

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 mainly conducted in experiments with highly controlled sensory input in a stationary state, with maximal body movement suppression. Such carefully designed experiments played a crucial role in revealing the fundamental cognitive processes and underlying mechanisms, with confounding variables being controlled and high signal-to-noise ratio neural data being acquired. Notably, as suggested by embodied cognition, human cognitive processes are intricately linked with the interaction between the body and the environment (Byrge, Sporns, & Smith, 2014; Chiel & Beer, 1997; Wilson, 2002). A very important way humans interact with the environment is through body movement. However, laboratory settings may fail to capture these interactions, therefore the role of body movement in cognition being largely overlooked.

Among the numerous body movements, walking, in particular, 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 the 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 aging populations facing increased hospitalization risks and patients with locomotor disorders struggling to navigate and interact with their environment. In such a sense, walking is a fundamental activity that is integral to daily living, understanding the cognition during walking can provide insights into broader aspects of human cognition and brain function.

Progress in walking-related research

44 One major area of research has focused on how the processing of visual and
45 auditory cues influences kinematics, such as gait, stride, postural adjustments, and
46 head-related patterns during walking (Burtan et al., 2021; Graci, Elliott, & Buckley,
47 2009; Hiraoka, Kunimura, Oda, Kawasaki, & Sawaguchi, 2020; Jahn, Strupp, Schneider,
48 Dieterich, & Brandt, 2001; Kao & Pierro, 2021). Some have also examined how
49 auditory and visual information processing affects some cognitive processes during
50 walking, such as obstacle avoidance, self-motion reproduction and speed estimation
51 in and other navigation-related purposes (Jetzschke, Ernst, Froehlich, & Boeddeker,
52 2017; Kolarik, Scarfe, Moore, & Pardhan, 2016; Muroi & Higuchi, 2017; Silva, Aravind,
53 Sangani, & Lamontagne, 2018; Zanchi, Cuturi, Sandini, Gori, & Ferre, 2023). Those
54 research, although did not directly measure the influence of walking on cognitive
55 tasks, provided some hints of how certain types of information is processed or
56 changed by walking: for instance, the finding showing that subjects exhibit more
57 cautious behaviour, with decreased walking speed and step length when peripheral
58 ~~occlusion~~ vision was occluded using an eye-protective goggles suggests the
59 importance of peripheral processing during walking (Graci, Elliott et al. 2009).

60
61 Another line of study, which assessed the influence of body movement on
62 cognitive processing drew more and more attention in the past 10 years (for reviews,
63 see (Schmidt-Kassow & Kaiser, 2023; Stangl, Maoz, & Suthana, 2023). These studies
64 usually employed a classic EEG dual-task methodology and compared the EEG
65 response between a movement condition and a static condition. This line of research
66 has revealed some interesting findings. One is that walking is associated with a
67 decrease in the amplitude of both visual and auditory P300 compared to standing
68 (Bradford, Lukos, Passaro, Ries, & Ferris, 2019; Chen, Cao, & Haendel, 2022; Gramann
69 et al., 2010; Ladouce, Donaldson, Dudchenko, & Ietswaart, 2019). Traditionally,
70 increased P300 amplitude may indicate enhanced attention or cognitive processing
71 resources allocated to a task, while a decreased amplitude may suggest decreased
72 attention or cognitive load. The reduced P300 amplitude was therefore considered as
73 neural marker of reduced attention due to cognitive-motor interference. Another
74 widely reported finding is that walking leads to reduced ongoing parietal-occipital
75 ongoing alpha power compared to standing, which has been repeatedly reported
76 independent of task feature and stimulus modalities (Cao, Chen, & Haendel, 2020;
77 Cao & Handel, 2019; Chen et al., 2022; Delaux et al., 2021; Ehinger et al., 2014; Lin,
78 Wang, & Jung, 2014). Alpha power has been well-documented as a reflection of
79 functional inhibition, with low alpha activity being considered as a signature of
80 regions engaged in active neuronal processing, whereas strong alpha oscillations
81 reflect the inhibition and disengagement of task-irrelevant cortical areas (Jensen &
82 Mazaheri, 2010; Klimesch, 2012). The reduction of alpha power due to walking
83 therefore might indicate a changed attentional state during walking. Some
84 researchers have also demonstrated that specific phases of walking can influence
85 neural and behavioural responses, as well as eye movement patterns in a different
86 way (Davidson, Verstraten, & Alais, 2024; Hollands, Marple-Horvat, Henkes, & Rowan,
87 1995; Lajoie, Teasdale, Bard, & Fleury, 1993; Patla & Vickers, 2003). Overall, there

88 are some significant findings about how walking influences the cognitive processing,
89 with quite some consistencies across modalities. These findings highlighted the
90 importance of considering walking as a behavioural state in fully understanding
91 human cognition.

