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2	Title:	Sensory-motor brain dynamics reflect architectural affordances
3		

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23
24

ABSTRACT (150 words)

Anticipating meaningful actions in the environment is an essential function of the brain. Such predictive mechanisms originate from the motor system and allow for inferring actions from environmental affordances, the potential to act within a specific environment. Using architecture, we provide a unique perspective to the abiding debate in cognitive neuroscience and philosophy on whether cognition depends on movement or is decoupled from our physical structure. To investigate cognitive processes associated with architectural affordances, we used a Mobile Brain/Body Imaging approach recording brain activity synchronized to head-mounted virtual reality. Participants perceived and acted upon virtual transitions ranging from non-passable to easily passable. We demonstrate that early sensory brain activity, upon revealing the environment and before actual movement, differed as a function of affordances. Additionally, movement through transitions was preceded by a motor-related negative component also depended on affordances. Our results suggest that potential actions afforded by an environment influence perception.

SIGNIFICANCE STATEMENT (118 words)

By using electroencephalography and virtual reality, our research provide a unique perspective to the centurial open-ended debate in cognitive neuroscience and philosophy on the relation between cognition, movement and environment. Our results indicate that cortical potentials vary as a function of bodily affordances reflected by the physical environment. Firstly, the results of this study implies that cognition is inherently related to potential movement of the body, thus we advance that action is interrelated with perception, actively influencing the perceivable environment. Secondly, as cortical potentials are influenced by the potential to move, which in turn is the task of architectural design, architects holds largely a privilege of human health, and thus potentially capable of provoking and preventing physiological conditions.

INTRODUCTION. The affordance of a given spatial environment, defined as the perception of possibilities for, or restraints on, action that the environment offers, is essential for an agent to produce meaningful behavior. Thus, the affordances of the spatial environment becomes a central concept for humans interacting with their world. The term *affordances* was first introduced by Gibson (1), and later specified by various authors including Clark who defines affordance as *"[…] the possibilities for use, intervention and action which the physical world offers a given agent and are determined by the 'fit' between the agent's physical structure, capacities and skills and the action-related properties of the environment itself."* (2). In light of emerging theories of embodied cognition, the perception of the environment may be dependent on proprioceptive mechanisms. According to predictive processing, a neuroscientifically based theory of embodied cognition (3–5), motor systems, similar to perceptual processes, aim at cancelling out continuously incoming bottom-up sensory signals with top-down predictions. In this perspective, movement emerges as a result of an *active inference* that attempts to either minimizing motor trajectory prediction errors by acting, and thus perceiving the unfolding of the predicted movement, or by changing perception itself (6–8). From the standpoint of active inference, motor systems suppress errors through a dynamic interchange of prediction and action. In other words, there are two ways to minimizing prediction errors; one is to adjust predictions to fit the current sensory input, while another is to adapt the unfolding of movement to make predictions come true. It is a unifying perspective on perception and action suggesting that action is both perceived and caused by perception (9). Hence, action, perception, and cognition coordinate to move the body in ways that conform a transitional set of expectations (10). The claim we seek to investigate in the present study is that perception is rooted in action, creating an action-perception loop, informed by dynamically (top-down/bottom-up) generated prediction errors. Ultimately, the argument is that perception is not the sole result of sensing the physical world, but unfolds as an ongoing interaction between sensory processes and bodily actions. Such a claim has philosophical and neuroscientific significance as the neural dynamics underlying perception would be intimately dependent on the affordances of a given environment.

To further investigate this claim, we used electroencephalographic (EEG) recordings to address the neural dynamics of action-perception interactions through affordance manipulations in architectural experiences. More specifically, we investigated the affordances of transitions as they form an ideal candidate due to their dynamic nature concerning the duration of altering one condition to another (11). We here confine transitions to *the passage between spaces* which, according to the enactivists' proposed action-perception loop, will be experience dependent on the affordances offered by the passage itself. From an architecturally historical point of view, the use of transitions have evidently been exploited at least since eleventh-thirteenth dynasties (e.g., Fazio et al., 2008, chaps. 1, 2, 5). Written interest in human experience of architectural settings has been established at least for the last two millennia (e.g., Norberg-Schulz, 1965; Palladio, 1997; Pallasmaa, 2011; Rasmussen, 1959; Vitruvius and Morgan, 1960). Despite transitions being ubiquitous in architecture, the underlying mechanisms of how transitions affect human perceivers appears to have taken an implicit, overlooked, and close to nonexistent position in architectural discourse, with few exceptions (15, 18–20). Due to the dynamic nature of architecture, an essential part of transitions and experiencing architecture is that of being able to act (21). Traditionally, investigations of architectural experiences are phenomenological – the description of phenomena in how experience gives access to a world of space and time (14, 22–24). Such descriptions find specifically movement of the individual to be an expression of a holistic experience of architecture (14, 22), linking the nature of movement to architectural experiences (25). Transitions in architecture depend on voluntary movement and thus a prerequisite for any transit is a goal, which in turn calls for action planning. Coarsely three parameters compose a transition: a motivated goal, a change in physical environment and the unfolding of action. All three parameters are interdependent, as reaching a goal depends on the affordance offered by an environment, and also propels the body in space contributing to experience.

3

100 Architectural transitions thus include the attenuation of an agent's experience through movements and how
101 such movements animate the body through environmental changes.
102
103 Data from neuroscientific experiments addressing this issue might contribute to discussions centered on
104 philosophical questions on how we relate to the world. For long, enactivists have implicated the reciprocal
105 dependency of the living organism, as a self-organized living system, and the embedded body in a world for
106 cognition (26–28). Enactivism is rooted in phenomenology (21, 29), similar to prominent architectural
107 theorists, who put body, action, and cognition central to experience. Active inference closely relates to
108 enactivism, in the sense that we act to perceive, and vice versa. Such a thesis rests on a hierarchical and
109 dynamic model of the world, which temporally dissociates lower sensorimotor inferences from higher
110 motivated goals, as fast and slow, respectively (30). Fast, lower sensorimotor inferences depict processes of
111 affordances, which thereby must be present in early stages of perception. Hierarchical affordance competition
112 (HAC; Pezzulo and Cisek, 2016) takes the temporal aspect of affordances much further, by suggesting that
113 cortical activity relates to the immediate decision of action selection, which occurs fluently during movement.
114 Such an account of temporally extended affordance is in accordance with active inferences.
115
116 To investigate the impact of environmental affordances on early sensory processing in actively transiting
117 humans, we used a Mobile Brain/Body Imaging approach (32–34) recording brain activity with EEG
118 synchronized to movement recordings and head mounted virtual reality (VR). This approach allows for
119 investigating brain dynamics of participants perceiving an environment and the transitions contained therein
120 as well as brain dynamics during the transitions itself. Previous studies investigating event-related potential
121 (ERP) activity in stationary participants demonstrated slow cortical potentials to indicate anticipative motor
122 behavior (for an overview, see Luck and Kappenman, 2011, chap. 8). Known motor-related cortical
123 components (MRCPs) are the readiness potential (RP; Kornhuber and Deecke, 2016), contingent negative
124 variation (CNV), and the stimulus-preceding negativity (SPN; Brunia, 2003), which can be seen as indicators
125 of predictive behavior (38). MRCPs are negative going waveforms preceding an actual, or imagined, motor
126 execution. However, these negative components are associated with multiple processes including sensory,
127 cognitive, and motor systems. In a study by Bozzacchi et al. (39), the authors attempted to measure affordances
128 of a physical object by evaluating whether the anticipated consequence of action itself influence the brain
129 activity preceding a self-paced action. The authors compared MRCPs of situations where it was possible to
130 reach out and grasp a cup, versus situations where it was impossible to grasp the cup, by tying the hands of the
131 participants. A motor execution was forced at all times. In situations where it was impossible to grasp the cup,
132 the authors reported an absence of early activity over the parietal cortex, and found instead increased activity
133 over the prefrontal cortex. The results were interpreted as reflecting an awareness of the inability to execute a
134 goal-oriented action. Closely related to the MRCPs is the post-imperative negative variation (PINV), a negative
135 going waveform that is present succeeding an imperative stimulus. It reflects the immediate motor execution
136 related to the onset of an imperative stimulus and was observed during experiments investigating learned
137 helplessness or loss of control (40, 41). The PINV thus allows linking of motor related potentials to anticipation
138 of affective states (42).
139
140 If an enactive account of perception, action and cognition is correct, affordances intimately relate to higher
141 hierarchical levels through low-level perceptual cues. Such an account would situate processing of affordances
142 at a similar stage as early perceptual processes and should reveal differences in sensory and motor-related
143 ERPs associated with the perceived affordance of an environment. To investigate whether brain activity is
144 altered depending on affordances offered by the environment, we presented human observers with
145 environmental stimuli that allowed or prohibited a transition from one room to the next. To this end,

146   participants were presented with a view into a room containing one door of different widths, allowing or
147   prohibiting a transition into the next room and thus providing different affordances. We expected to find
148   differences in cortical responses to co-vary as a function of affordances over sensory and motor areas. In
149   addition, we expected differences in motor-related cortical potentials as a function of the environmental
150   affordances when participants were instructed to walk through the door or to remain in the same room.

151

152   **METHODS**

153   **Participants.** 20 participants (9 female) without history of neurological pathologies were recruited from a
154   participant pool of the Technical University of Berlin, Berlin. All participants read and signed a written
155   informed consent about the experimental protocol, which was approved by the local ethics committee.
156   Participants received either monetary compensation (10€/hour) or accredited course hours. The mean age
157   was 28.1 years ($\sigma = 6.2$), all participants had normal or corrected to normal vision and none had a specific
158   background in architecture (no architects or architectural students). One participant was excluded due to
159   technical issues of the experimental setup.

160

161   **Paradigm description.** The experiment took place in the Berlin Mobile Brain/Body Imaging Laboratories
162   (BeMoBIL) with one of the experimental rooms providing a space of 160 m^2. The size of the virtual space
163   was 9 x 5 meters with a room size of 4.5 x 5 meters for the first room and a room size of 4.5 x 5 meters for
164   the second room. Participants performed a forewarned (S1-S2) *Go/NoGo* paradigm (pseudo-randomized
165   50/50) in the virtual reality environment that required them to walk from one room to a second room. Doors
166   of different width ranging from unpassable (20 cm, *Narrow*) to passable (100 cm, *Mid*) to easily passible
167   (1500 cm, *Wide*) manipulated the transition affordance between rooms. The experiment consisted of a 3 x 2
168   repeated measures design including the factors door width (*Narrow, Mid, Wide*; pseudo-randomized) and
169   movement instruction (*Go, NoGo*). A total of 240 trials per participant was collected with 40 trials for each
170   of the factor levels. One trial consisted of a participant starting in a dark environment on a predefined starting
171   square (see Figure 1). The "lights" would go on after a random inter-trial-interval (mean = 3 s, $\sigma = 1$ s), and
172   participants faced a room with a closed door. They were instructed to wait (mean = 6 s, $\sigma = 1$ s) for a color
173   change of the door with a change to green indicating a *Go* trial and a change to red indicating a *NoGo* trial.
174   In case of a green door, the participant walked towards the door, which would slide aside. Upon entering the
175   subsequent space, participants were instructed to find and virtually touch a red rotating circle by using the
176   controller. The circle would inform the participant to have earned another 0.1€ to their basic reimbursement
177   of 10 Euro per hour. After each trial, participants had to give an emotional rating for the environment
178   irrespective of whether they transitioned through the door (*Go* condition) or whether they remained in the
179   same room (*NoGo* condition) without transition. To this end, participants were instructed to go back to the
180   starting square, and fill in a virtual Self-Assessment Manikin (SAM) questionnaire, using a laser pointer
181   from the controller, and to subsequently pulling the response button located at the pointer finger to turn the
182   "lights off". The lights would go back on automatically to start the next trial.

