° but beyond this threshold, conscious correction kicked in.(105, 121) Another study using auditory cues manipulated footsteps and footsteps-related sound by introducing a temporal delay in real-time and demonstrated that the stepping correction occurred without conscious awareness with delays less than 120 milliseconds.(122) Furthermore, it has been suggested that energy cost may play a role in unintentional entrainment.(123) The subconscious negotiation of a shared stepping pattern between partners was demonstrated during a side-by-side treadmill walking task in healthy adults. This supports unintentional interpersonal synchronization in the absence of conscious effort compared to forced entrainment; however, the effect was transient and weak.(123) A similar effect was demonstrated during an over-ground walking task involving pairs that walked side-by-side while holding hands (tactile), visual (presence of another person), and auditory (sound of heel strike).(124, 125) Thus, external cue appears to affect one's behaviour without conscious perception. Unintentional synchronization shows activation in the orbitofrontal, ventrolateral, ventral prefrontal cortex, and lateral cerebellar hemispheres; whereas conscious adaptation activates the dorsolateral prefrontal cortex, anterior cingulate gyrus and premotor cortex(118), and these sites share some common regions with the mirror network.(126)

6 | CONCLUSION

This review summarised both the theoretical and brain mechanisms that underlie the effects of visual and auditory cues separately and when presented together. The use of combined visual and auditory cues that are biological in nature as well as unintentional synchronization may have a potential application in the field of rehabilitation.

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