92 93 **Multisensory processing during walking is not well-explored**

94
95 Despite the above-mentioned fruitful investigations directly or indirectly
96 reflecting the cognitive processing during walking, both lines of studies only focused
97 on only one individual modality, e.g. with task only including either visual or auditory
98 task/stimuli. Relatively little work has been performed to explore how multisensory
99 processes are integrated during walking. Even among those who have attempted to
100 investigate multisensory processing during walking, the focus is to investigate
101 whether one sensory modality is more important than another modality in affecting
102 walking related activities. Vision has been found to be influential in avoiding obstacle
103 and collisions, as well as alleviating split-belt locomotor adaptation effects, referring
104 to the continuously adjustment of the timing and coordination of each limb by
105 nervous system (Eikema et al., 2016; Kolarik et al., 2016; Silva et al., 2018). Some
106 bodily sensations including vestibular, somatosensory, and proprioceptive inputs play
107 crucial roles and can interact with visual processing to influence overall locomotor
108 function (Cano Porrás et al., 2020; Frissen, Campos, Souman, & Ernst, 2011). In some
109 occasions, those sensations could dominate the cognitive processes during walking.
110 Similarly, for audition, and tactile sensation, studies also still focused on how
111 integrating perception of auditory and tactile stimuli influence walking-related
112 patterns (Dollack, Perusquia-Hernandez, Kadone, & Suzuki, 2019; Eikema et al., 2016;
113 Gupta, Kelty-Stephen, Mangalam, McKindles, & Stirling, 2023; Jetzschke et al., 2017;
114 Pitman, Sutherland, & Vallis, 2021). Majority of studies still just make interpretations
115 based on how sensory process changes walking-related patterns, direct evidence of
116 how the human during walking process the sensory input across modalities is lacking.

117 118 **Sensory processing between modalities might work in an integrated way as shown** 119 **in animal models**

120
121 Research based on animal models have raised some interesting research
122 discussions and questions regarding the multisensory processing during locomotion.
123 There are animal studies showing that, unlike the facilitatory effect of locomotion on
124 visual cortical responses (Niell and Stryker, 2010), the activity of auditory cortical
125 neurons is suppressed (Schneider, Nelson, & Mooney, 2014; Schneider, Sundararajan,
126 & Mooney, 2018; Yavorska & Wehr, 2021). This suppression has been observed in
127 studies examining both auditory cortical neurons and simultaneous recordings of
128 auditory and visual regions of the thalamus (Williamson, Hancock, Shinn-
129 Cunningham, & Polley, 2015). Such suppression, however, was evidenced and
130 discussed as not just simple inhibition of external sound or self-generated sound by
131 feet, but a reflection of a neural resource allocation shifts from audition to vision

132 (Schneider et al., 2014; Zhou et al., 2014) and also as tradeoff with the emergence of
133 explicit and reliable coding of locomotion velocity (Vivaldo, Lee, Shorkey, Keerthy, &
134 Rothschild, 2023). One review has also suggested that the suppression observed in
135 the processing of auditory information could be associated with the reallocation of
136 processing resources away from acoustic input but toward somatosensory or visual
137 cues when individual actively explores the environment (Lohse, Zimmer-Harwood,
138 Dahmen, & King, 2022). Those animal work generally suggest that during locomotion,
139 sensory processing in different modalities might work in an integrated way to aid for
140 the perception, possibility due the limited resources. In an even broader sense, how
141 an individual's sensory processing influenced by locomotion is likely the result of
142 multiple factors being modulated and weighted together. It is worth noting that while
143 recent studies suggest similar findings in humans, there was no conclusive evidence
144 as animal studies. Overall, this highlights the need for systematic investigation into
145 multisensory processing.