183

184   In *Go*-trials, participants were instructed to walk towards the door and into the second room even in case the
185   door was too narrow to pass. This was done to control for motor execution in the *Go*-condition and to allow
186   movement towards the goal irrespective of the affordance (passable vs. unpassable). Upon touching the
187   surrounding walls, the walls would turn red and inform the participants they have failed to pass, and thus must
188   return to the start square, fill in the virtual SAM and start the next trial by pulling the trigger. Participants
189   would quickly notice that the narrow door (20 cm) was impossible to pass without producing the warning
190   feedback that they have failed to pass. All participants had a training phase to get accustomed to the VR
191   environment and the different conditions. The experimenter observed the participants from a control room,

192   separated from the experimental space, using two cameras and a mirrored display of the virtual environment
193   to reduce interactions to a minimum during the experiments.

194

195   Figure 1 about here

196

197   **Subjective and Behavioral data.** To investigate the subjective experience of the transitions, we introduced
198   the participants with a virtual Self-Assessment Manikin (SAM) questionnaire after each trial. The SAM is a
199   pictorial assessment of pleasure, arousal and dominance on a 5-point Likert scale (43). The manikin display
200   ranges from smiling to frowning (*pleasure*), from a dot in the stomach to an explosion (*arousal*) and from
201   being very small to very big (*dominance*). Participants were asked to self-assess their current state after each
202   trial. Furthermore, we measured the reaction time from the onset of the *Go*-stimulus (door color change) to
203   reaching the opening-threshold itself, to assess the behavior. The data was analyzed using ANOVA with the
204   width of the doors as repeated measures factor. In case of violation of normality and homogeneity, corrected
205   p-values are reported. For post-hoc analysis, the data was contrasted using Tukey HSD.

206

207   **EEG Recording and data analysis.** To investigate the impact of transitional affordances on human
208   cognition and brain dynamics, we used a MoBI approach (32–34, 44) recording human brain dynamics in
209   participants actively transitioning through virtual rooms. All data streams were recorded and synchronized
210   using LabStreamingLayer (LSL; Kothe, 2014). Participants wore a backpack, which held a high-performance
211   gaming computer to render the VR environment (Zotac, PC Partner Limited, Hong Kong, China) attached to
212   two batteries and an EEG amplifier system. We combined a Windows Mixed Reality (WMR; 2.89", 2880 x
213   1440 resolution, update rate at 90 Hz, 100 degree field of view with a weight of 440 grams, linked to the
214   Zotac computer through HDMI) headset and one controller by ACER to display and interact with the virtual
215   environment based on Unity (see Figure 2). Events for recordings of performance and physiological data
216   were triggered by the position of the participant in the tracking space or by the respective response buttons of
217   the remote control. Specific events, such as touching the wall, all button presses, transitioning through the
218   door, answering the questionnaire and all cases of "lights on" (and off), were synchronized with the recorded
219   brain activity and the presented VR environment through LSL.

220

221   Figure 2 about here

222

223   EEG data was acquired continuously with a 64 channels EEG system (eegoSports, ANT Neuro, Enschede,
224   Netherlands), sampled with 500 Hz. Impedances were kept below 10 kOhm. The computational delay
225   generated by the interaction of ANT Neuro software, Windows Mixed Reality and Unity was measured to be
226   20 ms (σ = 4), which was taken into account during the analysis by subtracting the average delay from each
227   event latency. With a jitter of 4 ms, we considered the delay to have little to no impact on the ERPs. Offline
228   analysis were conducted using MATLAB (MathWorks, Natick, MA, USA) and the EEGLAB toolbox (46).
229   The raw data were band-pass filtered between 1 Hz and 100 Hz and down-sampled to 250 Hz. Channels with
230   more than five standard deviations from the joint probability of the recorded electrodes were removed and
231   subsequently interpolated. The datasets were then re-referenced to an average reference and adaptive mixture
232   independent component analysis (AMICA; Palmer et al., 2011) was computed on the remaining rank of the
233   data using one model with online artifact rejection in five iterations. The resultant ICA spheres and weights
234   matrices were transferred to the raw dataset that was preprocessed using the identical preprocessing parameters
235   like the ICA dataset, except the filtering, which used a band-pass filter from 0.2 Hz to 40 Hz. Subsequently,
236   independent components (ICs) reflecting eye movements (blinks and horizontal movements) were removed
237   manually based on their topography, their spectrum, and their temporal characteristics.

6

238

239 Epochs were created time-locked to the onset of the room including the closed door ("Lights on") from -500
240 ms before to 1500 ms after stimulus onset for *Narrow*, *Mid* and *Wide* door trials. Similarly, another set of
241 epochs were time-locked to the second stimulus *Go/NoGo* from -500 ms before to 1000 ms after onset of the
242 stimulus for *Narrow*, *Mid* and *Wide* door trials. On average, 15% (σ = 10.8) of all epochs were automatically
243 rejected when they deviated more than five standard deviations from the joint probability and distribution of
244 the activity of all recorded electrodes.

245

246 The visual-evoked potentials as well as MRCPs were analyzed at central midline electrodes (*Fz, FCz, Cz, Pz,*
247 *POz* and *Oz*) covering all relevant locations including the visual and the motor cortex as reported in previous
248 studies (39, 48). As stimuli were distributed across the complete visual field and participants walked through
249 the virtual spaces, we did not expect any lateralization of ERPs. All channels were analyzed, however only
250 three channels (*FCz, Pz* and *Oz*) are reported and discussed in-text according to reported results by Bozzacchi
251 et al. (39). The analysis results of all six channels can be found in the supplementary material. For peak analysis
252 of the P1-N1 complex, the grand average peaks were estimated and individual peaks were defined as the
253 maximum positive and negative peak in the time window surrounding the grand average P1 and N1 peak (+/-
254 10 ms from peak), respectively. An automatic peak detection algorithm detected the peaks in the averaged
255 epochs for each participant. Multiple peaks were detected and systematically weighed depending on the
256 magnitude, the distance to the grand-average peak latency that was determined by visual inspection of grand
257 average ERP, and the polarity (please see algorithm in the supplementary material). For anterior N1 and
258 posterior P1, by visual inspection of the grand average ERPs, the grand-average latency was estimated to be
259 140 ms with a search window for individual peaks ranging from 50 – 200 ms. For the anterior P1 and posterior
260 N1 the grand-average peak latency was estimated to 215 ms with a search window for individual peaks ranging
261 from 140 – 290 ms.

262

263 Mean peak amplitudes were analyzed using a 3 x 3 repeated measures ANOVA using the door width (*Narrow,*
264 *Mid, Wide*) and electrode as repeated measures. The results descriptions focus on the visual evoked P1
265 component at posterior electrodes (*Pz, POz* and *Oz*) and the N1 component at frontal leads (*Fz, FCz* and *Cz*)
266 based on separate ANOVAs. For the N2 and P2 component at posterior electrodes (*Pz, POz* and *Oz*) and frontal
267 leads (*Fz, FCz* and *Cz*), separate ANOVAs were computed in the time-range of 140 – 290 ms. For the later
268 motor related potentials, an ANOVA was computed for the mean amplitude in the time-range from 600 to 800
269 ms. The data was analyzed using a 2 x 3 x 6 factorial repeated measures ANOVA with the factors imperative
270 stimulus (*Go* and *NoGo*), door width (*Narrow, Mid* and *Wide*), time window (600-700 ms, 700-800 ms) and
271 electrode location (*Fz, FCz, Cz, Pz, POz* and *Oz*). For post-hoc analysis, the data was contrasted using Tukey
272 HSD. In case of violations of the sphericity, corrected p-values are reported. All ANOVA were computed as
273 linear mixed models and all p-values for Tukey HSD contrasts were adjusted using Bonferroni method to
274 account for "within" study design.

275

276 **RESULTS**

277

278 **Subjective and Behavioral results**

279

280 **SAM Ratings.** A 2 x 3 factorial repeated measures ANOVA with the factors imperative stimulus (*Go* and
281 *NoGo*) and door width (*Narrow, Mid* and *Wide*) for each emotional dimension of the SAM questionnaire
282 revealed differences in the main effect for width: *Arousal* ($F_{2,4326} = 95.12, p < 0.0001$), *Dominance* ($F_{2,4326} =$
283 *46.42, p < 0.0001*) and *Valence* ($F_{2,4326} = 188.65, p < 0.0001$). For the imperative stimulus, differences were

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284 found for *Arousal* ($F_{2, 4326} = 443.54, p < 0.0001$), *Dominance* ($F_{2, 4326} = 435.49, p < 0.0001$), and *Valence* ($F_{2, 4326} = 446.20, p < 0.0001$). Interaction effects revealed significant difference for all interactions (*all p < 0.0001*). Post-hoc contrasts using Tukey HSD (Figure 3) showed no significant differences for *NoGo* in *Arousal*, however significant differences were identified for *Go* between *Narrow-Mid* ($p < 0.0001$), *Narrow-Wide* ($p < 0.0001$) and *Mid-Wide* ($p < 0.0001$). For *NoGo* in *Dominance* no significant differences were revealed between *Narrow-Mid* ($p = 0.1376$), as opposed to *Narrow-Wide* ($p < 0.0001$) and *Mid-Wide* ($p = 0.0334$), whereas for *Go* no significant differences were found for *Mid-Wide* ($p = 0.2199$), as opposed to *Narrow-Mid* ($p < 0.0001$) and *Narrow-Wide* ($p < 0.0001$). For *Valence*, significant difference were revealed for all contrasts for *Go, Narrow-Mid* ($p < 0.0001$), *Narrow-Wide* ($p < 0.0001$) and *Mid-Wide* ($p < 0.0001$). However, for *NoGo* significant differences were only identified for *Narrow-Mid* ($p < 0.0001$) and *Narrow-Wide* ($p < 0.0001$).

296 Figure 3 about here

298 **Performance.** To investigate the time it took participants from the *Go*-stimulus to passing the door, a one-way ANOVA with repeated measures for different door widths was computed revealing a significant difference for the factor door widths ($F_{2,36} = 6.404, p = 0.0042$; Figure 4). Post-hoc comparison (Tukey test) showed no significant differences in behavior when approaching the *Narrow* or *Mid* wide doors ($p > 0.1$), a tendency to be slower when approaching *Mid* as compared to *Wide* doors ($p < 0.1$), and a significant difference between approaching *Narrow* as compared to *Wide* door ($p < 0.001$) with significantly faster approach times for the *Wide* door condition.

306 Figure 4 about here

308 **EEG - Early event-related potentials**

310 **Posterior P1.** With onset of the lights that allowed participants to see the room including the door ("Lights on"), the ERPs demonstrated a clear P1-N1 complex most pronounced over the occipital midline electrode with a first positive component around 100 ms, followed by a negative peak around 200 ms (Figure 5.1 and see Figure 5.2 in supplementary materials for full six channels). At the frontal midline electrode, this pattern was inversed and a negative component around 100 ms was followed by a positive peak observed around 200 ms. The 3 x 3 repeated measures ANOVA on P1 amplitudes for posterior electrodes revealed significant main effects for both the factors widths ($F_{2,108} = 8.163, p = 0.005$) and channel ($F_{2,36} = 15.868, p < 0.0001$). The interaction effect was not significant ($F_{4,108} = 1.669, p = 0.1624$). Post-hoc comparisons using Tukey HSD test revealed significant differences in peak amplitudes at channel *Oz* between *Narrow* and *Mid* wide transitions ($p = 0.0021$) and between *Narrow* and *Wide* transitions ($p = 0.0065$) but no differences between *Mid* and *Wide* transitions ($p = 1$). Tukey contrasts yielded no significant differences between electrodes, with differences in P1 amplitudes at *POz* comparing *Narrow* and *Wide* transitions ($p = 0.028$).

323 Figure 5.1 about here

325 **Posterior N1.** The 3 x 3 repeated measure ANOVA on N1 amplitudes for posterior electrodes revealed a significant main effect for the factor door widths ($F_{2,108} = 4.348, p = 0.0153$) and no significant impact for the factor channels ($F_{2,36} = 0.0893, p = 0.9147$), nor the interaction ($F_{4,108} = 1.304, p = 0.2731$). Post-hoc Tukey HSD contrasts revealed no significant differences for *Pz* and *POz*. However, similar to posterior P1, significant

329 differences at *Oz* for the comparison of Narrow and Mid wide transitions ($p = 0.0113$) and for the comparison
330 of *Narrow* and *Wide* transitions ($p = 0.0372$) were found (Figure 6).
331

332 Figure 6 about here

333

334 **Anterior P1.** An inverse pattern was observed for amplitudes over anterior leads with a main effect of door
335 widths that differed depending on the affordances ($F_{2,108} = 11.071, p < 0.0001$). The main effect of channels
336 also reached significance ($F_{2,36} = 5.3627, p = 0.0092$). Tukey HSD contrasts revealed significant differences
337 only between *Narrow* and *Wide* transitions for *FCz* ($p = 0.0071$) and *Cz* ($p = 0.0214$), and a tendency at *Fz* ($p
338 = 0.0717$). The interaction was not significant.

339

340 **Anterior N1.** The 3 x 3 repeated measures ANOVA on N1 amplitudes for anterior electrodes revealed no
341 significant main effect for the factor door widths ($F_{2,108} = 1.823, p = 0.1663$). In contrast, the main effect of
342 channels reached significance ($F_{2,108} = 8.109, p = 0.0012$). The interaction did not reach significance.
343

344 **EEG - Motor-related processes.** After onset of the imperative stimulus a positive peak at anterior leads and
345 a negative peak at posterior leads were observed. For sake of brevity, this potential complex is referred to as
346 early post imperative complex (EPIC). Reflecting similar cortical polarity as the P1-N1 complex, the EPIC
347 was analyzed in a similar way, separating anterior leads (*Fz, FCz* and *Cz*) from posterior leads (*Pz, POz* and
348 *Oz*), and detecting single peaks in individual averages.

349

350 **Anterior EPIC.** A 2 x 3 x 3 repeated measures ANOVA revealed significant difference in the main effect for
351 widths ($F_{2,270} = 4.21, p = 0.0157$), imperative stimulus ($F_{1,270} = 23.66, p < 0.0001$), and for channel ($F_{2,36} =
352 6.70, p = 0.0033$). No interaction effect was observed. The Bonferroni-corrected post-hoc Tukey HSD revealed
353 no significant differences between the transition widths for different channels or imperative stimuli.

354

355 **Posterior EPIC.** The identical ANOVA for the posterior potentials of the EPIC revealed no significant impact
356 of transition widths ($F_{2,270} = 2.001, p = 0.1371$) nor imperative stimulus ($F_{1,270} = 2.30, p = 0.1298$). Significant
357 differences in EPIC amplitude were observed for the factor channel ($F_{2,36} = 5.45, p = 0.0085$). Since
358 topographical differences were not in the focus of this study, no further post-hoc contrasts were computed. No
359 interaction was significant.

360

361 **PINV.** In the preparation time prior to the onset of the door color change, indicating either to walk through the
362 door or to remain in the same room, we observed no systematic negative going waveform as reported in
363 previous studies (37, 49). However, after onset of the color change, a pronounced positivity, followed by a
364 long-lasting negative waveform over fronto-central locations was observed in the ERP (Figure 7.1 and see
365 Figure 7.2 in supplementary material for full six channels). This negative waveform resembled a post-
366 imperative negative variation (PINV) as described in previous studies (40, 42, 50). The PINV component was
367 observed 600-800 ms post imperative stimulus (color change of the door) and varied as a function of the
368 affordance of the environment (door width). A global 2 x 3 x 6 factorial repeated measures ANOVA was
369 computed to analyze the MRCPs using *Go/NoGo*, *Width* and *Electrode* as repeated measures. The ANOVA
370 revealed significant differences in the main effect for *Go/NoGo* ($F_{1,540} = 19.54, p < 0.0001$) and for *Electrode*
371 ($F_{5,90} = 16.69, p < 0.0001$). Significant differences were reported for the interaction effect of
372 *Go/NoGo:Channel* ($F_{5,540} = 5.25, p = 0.0001$) and for *Width:Channel* ($F_{10,540} = 2.61, p = 0.0042$).

373

374 Figure 7.1 about here

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375

376 Post-hoc contrasts, using Tukey HSD, revealed significant differences only for the *Go* condition, as opposed
377 to the *NoGo* condition (Figure 8.1). Similar to the early evoked potentials, differences were only observed in
378 frontal and occipital sites and between *Narrow* and *Mid* door widths over *FCz* ($p = 0.0059$) and *Oz* ($p <$
379 0.0001), as well as between *Narrow* and *Wide* doors at *FCz* ($p = 0.0323$) and *Oz* ($p < 0.0001$). No differences
380 were observed between the *Mid* and *Wide* doors (Figure 8.2 in the supplementary material for all six channels).

381

382 Figure 8.1 about here

383

384 **DISCUSSION**
385 The main goal of this study was to assess whether brain activity is altered depending on the affordances offered
386 by the environment. If such an account holds true, affordances should systematically modulate behavior and
387 brain activity. Specifically, we hypothesized that perceptual processes co-vary with the environmental
388 affordances leading to behavioral changes and that motor-related cortical potentials would vary as a function
389 of affordances.

390

391 **SAM and approach time.** The results of the questionnaire should be interpreted with caution due to the
392 amount of trials per participant, the varying sensitivity to VR and the different skills of subjective emotional
393 evaluation. The analysis of subjective ratings revealed significant differences between different *Go* trials, but
394 no differences for *NoGo* trials regarding *Arousal* ratings. When given a *NoGo*, participants responded
395 perhaps arbitrarily, feeling unburdened, causing no significant difference among the three door widths.
396 Notably, in cases of *NoGo*, all participants perceived a similar scene standing in front of a red (*NoGo*) door,
397 turning around and answering the virtual SAM. The only variable in this sense was the door width, while the
398 only difference from *NoGo* to *Go*, was the action itself. The subjective ratings highlight the influence of
399 action on evaluating the environment. If space was to be investigated statically (comparable to the case of
400 *NoGo*), we would not have been able to detect any differences for *Arousal* for varying door sizes, potentially
401 due to the absence of action. Varying door sizes for *Go* trials yielded differences between passable and
402 impassable conditions for *Dominance,* reporting that *Narrow* door was more dominating than *Mid* and *Wide*.
403 However, for *Valence* we observed an increasing score the narrower the door, which is the opposite behavior
404 observed for *Arousal*. These results indicate that being able to pass easily is more exciting, less pleasant and
405 less dominating. This effect is perhaps grounded in the monetary reward participants could receive only
406 when successfully passing through to the next room. Most importantly, however, the findings indicate that
407 subjective reports differ significantly dependent on whether participants actively moved through the rooms
408 or not implying an impact of action affective ratings of an environment. We speculate whether the
409 omnipresent significant differences may be rooted in uniqueness of emotional states that varies from
410 participant to participant. Such an account of emotional ratings is currently gaining credibility (51, 52).

411

412 The time it took participants to reach the door after onset of the imperative color change varied according to
413 the environmental affordance. Participants approached the *Wide* door significantly faster than *Mid* and *Narrow*
414 doors, while there was no significant difference for *Mid* and *Narrow* transitions. While the *Wide* door clearly
415 offered a passage without greater computational demands regarding the motor plan and execution, the *Mid*
416 door width, being ambiguously wide/narrow, might have triggered motor processes simulating a transition to
417 estimate whether the door was passable or not. In this sense, the *Mid* and *Narrow* doors, causing uncertainty,
418 might have delayed approach times due to increasing processing demands. Admittedly, results derived from
419 the approach time are limited, partly due to the caused fatigue of operating a physically demanding task for a
420 relatively long time period, and partly due to the subjective manner and interpretation of passing a door that is

421 seemingly impossible to pass. This caused participants to develop different approach strategies which caused
422 different delays. However, the fact that participants, in general, spent significantly more time approaching the
423 *Narrow* doors compared to *Wide* doors provides sufficient guidance for the analyses of cortical measures
424 associated with these differences.

425
426 **Cortical measures**
427
428 **Early evoked potentials.** As an initial insight into the association of affordances and cortical potentials, we
429 analyzed the early visual-evoked potentials. We expected to find differences in the stimulus-locked ERP at
430 occipital channels reflecting differences in sensory processing of affordance-related aspects of the transition.
431 Importantly, based on the assumption of fast sensorimotor active inferences that should be reflected in
432 action-directed stimulus processing influencing not only sensory but also motor-related activity, we
433 hypothesized to also find differences in the ERP over motor areas in the same time window as sensory
434 potentials (i.e., between 50 and 200 ms). As illustrated in the analysis, we found significant differences in
435 amplitudes of the visually evoked P1 component over the central occipital electrode dependent on the
436 affordance of the transition. In addition, in line with our hypothesis, we also found a difference over fronto-
437 central leads starting around 50 ms and lasting until 200 ms after onset of the doors display. Taken together,
438 no significant differences in peak amplitudes were found when comparing the passable *Mid* and *Wide* doors
439 while peak amplitude associated with both door widths significantly differed from impassable *Narrow* doors.
440 Note that the visual scene of the three doors are comparable as they contained same physical contrasts, and
441 that participants at this point did not know whether to go or not as they were merely introduced to the setting
442 they might have to pass in a couple of seconds. As no significant differences were found for *NoGo*, it
443 functions as a matching control, and thus we can interpret the differences in *Go* as affordance manipulation.
444 These results indicate that impassable doors with poor affordances produce significantly different early
445 evoked potentials compared to passable doors particularly at fronto-central and occipital sites. Thus,
446 environmental affordances, in terms of being able to program bodily trajectory to transit spaces, yield a
447 significant measurable effect on early cortical potentials best pronounced over frontal and occipital sites at
448 approximately 200ms after first view of the environment.