146
147 Considering the cognition in human, in real world scenario, human almost do not
148 walk while detecting something in a complete two-dimension panel, e.g. the screen
149 in front, or an auditory information attached to ears in left or right. Instead, an often
150 happen condition is to notice, reach or explore something actively while walking,
151 multiple external sensory information can also interact with walking-generated visual,
152 auditory and other body-related sensory input. From a fundamental science point of
153 view, it is worth investigating whether walking negatively affects auditory behavioral
154 task performance and neural responses to visual stimuli, as observed in animal
155 studies. This question is closely related to how attention is allocated during walking.
156 Practically, it is also relevant to real-world scenarios, such as how walking is allocated
157 crossing a street or avoiding people and other obstacles. To answer these questions,
158 it is crucial to understand how walking influences attention allocation dynamics and
159 associated neural patterns. This area of research holds significant interest for future
160 studies.

161
162 To summarize, recent research has made significant progress in understanding
163 how walking influences sensory processing in individual modalities. However,
164 questions related to multisensory processing during walking remain numerous and
165 are not yet well explored in humans. Future research should aim to investigate how
166 multisensory information is integrated during walking, this line of inquiry is essential
167 for advancing our understanding of human cognition in real-world scenarios.

168 169 **References:**

- 170 Bradford, J. C., Lukos, J. R., Passaro, A., Ries, A., & Ferris, D. P. (2019). Effect of
171 locomotor demands on cognitive processing. *Scientific Reports*, *9*. doi:ARTN
172 9234
173 10.1038/s41598-019-45396-5
174 Burtan, D., Joyce, K., Burn, J. F., Handy, T. C., Ho, S., & Leonards, U. (2021). The nature
175 effect in motion: visual exposure to environmental scenes impacts cognitive

- 176 load and human gait kinematics. *R Soc Open Sci*, 8(1), 201100.
177 doi:10.1098/rsos.201100
- 178 Byrge, L., Sporns, O., & Smith, L. B. (2014). Developmental process emerges from
179 extended brain-body-behavior networks. *Trends Cogn Sci*, 18(8), 395-403.
180 doi:10.1016/j.tics.2014.04.010
- 181 Cano Porras, D., Zeilig, G., Doniger, G. M., Bahat, Y., Inzelberg, R., & Plotnik, M. (2020).
182 Seeing Gravity: Gait Adaptations to Visual and Physical Inclines - A Virtual
183 Reality Study. *Frontiers in Neuroscience*, 13. doi:10.3389/fnins.2019.01308
- 184 Cao, L., Chen, X., & Haendel, B. F. (2020). Overground Walking Decreases Alpha
185 Activity and Entrained Eye Movements in Humans. *Front Hum Neurosci*, 14,
186 561755. doi:10.3389/fnhum.2020.561755
- 187 Cao, L., & Handel, B. (2019). Walking enhances peripheral visual processing in
188 humans. *PLoS Biol*, 17(10), e3000511. doi:10.1371/journal.pbio.3000511
- 189 Chen, X., Cao, L., & Haendel, B. F. (2022). Human visual processing during walking:
190 Dissociable pre- and post-stimulus influences. *Neuroimage*, 264, 119757.
191 doi:10.1016/j.neuroimage.2022.119757
- 192 Chiel, H. J., & Beer, R. D. (1997). The brain has a body: adaptive behavior emerges
193 from interactions of nervous system, body and environment. *Trends Neurosci*,
194 20(12), 553-557. doi:10.1016/s0166-2236(97)01149-1
- 195 Davidson, M. J., Verstraten, F. A. J., & Alais, D. (2024). Walking modulates visual
196 detection performance according to stride cycle phase. *Nat Commun*, 15(1),
197 2027. doi:10.1038/s41467-024-45780-4
- 198 Debener, S., Minow, F., Emkes, R., Gandras, K., & De Vos, M. (2012). How about
199 taking a low-cost, small, and wireless EEG for a walk? *Psychophysiology*,
200 49(11), 1617-1621. doi:10.1111/j.1469-8986.2012.01471.x
- 201 Delaux, A., de Saint Aubert, J. B., Ramanoel, S., Becu, M., Gehrke, L., Klug, M., . . .
202 Arleo, A. (2021). Mobile brain/body imaging of landmark-based navigation
203 with high-density EEG. *Eur J Neurosci*, 54(12), 8256-8282.
204 doi:10.1111/ejn.15190
- 205 Dollack, F., Perusquia-Hernandez, M., Kadone, H., & Suzuki, K. (2019). Head
206 Anticipation During Locomotion With Auditory Instruction in the Presence
207 and Absence of Visual Input. *Front Hum Neurosci*, 13, 293.
208 doi:10.3389/fnhum.2019.00293
- 209 Ehinger, B. V., Fischer, P., Gert, A. L., Kaufhold, L., Weber, F., Pipa, G., & Konig, P.
210 (2014). Kinesthetic and vestibular information modulate alpha activity during
211 spatial navigation: a mobile EEG study. *Front Hum Neurosci*, 8, 71.
212 doi:10.3389/fnhum.2014.00071
- 213 Eikema, D. J., Chien, J. H., Stergiou, N., Myers, S. A., Scott-Pandorf, M. M., Bloomberg,
214 J. J., & Mukherjee, M. (2016). Optic flow improves adaptability of
215 spatiotemporal characteristics during split-belt locomotor adaptation with
216 tactile stimulation. *Exp Brain Res*, 234(2), 511-522. doi:10.1007/s00221-015-
217 4484-5
- 218 Frissen, I., Campos, J. L., Souman, J. L., & Ernst, M. O. (2011). Integration of vestibular
219 and proprioceptive signals for spatial updating. *Experimental Brain Research*,

- 220 212(2), 163-176. doi:10.1007/s00221-011-2717-9
- 221 Graci, V., Elliott, D. B., & Buckley, J. G. (2009). Peripheral visual cues affect minimum-
222 foot-clearance during overground locomotion. *Gait Posture*, 30(3), 370-374.
223 doi:10.1016/j.gaitpost.2009.06.011
- 224 Gramann, K., Gwin, J. T., Bigdely-Shamlo, N., Ferris, D. P., & Makeig, S. (2010). Visual
225 evoked responses during standing and walking. *Frontiers in Human
226 Neuroscience*, 4. doi:ARTN 20210.3389/fnhum.2010.00202
- 227 Gupta, A., Kelty-Stephen, D. G., Mangalam, M., McKindles, R. J., & Stirling, L. (2023).
228 Walking speed and dual task input modality impact performance on a self-
229 paced treadmill. *Appl Ergon*, 109, 103986. doi:10.1016/j.apergo.2023.103986
- 230 Hiraoka, K., Kunimura, H., Oda, H., Kawasaki, T., & Sawaguchi, Y. (2020). Rhythmic
231 movement and rhythmic auditory cues enhance anticipatory postural
232 adjustment of gait initiation. *Somatosens Mot Res*, 37(3), 213-221.
233 doi:10.1080/08990220.2020.1777959
- 234 Hollands, M. A., Marple-Horvat, D. E., Henkes, S., & Rowan, A. K. (1995). Human Eye
235 Movements During Visually Guided Stepping. *J Mot Behav*, 27(2), 155-163.
236 doi:10.1080/00222895.1995.9941707
- 237 Jahn, K., Strupp, M., Schneider, E., Dieterich, M., & Brandt, T. (2001). Visually induced
238 gait deviations during different locomotion speeds. *Exp Brain Res*, 141(3),
239 370-374. doi:10.1007/s002210100884
- 240 Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory
241 alpha activity: gating by inhibition. *Front Hum Neurosci*, 4, 186.
242 doi:10.3389/fnhum.2010.00186
- 243 Jetzschke, S., Ernst, M. O., Froehlich, J., & Boeddeker, N. (2017). Finding Home:
244 Landmark Ambiguity in Human Navigation. *Frontiers in Behavioral
245 Neuroscience*, 11. doi:10.3389/fnbeh.2017.00132
- 246 Kao, P. C., & Pierro, M. A. (2021). Dual-task treadmill walking at self-paced versus
247 fixed speeds. *Gait Posture*, 89, 92-101. doi:10.1016/j.gaitpost.2021.07.001
- 248 Klimesch, W. (2012). alpha-band oscillations, attention, and controlled access to
249 stored information. *Trends Cogn Sci*, 16(12), 606-617.
250 doi:10.1016/j.tics.2012.10.007
- 251 Kolarik, A. J., Scarfe, A. C., Moore, B. C., & Pardhan, S. (2016). An assessment of
252 auditory-guided locomotion in an obstacle circumvention task. *Exp Brain Res*,
253 234(6), 1725-1735. doi:10.1007/s00221-016-4567-y
- 254 Ladouce, S., Donaldson, D. I., Dudchenko, P. A., & Ietswaart, M. (2019). Mobile EEG
255 identifies the re-allocation of attention during real-world activity. *Sci Rep*, 9(1),
256 15851. doi:10.1038/s41598-019-51996-y
- 257 Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static
258 and dynamic equilibrium. *Exp Brain Res*, 97(1), 139-144.
259 doi:10.1007/BF00228824
- 260 Lin, Y. P., Wang, Y., & Jung, T. P. (2014). Assessing the feasibility of online SSVEP
261 decoding in human walking using a consumer EEG headset. *J Neuroeng
262 Rehabil*, 11, 119. doi:10.1186/1743-0003-11-119
- 263 Lohse, M., Zimmer-Harwood, P., Dahmen, J. C., & King, A. J. (2022). Integration of