449
450 Considering the affordance-specific pattern observed for the early P1-N1-complex, prior studies have shown
451 this visual evoked potential complex to reflect attentional processes associated with spatial or feature-based
452 aspects of stimuli (53–57). Attended stimuli elicit larger P1-N1 amplitudes than unattended ones. Based on
453 these findings, the results suggest that passable transitions were associated with increased attentional
454 processing. Approaching the affordance-specific pattern of P1-N1-complex using active inferences (58), the
455 difference confirms the assumption that perceptual processes co-vary with environmental affordances. In this
456 sense, the amplitude difference might be credited to the process of active inference of whether the body can
457 actively move and transit at all. This implies that visual attention is also guided by action-related properties of
458 the environment and support the concept of fast, lower sensorimotor active inferences, explained as
459 hierarchical and dynamic model of the world. Similar to HAC (31) and active inference (30, 59), these findings
460 are in line with parallel cortical processes integrating sensory information to specify currently available
461 affordances. Similarly, this means that, how one might act upon the environment is an ongoing process of
462 affordances, taking place as early as perceptual processes, and which situates actions in an intimate position
463 with perception. Such early processes are deeply involved in the impression of the environment for an agent
464 pointing towards the importance of movement in cognition, and of how an agent enacts the world. Given
465 affordances are processed at such an early stage, we speculate whether the impression of an environment

466 compose the immediate experience of the environment in a particular setting. Such an immediate experience
467 fits with the term *atmospheres* as defined by Zumthor (60) "I enter a building, see a room, and – in a fraction
468 of a second – have this feeling about it", and thus relating the instantaneous emerging experience of space to
469 affordances and action in general.
470

471 **Motor-related potentials.** Although the ERP plots indicate an affordance-trend of the EPIC, statistical tests
472 revealed no significant differences. However, *Narrow* door width elicited the greatest amplitude, both in case
473 of anterior positivity and posterior negativity. In line with prediction errors and affordances, the increased
474 amplitude associated with *Narrow* transitions can be interpret as a reflection of the body simply not fitting,
475 and yet forced to interact with the transition. Recall that prior to the imperative stimulus, participants have
476 been standing for 6 s ($\sigma = 1$ s). The EPIC may have an influence on the PINV. The nature of the PINV
477 component is not as well investigated as other ERP components, limiting the reliability of an interpretation
478 based on only a few studies that treat the component as modality-unspecific, and rather "*consider the PINV*
479 *as an electrocortical correlate of a cognitive state*" (61). Since the study by Gauthier and Gottesmann (62)
480 the PINV, similar to affordances, has been hypothesized to act as a marker of change in psychophysiological
481 state. Ever since, the PINV has been used to investigate depression, schizophrenia, learned helplessness and
482 loss of control (40–42, 63, 64). Results show depressive and schizophrenic participants to exhibit an
483 increased PINV that is explained as increased vulnerability for loss of control, as well as increased
484 anticipation for future affective events (40, 42, 50). If an increased PINV reflects increased vulnerability for
485 future events, as we observed for impassable doors, then the component, constituted by continuous motor
486 potential activity, sheds new light on affordances as an intrinsic affective property of action itself. Casement
487 and colleagues (42) even suggested the PINV to depend on lack of control as the state of having no
488 influence; depriving the potential to act. This could explain the difference in the *Narrow* condition, as
489 participants were instructed to attempt to pass at all times until failure leading to a sense of loss of control.
490 Only in cases of *Go* did we observe a difference in the PINV component, which varied similar to the P1-N1-
491 complex. Amplitudes of the component for *Narrow* doors were significantly different from *Mid* and *Wide*
492 doors, while the passable conditions did not differ from one another. Further, there were no significant
493 differences in the PINV component in cases of *NoGo*, emphasizing the importance of the motor execution
494 itself to evoke the PINV component. These results point towards the PINV component as an expression of
495 willingness to execute an act restricted beyond ones' own control, i.e. a designed environment. Thus, the PINV
496 might serve as an excellent marker for affordances.

497 The presented results of the PINV are consistent with the observed increase in activity over fronto-central sites
498 by Bozzacchi et al. (39). Bozzacchi and colleagues concluded that the meaning of the action and awareness of
499 being able to act – affordances – affect action preparation, which is here understood as the motor-related
500 potential prior to movement onset. We argue that the PINV component might reflect a willingness, or even
501 intentional, aspect of affordances. This would mean that the PINV is not modulated by the perception (that the
502 door is a different visual information), but reveals something about the intention of movement – which we
503 translate to affordances. For this reason, we find significant differences in cases of *Go*, but not in *NoGo*, and
504 further for passable compared to impassable. In light of HAC (31), a potential explanation for the absence of
505 differences in the *NoGo* trials, is related to the immediate action selection, which in all cases (*Narrow, Mid*
506 and *Wide*) is a simple turn to answer the questionnaire, and thus present the participant with identical
507 affordances. When instead given a *Go*, cortical processes require an action selection related to the anticipated
508 motor trajectory, which differs according to the affordances of the door width. Regarding the temporal aspect
509 of transitioning to the next room, HAC suggests the higher levels bias the lower level competitions, which
510 operate at the level of action itself, through a cascade of expected next affordances. The lower levels have a

12

511 continuous competition of how to satisfy the higher expectations. Action selection, executed while unfolding
512 the planned movements in a continuous manner, depend on the expectation of next affordances. Taken
513 together, the post-hoc analyses revealed differences grouped for passable as compared to impassable doors
514 throughout all channels, except for *Pz*. We do not observe any differences between *Mid-Wide*, but find
515 significant differences between *Narrow-Mid* and *Narrow-Wide*. The greatest differences were found over
516 fronto-central and occipital sites. Similar to the early evoked potentials, these results indicate that
517 environmental affordances impact neural activity prior to action depending on whether one has to act or not.
518
519 Notably, regarding architectural experience, since the PINV component was only expressed in the *Go*
520 condition (forced interaction with the environment), these findings support the importance of movement for
521 architectural experience, in a sense that action or even only the perception of action possibilities alters brain
522 activity. Visually guiding and propelling the body in space greatly influences the continuous emerging of
523 affordances, which in turn affect the human experience. We found differences in fronto-central and occipital
524 areas, prior to movement through space with the post-imperative negative going waveform most pronounced
525 over *FCz* indicated an involvement of the supplementary motor area (SMA) as reported by Bozzacchi et al.
526 (39). Interestingly, earlier studies showed involvement of SMA in visually guided actions (65), which is the
527 essence of active inferences. The PINV can be generated independently from the re-afferent signal, which is,
528 in terms of active inference, understood as ascending (bottom-up) proprioceptive prediction-errors (66). This
529 suggests the PINV component might reflect descending (top-down) predictions, rendering SMA as an essential
530 area of action-perception loop, and thus crucial for processing continuous affordances. This account might
531 resolve the finding of fronto-central differences in *Go* trials only. The SMA is anatomically bridging the frontal
532 cortex with motor cortex – perhaps also functionally as argued by Adams et al. (66), as this anatomical nature
533 fits with the proposed hierarchical characteristics of forward and backward projections in active inferences.
534

CONCLUSION

535
536 The present study provides strong evidence for affordances to be processed as early as perceptual processes,
537 linking action and perception in a similar manner to active inference. The results points towards a conception
538 of the brain that seems to deal with "how can I act" while in parallel processes referring to "what do I perceive"
539 take place. The results thus support the assumption that perception of the environment is influenced by
540 affordances and action itself – hence, affordances and action can influence experience of an environment. Due
541 to the importance of affordances and action for brain dynamics, this further emphasizes and qualifies the
542 general idea of enactivism as a holistic approach to investigate cognition. We do not claim that architectural
543 affordances are directly represented as a specific event-related potential component; however, we provide
544 evidence for an action-perception account of cognition, which systematically differentiates according to the
545 definition of affordances.

546 The nature of the analyzed brain activity emphasizes the importance of the intentional movement. Our results
547 are consistent with the concept of continuous affordances as explained by active inferences. In terms of
548 architecture, the results shed light on why transitions have been a constant throughout the history of
549 architecture, perhaps especially in religious and other buildings that actively aimed at producing a certain
550 experience of presence. Thus, the fact that we are predictive beings, in terms of architecture, means we should
551 take into consideration how bodily movement alters perception. By altering perception, this would ultimately
552 lead spaces to have a potentially physiological impact on users. Much remains to be uncovered in architectural
553 cognition. Moving and transitioning in space, is continuously constructing a prediction of a world, a world that
554 we perceive dependent on our action potentials, which informs brain, body and mind. Transitions in
555 architecture form a holistic entity of architectural experience expressed as the unfolding of motor planning,

556 spatial sequences and predictive mechanisms. Similar to Zeki (67), we speculate whether the ancient interest
557 in tailoring transitions and sequences may have developed as a trial-and-error of active-narration, perhaps
558 rooted in ancient knowledge of the predictive mind and action-perception parallel processing nature of the
559 human being.

560

565

566 **COMPETING INTERESTS.** The authors declare no competing interests.
567
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Figure legends

Figure 1

Fig. 1 – **(A)** Participants were instructed to stand in the start-square. A black sphere would restrict their vision to pure black for 3 seconds, σ = 1. The moment the black sphere disappears, participants perceive the door they have to pass. They wait for the imperative stimulus, either a green door (Go) or a red door (NoGo), for 6 seconds, σ = 1. In case of Go, participants were instructed to pass the opening, virtually touch the red circle, which in turn would release a monetary bonus, return to start square and answer the virtual SAM questionnaire. In case of NoGo, participants were instructed to turn around and answer the virtual SAM. **(B)** The three different doors were dimensioned as following *Narrow* 0.2 meter, *Mid* 1 meter and *Wide* 1.5 meters. Note the color code for each door as they are used throughout the paper. **(C)** The diagrammatic timeline depicts a the sequences of events for a single trial in conceptual manner.

Figure 2

Fig. 2 – Mobile Brain/Body Imaging setup. The participants wore a backpack, carrying a high-performance gaming computer (Zotac, Cyan color), powered by two batteries (Red color). An EEG amplifier (ANT eegoSports, Yellow color) was attached to the backpack and connected to the computer. The participants wore a VR head mounted display (Windows mixed reality) on top of a 64 channel cap. This setup allowed participants to freely move around while recording data.

Figure 3

Fig. 3 – Box plot of the SAM questionnaire results for the three different SAM scales (*arousal*, *dominance*, and *valence*) as a function of the door width (*Narrow*, *Mid*, *Wide*). The left column displays the pictorial representation of the SAM manikin for the highest value of each condition presented. The middle column displays the SAM ratings for the Go condition. The right column displays the SAM ratings for the NoGo-condition. Means are indicated by dashed line, while medians are solid line. Adjusted p values are reported.

Figure 4

Fig. 4 – Rain-cloud plot of approach times for each door width condition. Post-hoc comparisons using Tukey test are displayed with a dot < 0.1 and * < 0.05 and *** < 0.001. Means are indicated by dashed line, while medians are displayed as solid lines.

Figure 5.1

Fig. 5.1 – Three time-locked ERPs (*FCz, Pz* and *Oz*) at the onset of "Lights On" event. *Narrow* condition in yellow, *Mid* condition in blue and *Wide* condition in red. Two time windows are indicated with dashed-lines and grey transparent box. The first time window (50 – 200 ms) mark the anterior N1 and posterior P1, while the second window (140 – 290 ms) mark the anterior P1 and posterior N1. The components are marked with arrows.

Figure 6

Fig. 6 – **Posterior P1**. Rain-cloud plot of detected mean amplitude of positive peak in time-locked event "Lights on" in the time range of 50 to 200 ms for *Pz, POz* and *Oz*. Means are indicated by dashed line, while medians are solid line. Significance is calculated using Tukey HSD. We observed significant differences for *Oz* between *Narrow-Mid* ($p = 0.0021$) *and Narrow-Wide* ($p = 0.0065$), while for *POz* in *Narrow-Wide* revealed significant difference ($p = 0.028$), however no significant differences were observed in other electrodes and other contrasts. **Posterior N1.** Rain-cloud plot of detected mean amplitude of negative peak in time-locked event "Lights on" in the time range of 140 to 290 ms for *Pz, POz* and *Oz*. We observed significant differences only for *Oz* in *Narrow-Mid* ($p = 0.0113$) and *Narrow-Wide* ($p = 0.0372$). **Anterior N1.** Rain-cloud plot of detected mean amplitude of negative peak in time-locked event "Lights on" in the time range of 50 to 200 ms for *Fz, FCz* and *Cz* We observed no significant differences for any electrode. **Anterior P1.** Rain-cloud plot of detected mean amplitude of negative peak in time-locked event "Lights on" in the time range of 140 to 290 ms for *Fz, FCz* and *Cz* We observed significant differences in all electrodes in *Narrow-Wide*, with the exception of only a tendency in *Fz* ($p = 0.0717$), *FCz* ($p = 0.0071$) and *Cz* ($p = 0.0214$). **Double plot.** Frontal (dashed-line) and posterior (solid-line) time-locked ERPs (*Fz* and *Oz*) at the onset of "Lights On" event. *Narrow* condition in yellow, *Mid* condition in blue and *Wide* condition in red. Two time windows are indicated with dashed-lines and grey transparent box. The first time window (50 – 200 ms) mark the anterior N1 and posterior P1, while the second window (140 – 290 ms) mark the anterior P1 and posterior N1.

Figure 7.1

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847   Fig. 7 – Three time-locked ERPs (*FCz, Pz* and *Oz*) at the onset of Go/NoGo. *Narrow* condition in yellow, *Mid* condition in blue and
848   *Wide* condition in red. The time window, indicated with dashed-lines and grey transparent box, illustrates the selected time window
849   to analyze the MRCP by a global 2 x 3 x 6 factorial repeated measures ANOVA. Anterior and posterior PINV are marked with
850   arrows.
851

852   **Figure 8.1**
853   Fig. 8.1 – Rain-cloud plots of mean amplitude of negative development in time-locked event of Go/NoGo in the time range of 600 to
854   800 ms for *FCz, Pz* and *Oz*. Means are indicated by dashed line, while medians are solid line. The Tukey HSD contrast revealed
855   differences only in *FCz* and *Oz,* and between *Narrow-Mid* for *FCz* ($p = 0.0059$) and for *Oz* ($p < 0.0001$), and between *Narrow-Wide*
856   for *FCz* ($p = 0.0323$) and for *Oz* ($p < 0.0001$). No differences were observed for NoGo.
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Supplementary figure legends

Figure 5.2 – supplementary

Fig. 5.2 – ERP plots of "Lights On" stimulus for all six channels (*Fz, FCz, Cz, Pz, POz* and *Oz*). *Narrow* condition in yellow, *Mid* condition in blue and *Wide* condition in red. N1-P1-complex are marked with arrows.

Figure 7.2 - supplementary

Fig. 10 – ERP plots of the total six channels only for Go trials. ANOVA with repeated measures of time-locked ERP, where the increasing darkness behind the plots indicates the increasing level of significance. The repeated measures ANOVA revealed Fz ($F_{2,36}$ = 4.546, p = 0.0174), FCz ($F_{2,36}$ = 7.116, p = 0.0025), Cz ($F_{2,36}$ = 4.116, p = 0.0236), Pz ($F_{2,36}$ = 0.089, p = 0.915), POz ($F_{2,36}$ = 1.708, p = 0.196) and Oz ($F_{2,36}$ = 14.39, p < 0.0001). We observed no difference for NoGo – however, we observed a difference within frontocentral and occipital sites for Go trials.

Figure 8.2 – supplementary

Fig. 11 – Rain-cloud plot of the mean amplitude of selected six channels between 600 – 800 ms post imperative stimulus – PINV component. Means are indicated by dashed line, while medians are solid line. We compared (Tukey test) the *Width* within Go and NoGo conditions, and observed only significant differences for Go condition. We observed differences within frontocentral and occipital sites.

20

Figures

Figure 1:

A — 9 m / 29.52 ft; 5 m / 16.4 ft; 3 m / 9.84 ft; 3 ±1 s In the dark; 6 ±1 s Waiting; Go/NoGo; Self-Assessment manikin

B — Narrow 0.2 m; Mid 1 m; Wide 1.5 m

C — In the dark 3 s ±1; Lights on 6 s ±1; NoGo; Go; Coin; SAM; Restart
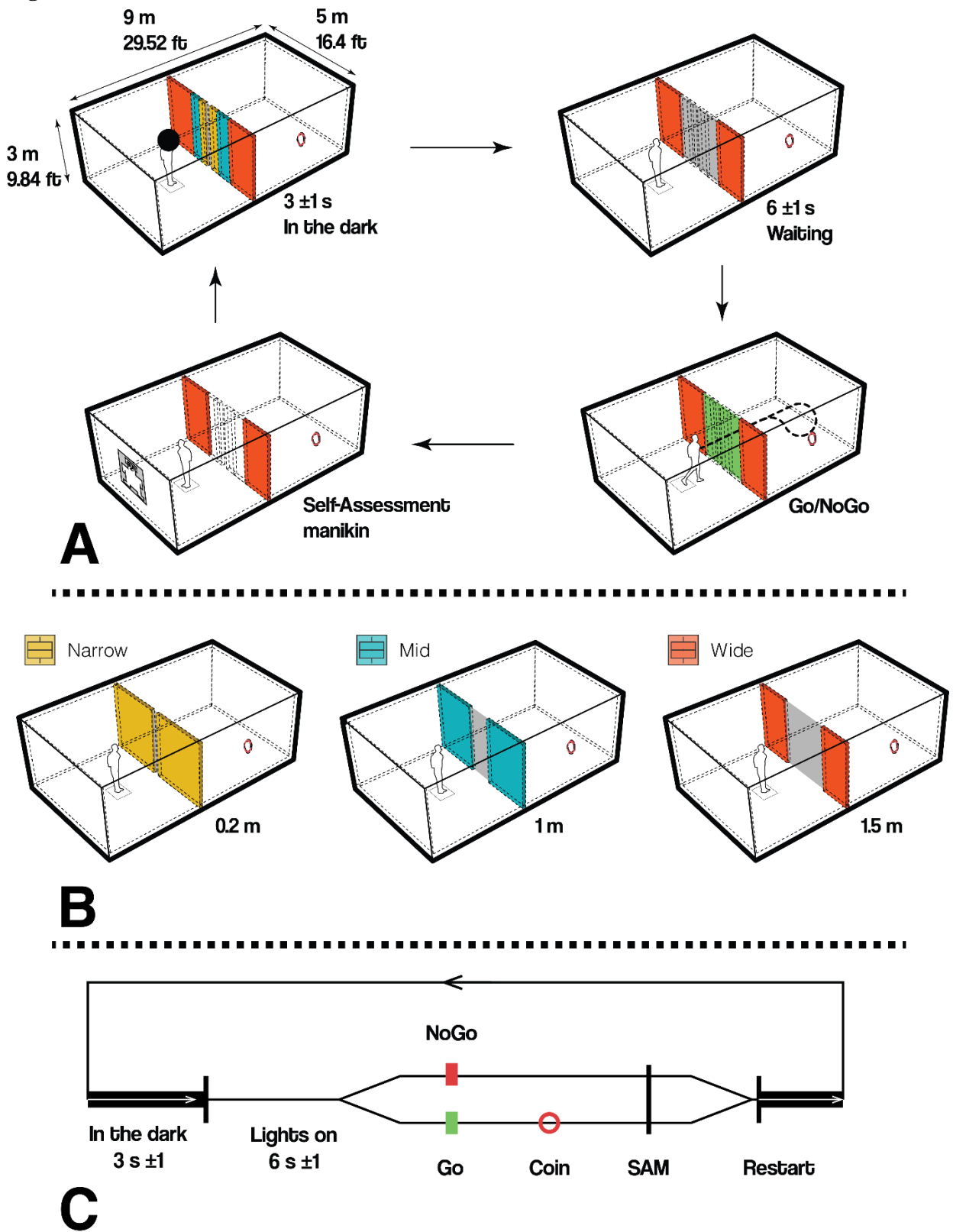
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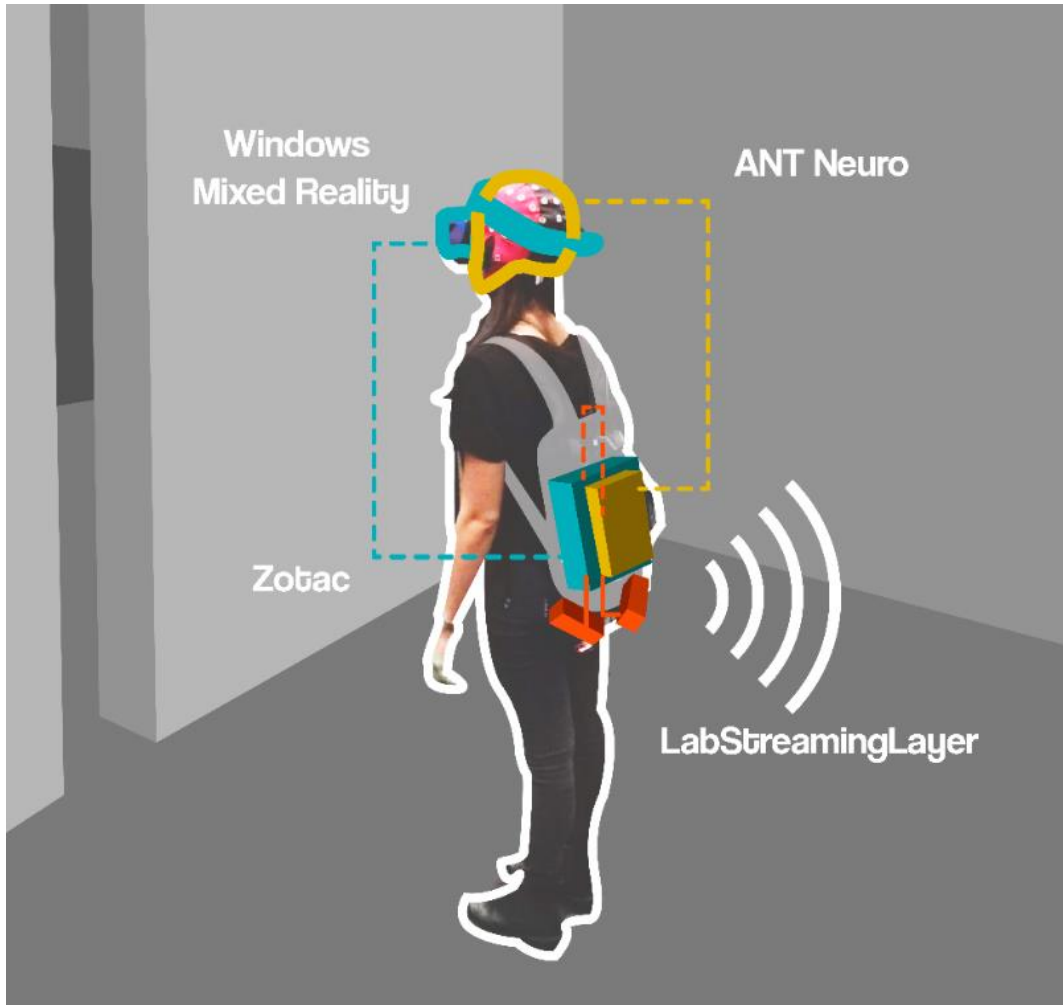
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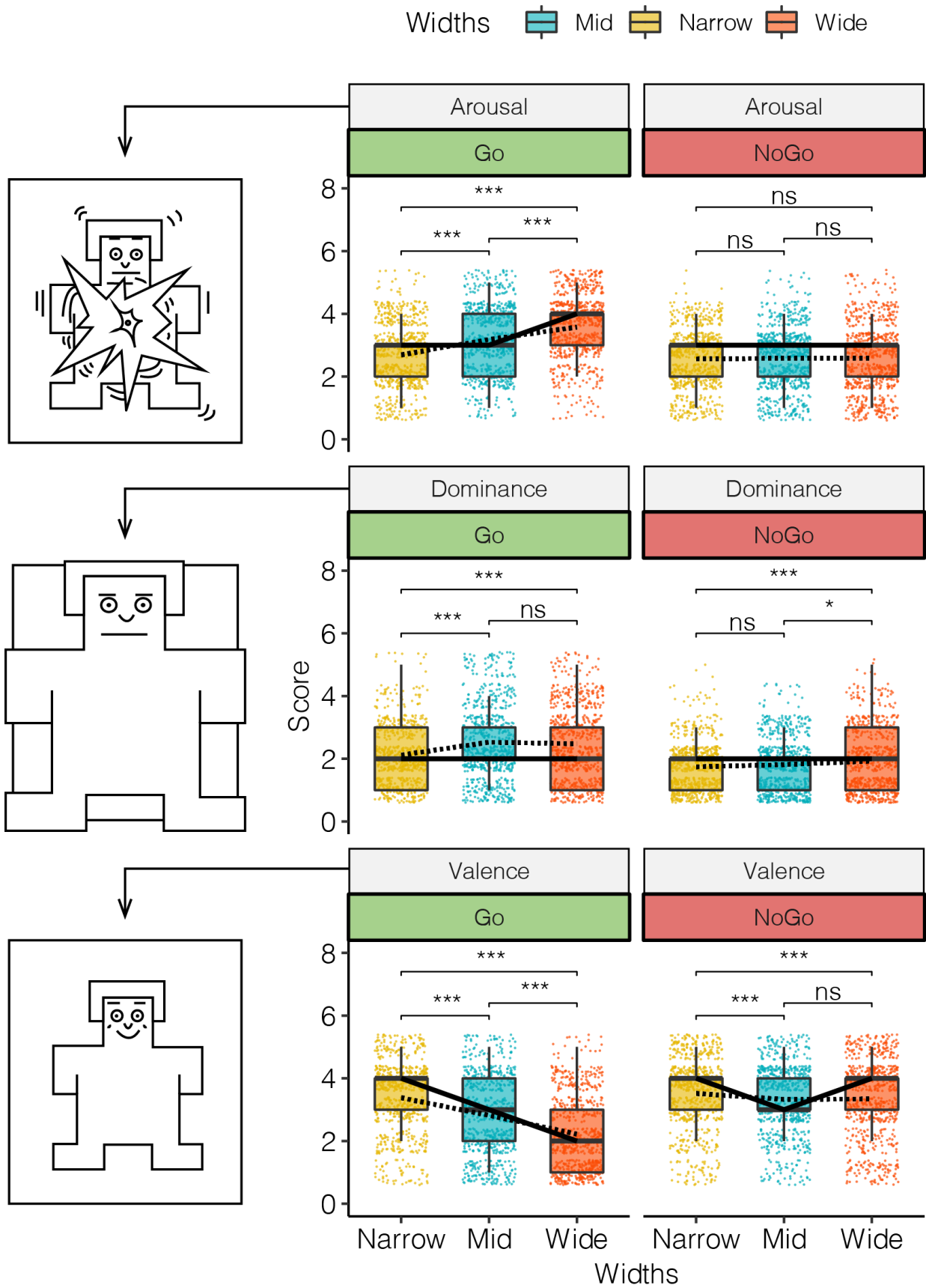
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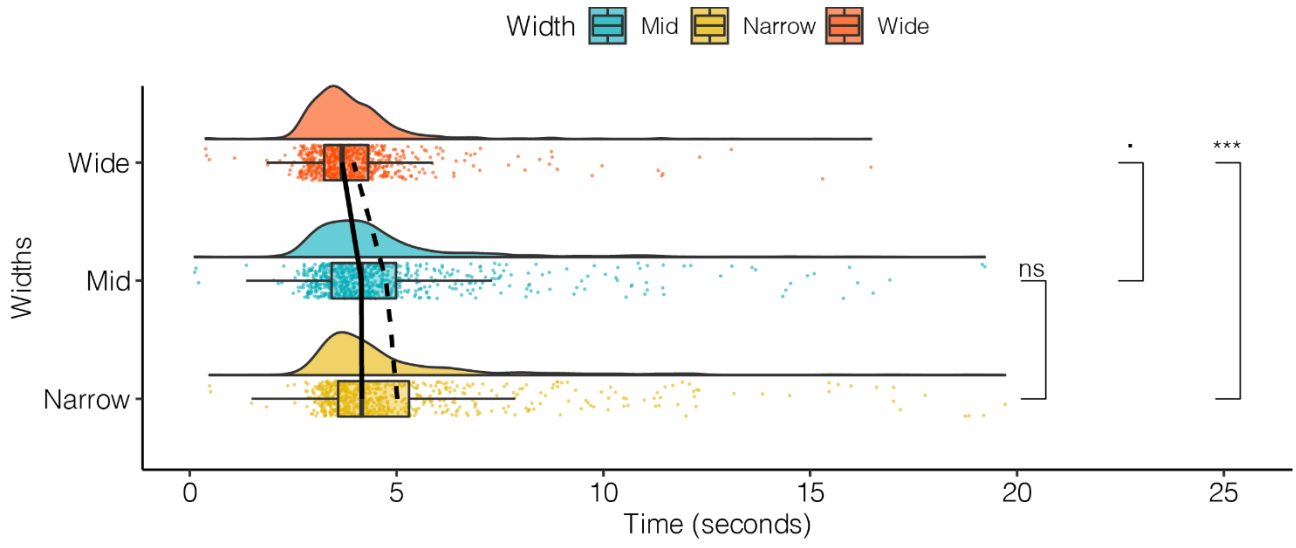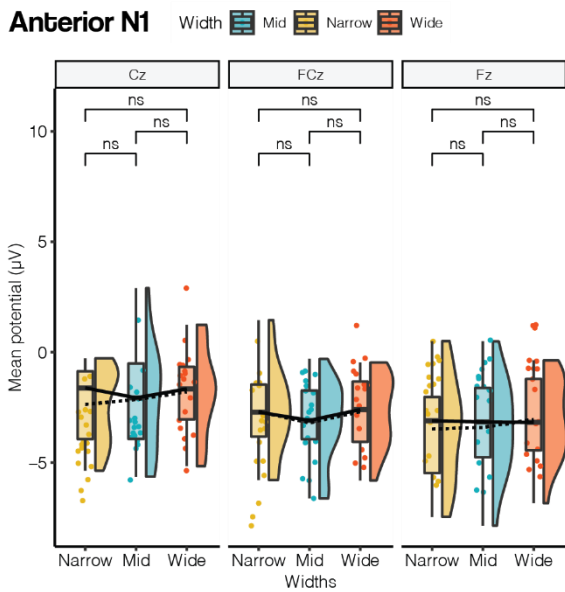