- 264 somatosensory and motor-related information in the auditory system. *Front*
265 *Neurosci*, 16, 1010211. doi:10.3389/fnins.2022.1010211
- 266 Muroi, D., & Higuchi, T. (2017). Walking through an aperture with visual information
267 obtained at a distance. *Exp Brain Res*, 235(1), 219-230. doi:10.1007/s00221-
268 016-4781-7
- 269 Patla, A. E., & Vickers, J. N. (2003). How far ahead do we look when required to step
270 on specific locations in the travel path during locomotion? *Exp Brain Res*,
271 148(1), 133-138. doi:10.1007/s00221-002-1246-y
- 272 Pitman, J., Sutherland, K., & Vallis, L. A. (2021). Exploring the cognitive demands
273 required for young adults to adjust online obstacle avoidance strategies. *Exp*
274 *Brain Res*, 239(3), 1009-1019. doi:10.1007/s00221-020-06006-3
- 275 Schmidt-Kassow, M., & Kaiser, J. (2023). The brain in motion-cognitive effects of
276 simultaneous motor activity. *Frontiers in Integrative Neuroscience*, 17.
277 doi:ARTN 1127310
278 10.3389/fnint.2023.1127310
- 279 Schneider, D. M., Nelson, A., & Mooney, R. (2014). A synaptic and circuit basis for
280 corollary discharge in the auditory cortex. *Nature*, 513(7517), 189-194.
281 doi:10.1038/nature13724
- 282 Schneider, D. M., Sundararajan, J., & Mooney, R. (2018). A cortical filter that learns to
283 suppress the acoustic consequences of movement. *Nature*, 561(7723), 391-
284 395. doi:10.1038/s41586-018-0520-5
- 285 Silva, W. S., Aravind, G., Sangani, S., & Lamontagne, A. (2018). Healthy young adults
286 implement distinctive avoidance strategies while walking and circumventing
287 virtual human vs. non-human obstacles in a virtual environment. *Gait &*
288 *Posture*, 61, 294-300. doi:10.1016/j.gaitpost.2018.01.028
- 289 Stangl, M., Maoz, S. L., & Suthana, N. (2023). Mobile cognition: imaging the human
290 brain in the 'real world'. *Nat Rev Neurosci*, 24(6), 347-362.
291 doi:10.1038/s41583-023-00692-y
- 292 Vivaldo, C. A., Lee, J., Shorkey, M., Keerthy, A., & Rothschild, G. (2023). Auditory
293 cortex ensembles jointly encode sound and locomotion speed to support
294 sound perception during movement. *PLoS Biol*, 21(8), e3002277.
295 doi:10.1371/journal.pbio.3002277
- 296 Williamson, R. S., Hancock, K. E., Shinn-Cunningham, B. G., & Polley, D. B. (2015).
297 Locomotion and Task Demands Differentially Modulate Thalamic Audiovisual
298 Processing during Active Search. *Current Biology*, 25(14), 1885-1891.
299 doi:10.1016/j.cub.2015.05.045
- 300 Wilson, M. (2002). Six views of embodied cognition. *Psychon Bull Rev*, 9(4), 625-636.
301 doi:10.3758/bf03196322
- 302 Yavorska, I., & Wehr, M. (2021). Effects of Locomotion in Auditory Cortex Are Not
303 Mediated by the VIP Network. *Front Neural Circuits*, 15, 618881.
304 doi:10.3389/fncir.2021.618881
- 305 Zanchi, S., Cuturi, L. F., Sandini, G., Gori, M., & Ferre, E. R. (2023). Vestibular
306 contribution to spatial encoding. *Eur J Neurosci*, 58(9), 4034-4042.
307 doi:10.1111/ejn.16146

308 Zhou, M., Liang, F., Xiong, X. R., Li, L., Li, H., Xiao, Z., . . . Zhang, L. I. (2014). Scaling
309 down of balanced excitation and inhibition by active behavioral states in
310 auditory cortex. *Nat Neurosci*, *17*(6), 841-850. doi:10.1038/nn.3701
311