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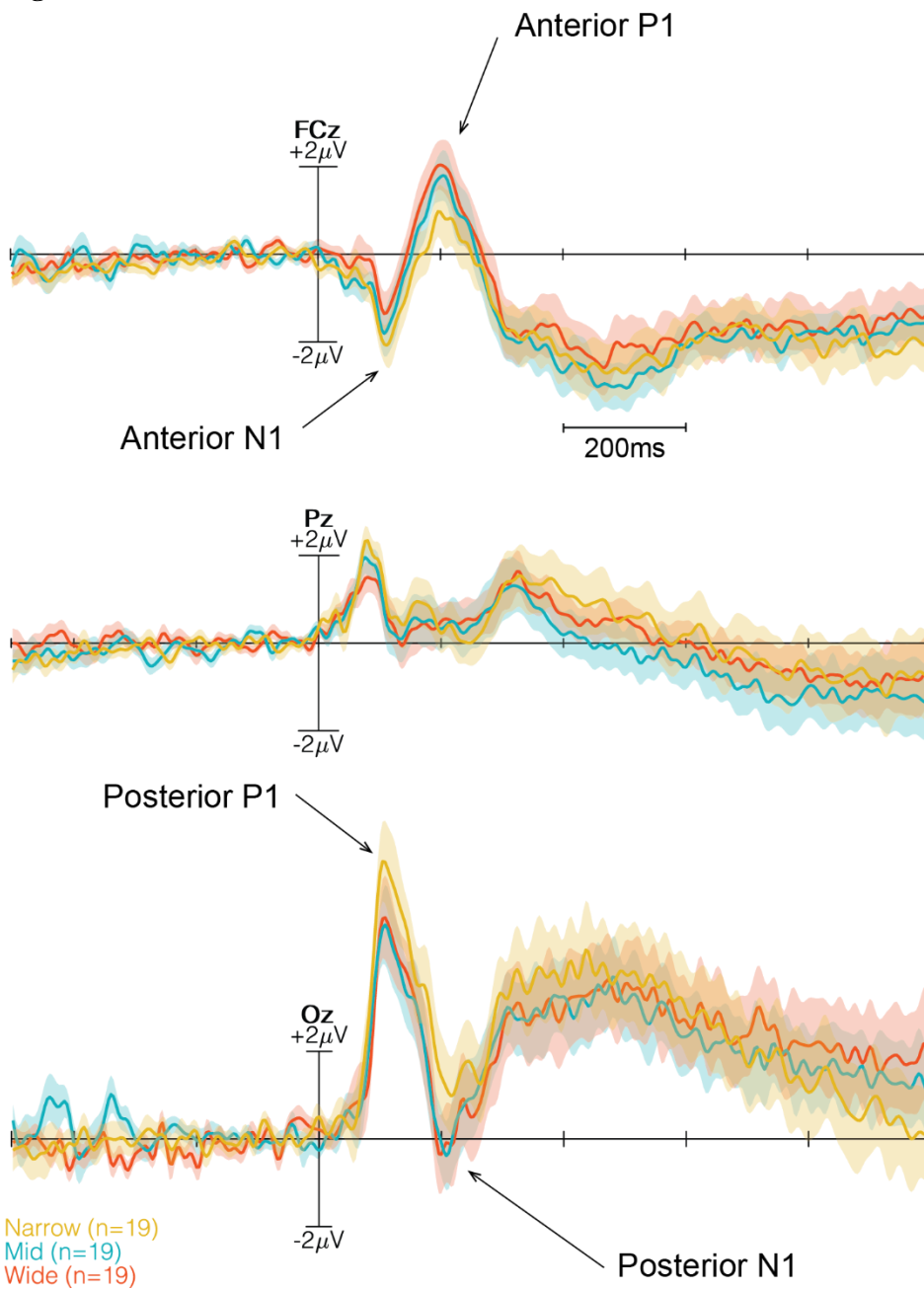
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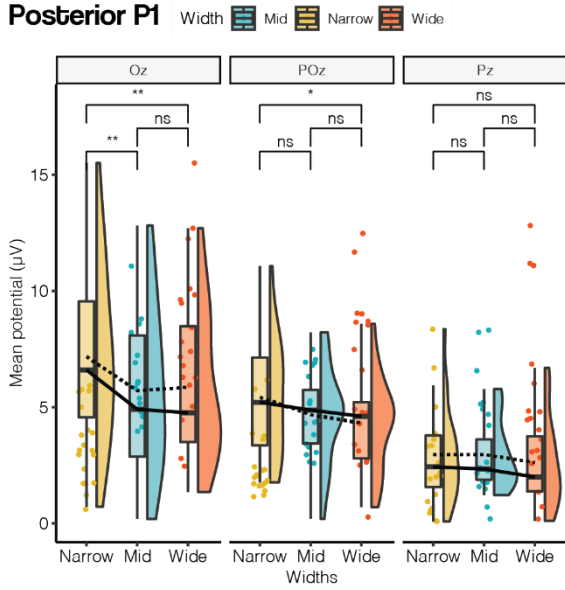
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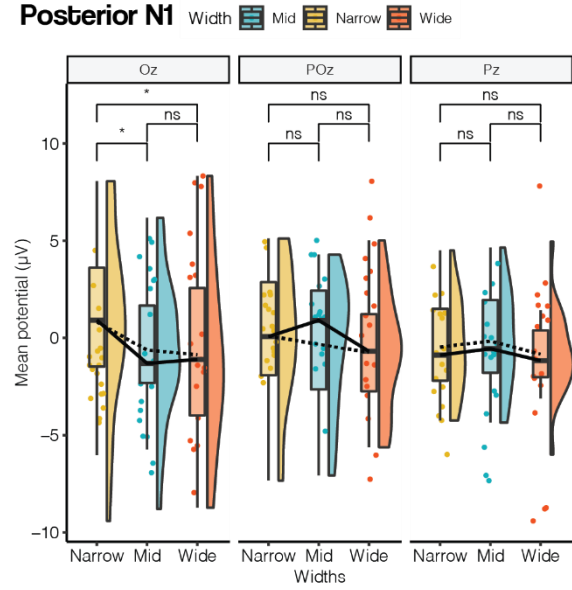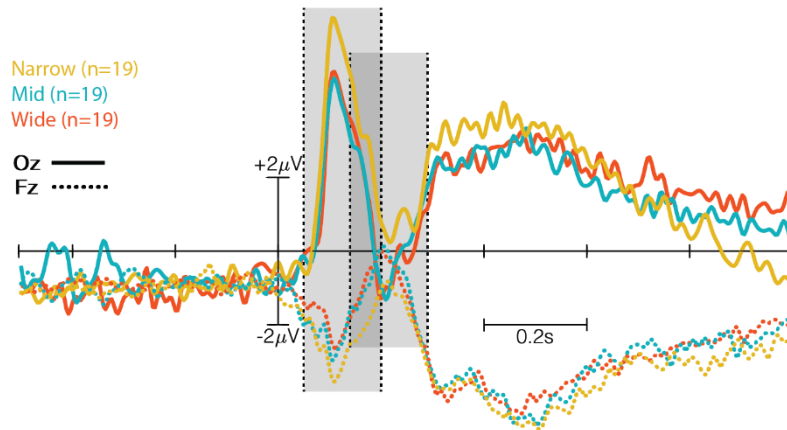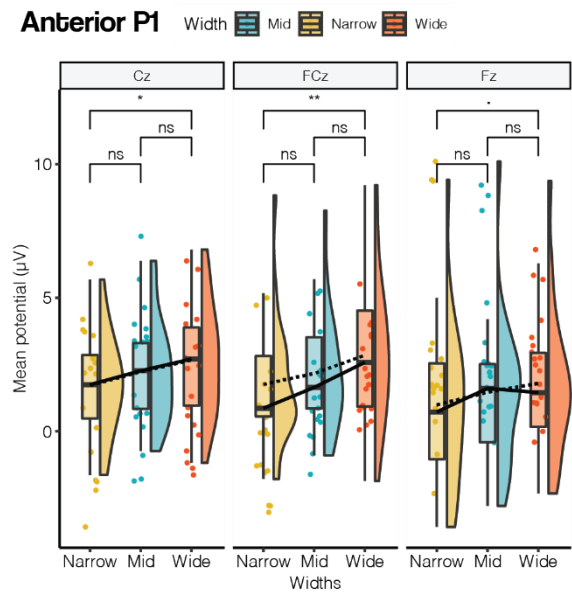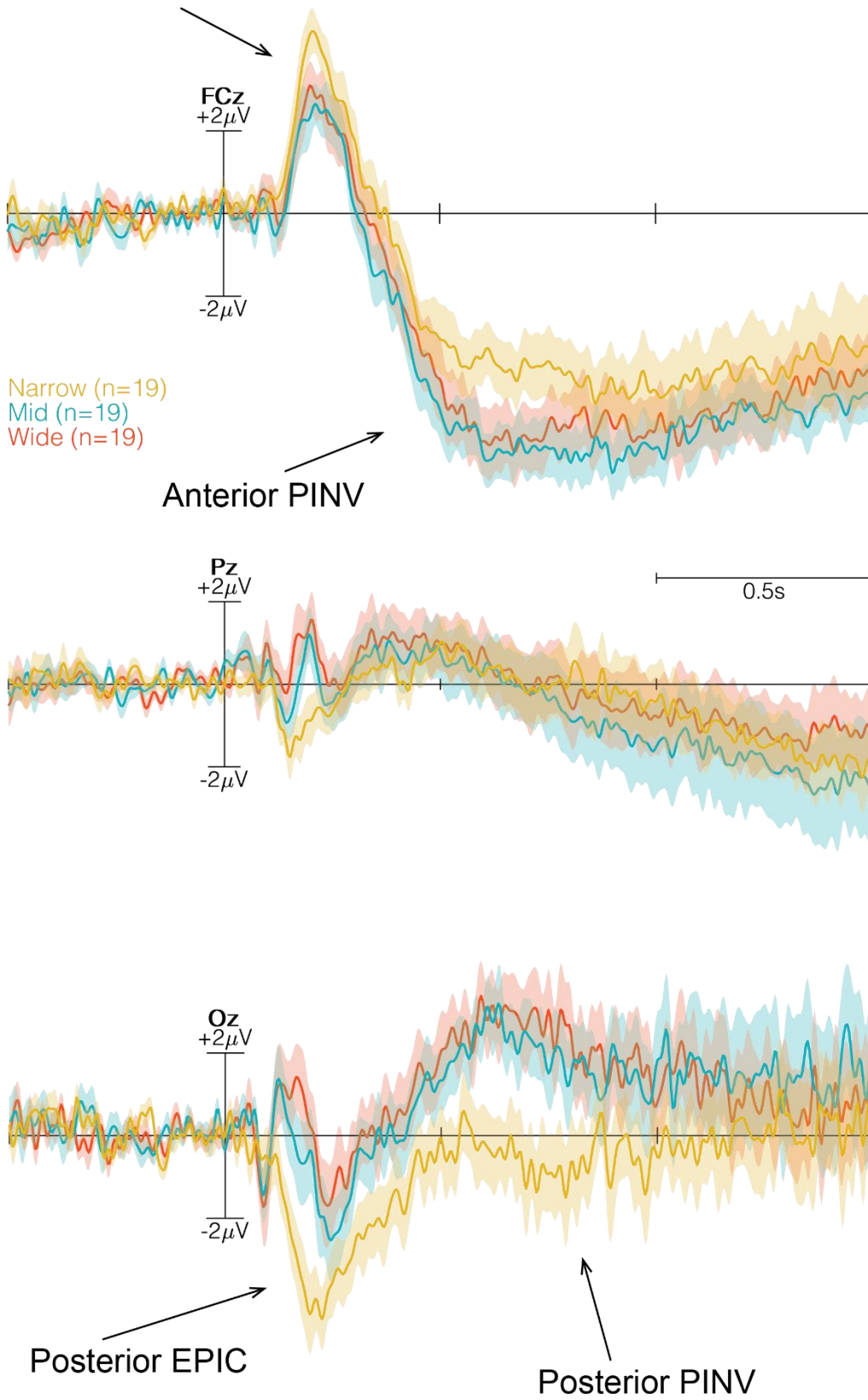
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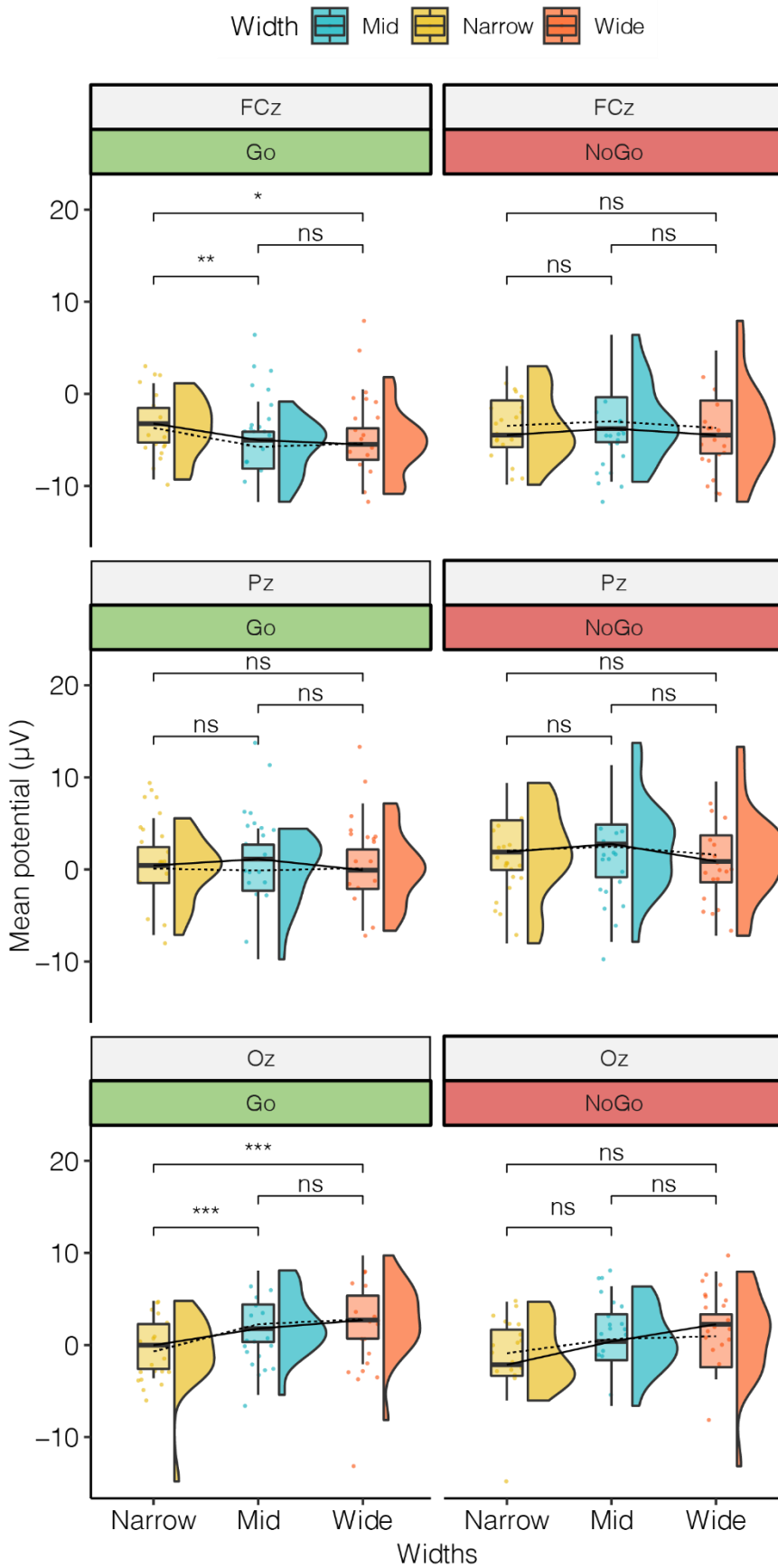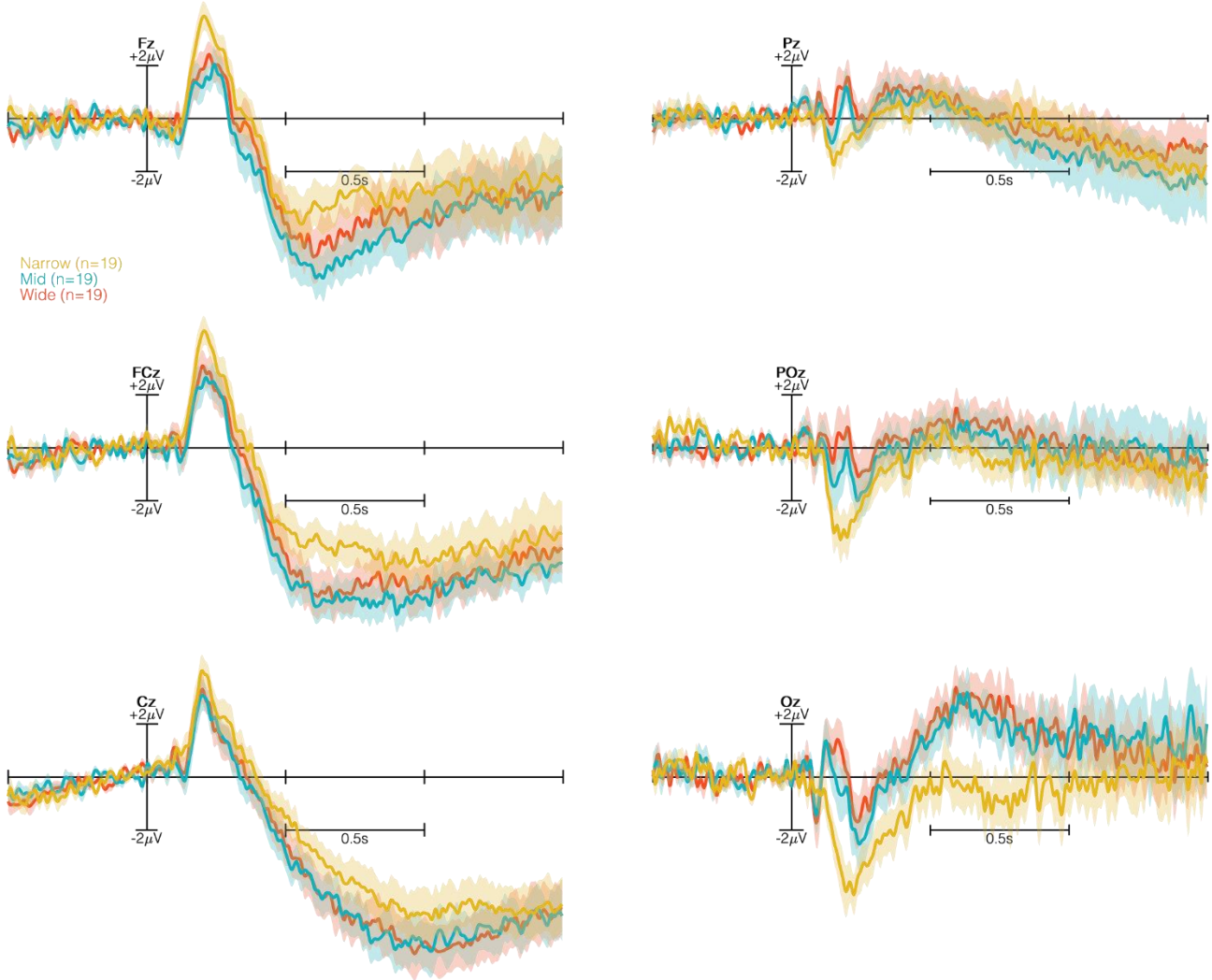

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901 # Supplementary figures
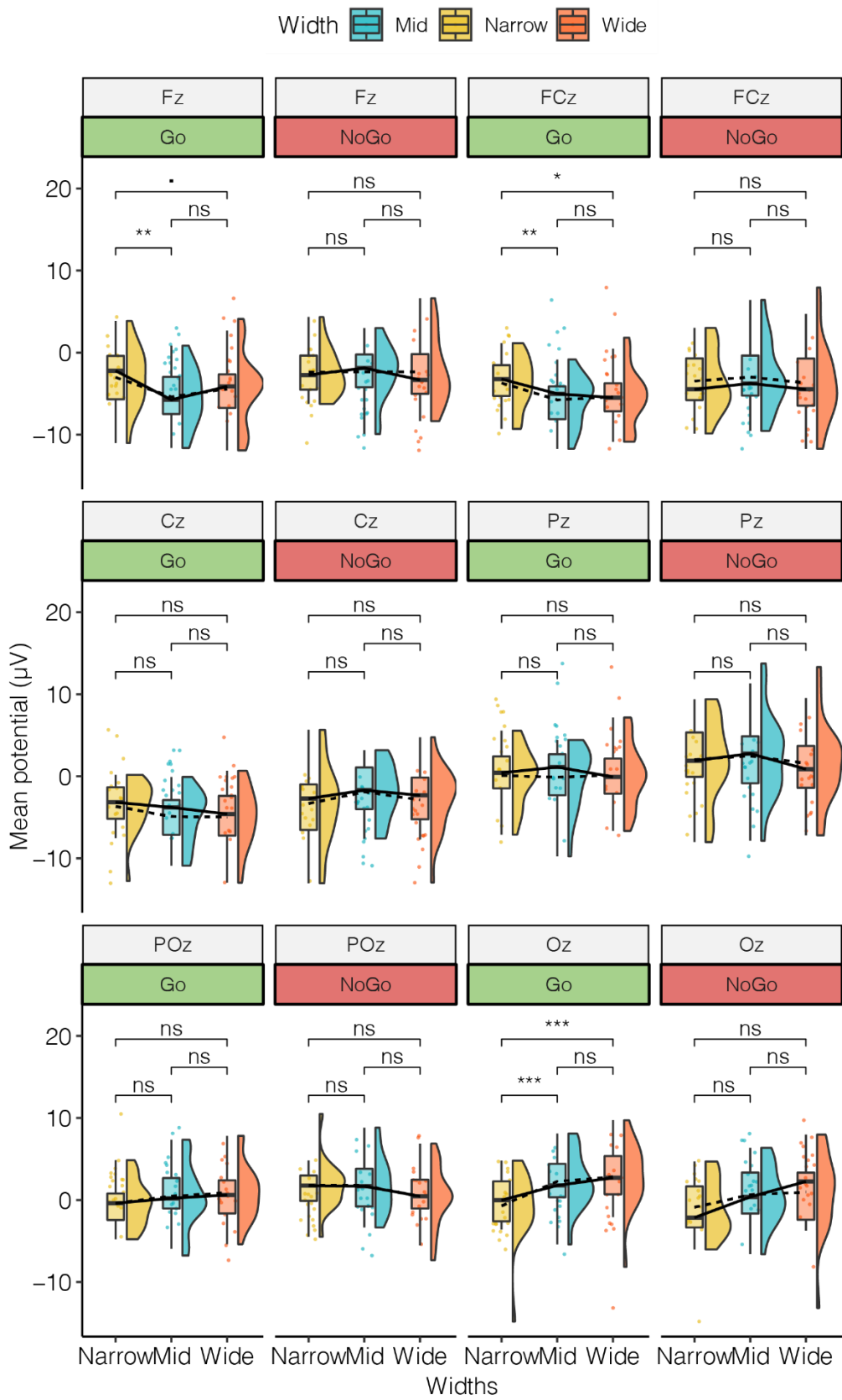
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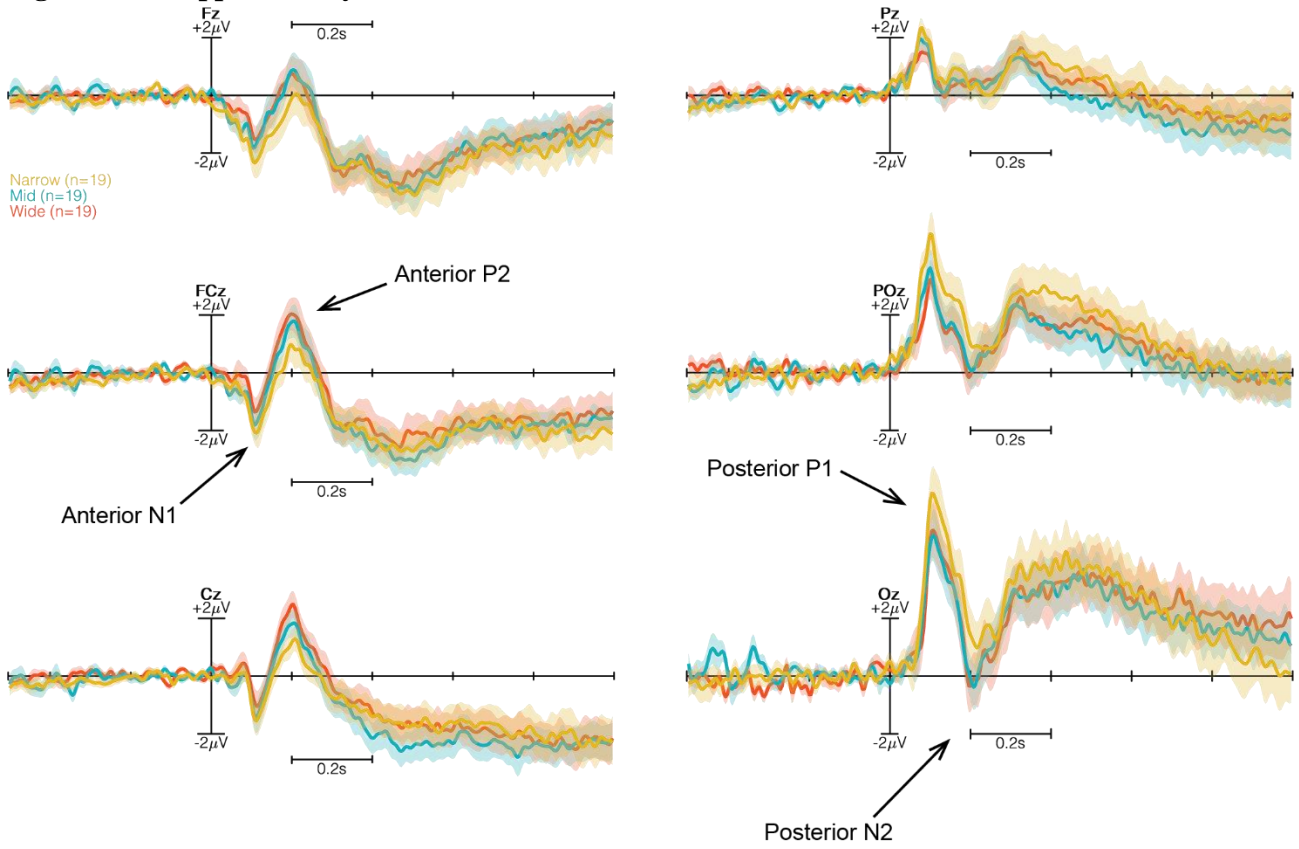
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906 **Figure 7.2 – supplementary:**

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Figure 8.2 - supplementary: