

Title: EEG alpha and theta signatures of socially and non-socially cued working memory in virtual reality

Running title: Alpha and theta in cued WM

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Abstract (200 words)

In this preregistered study (<https://osf.io/s4rm9>) we investigated the behavioural and neurological (EEG; alpha (attention) and theta (effort)) effects of dynamic non-predictive social and non-social cues on working memory. In a virtual environment realistic human-avatars dynamically looked to the left or right side of a table. A moving stick served as a non-social control cue. Kitchen items were presented in the valid cued or invalid un-cued location for encoding. Behavioural findings showed a similar influence of the cues on working memory performance. Alpha power changes were equivalent for the cues during cuing and encoding, reflecting similar attentional processing. However, theta power changes revealed different patterns for the cues. Theta power increased more strongly for the non-social cue compared to the social cue during initial cuing. Further, while for the non-social cue there was a significantly larger increase in theta power for valid compared to invalid conditions during encoding, this was reversed for the social cue, with a significantly larger increase in theta power for the invalid compared to valid conditions, indicating differences in the cues' effects on cognitive effort. Therefore, while social and non-social attention cues impact working memory performance in a similar fashion, the underlying neural mechanisms appear to differ.

Keywords: EEG, gaze, social, joint attention, virtual reality

Eye gaze is highly important in human communication (Kleinke, 1986), and people will generally follow other people's eye gaze, engaging in joint attention (see Frischen, Bayliss, & Tipper, 2007). Joint attention is linked to theory of mind (e.g. Charman et al., 2000) which leads to mentalising and perspective taking (Frith & Frith, 2006). This gaze following behaviour is typically investigated using an adapted Posner cuing task (e.g. Posner, 1980) whereby targets are presented in a valid, cued or in an invalid, un-cued location. Despite the uninformative nature of the cues, validly cued targets are generally responded to faster than those invalidly cued, with this being found both for eye gaze cues (e.g. Driver et al., 1999; Friesen & Kingstone, 1998; Frischen et al., 2007; Gregory, 2021; Gregory & Jackson, 2021), and other non-social communicative cues such as arrows and directional words (e.g. Gregory & Jackson, 2021; Hommel et al., 2001; Ristic et al., 2002; Tipples, 2002, 2008).

While cuing effects are not unique to eye gaze, joint attention is shown to have a unique effect upon higher order cognitive processes, with equivalent effects not found for non-social controls. For example joint attention has been found to improve language comprehension in children (Tomasello, 1988; Tomasello & Farrar, 1986) and adults (Hanna & Brennan, 2007; Knoeferle & Kreysa, 2012), to influence memory processes in infants (Cleveland et al., 2007; Striano et al., 2006; Wu et al., 2011; Wu & Kirkham, 2010) and adults (Dodd et al., 2012; Gregory & Jackson, 2017; Richardson et al., 2012; Shteynberg, 2010), and to influence perceived object value (Bayliss et al., 2007; Madipakkam et al., 2019; van der Weiden et al., 2010). These uniquely social effects are considered to reflect default altercentric (other-centred) processing (Kampis & Southgate, 2020), where humans cannot help but be influenced by the perspective of others. Evidence therefore suggests that objects seen under shared/ joint attention undergo enhanced processing due to the uniquely social influence of mutual gaze (Becchio et al., 2008; Shteynberg, 2010).

While evidence shows that joint attention enhances working memory for simple objects (Gregory & Jackson, 2017, 2019), the mechanisms of this effect are currently unknown. For example, it is unclear if joint attention influences memory for multidimensional information (Baddeley, 2010). Information that captures attention is found to be favoured by working memory (Awh et al., 2006) and these attention and memory processes are linked to neural oscillatory activity in the alpha (8 – 12Hz) and theta (3 – 7Hz) bands (Klimesch, 1999). Alpha desynchronization (decrease in power), is related to enhanced attentional processing of target stimuli (Hanslmayr et al., 2005; Sauseng et al., 2005). Theta synchronisation (increase in power) is related to effortful cognitive control processes (Cavanagh & Frank, 2014; Demiralp & Başar, 1992; Min & Park, 2010; Noonan et al., 2018). In memory, increased theta power at encoding and retrieval is related to better recall of stimuli (see Hsieh & Ranganath, 2014 for a review) and increases in task demands lead to greater theta synchronisation (e.g. Gevins, Smith, McEvoy, & Yu, 1997; Jensen & Tesche, 2002).

Changes in alpha and theta rhythms also reflect social processing. During perspective taking, theta oscillations occur in brain areas linked to mentalising processes (Bögels et al., 2015; Seymour et al., 2018; Wang et al., 2016). Further gaze processing deficits in schizophrenia have been linked to irregular theta activity (Grove et al., 2021), and theta is also linked to social exclusion (Cristofori et al., 2013, 2014). When using real humans as stimuli (not photographs), alpha power is found to be modulated by eye gaze. For example, alpha power desynchronization is more pronounced for direct than averted gaze (Chapman et al., 1975), and direct gaze triggers approach related alpha activity while averted gaze triggers avoidance related activity (Hietanen et al., 2008; Pönkänen et al., 2011). Further, higher alpha desynchronization is triggered by a joint attention compared to no joint attention condition in an otherwise identical task (Lachat et al., 2012). Finally, using a humanoid robot in an

innovative gaze cuing task, it was found that eye contact prior to gaze shift results in higher alpha desynchronization compared to no eye contact prior to shift (Kompatsiari et al., 2021).

When photographs instead of real people are used as gaze cues the effects of gaze on alpha are absent (Hietanen et al., 2008). Indeed, there are a range of important variations found in people's responses to real people compared to photographic or video stimuli (see Risko et al., 2016). However, while the use of real people as stimuli is a useful and enlightening method, this can produce limitations in complexity, replicability and the types of behaviours that can be investigated. As an alternative, Wykowska and colleagues have successfully used robots as social stimuli in social cognition research (Kompatsiari et al., 2018, 2021; Willemse et al., 2018; Wykowska et al., 2016). This demonstrates that it is not always necessary to use real people when studying social phenomenon. Indeed, research shows that interactions with virtual humans are comparable to real human interaction (see Bombari et al., 2015).

In the current pre-registered study (<https://osf.io/s4rm9>), we investigated the effect of dynamic eye gaze on working memory using virtual human avatars. Critically, we recorded EEG to investigate oscillatory power changes in alpha, reflecting attentional effects, and theta, reflecting cognitive effort, during the task. To our knowledge this is the first investigation of theta and alpha oscillations with respect to the effect of gaze cuing on working memory. Notably, to our knowledge, this is also the first investigation of theta oscillations in gaze cuing more generally.

Presented using a head mounted display, 3D avatars looked up to engage the participant in eye contact before looking down to the left or right. Reflecting real gaze behaviour, the avatars eyes shifted gaze direction rapidly in the direction of head turn (i.e. Hayhoe et al., 2012). Unlike traditional cuing tasks where items are presented to the side of the cue, here target kitchen items (bowl, plate, cup and teapot) appeared on the left or right

side of a table below the cue. This allowed investigation of the influence of cues in a more realistic environment where cue and target are not on the same visual plain. Participants were asked to remember multidimensional (i.e. Baddeley, 2010) location and status information about the four presented items. A dynamic 3D stick was presented as a non-social control cue which reflected the movement of the social avatar (Figure 1), allowing investigation of movement versus social cuing effects on working memory. Neural activity was assessed during cue shift, encoding and retrieval.

Generally in memory research theta power changes are prevalent in anterior sites, while alpha changes tend to be posterior (Jensen et al., 2002; Khader et al., 2010; Sauseng et al., 2010). Therefore, if the cues directly impact working memory encoding, effects would be expected in these areas. However, these effects have not been tested in the context of social and non-social cuing in VR, therefore, our analysis does not focus on specific locations.

The following predictions were pre-registered; 1) in the social gaze cue condition only we predicted working memory performance would be better in the valid compared to the invalid condition. 2) We predicted alpha and theta power would be more strongly affected by the shift of the social compared to the non-social cue (i.e. Kompatsiari et al., 2021; Lachat et al., 2012). 3) In the social gaze cue condition only, we predicted there would be stronger theta power increases and stronger alpha power decreases for the valid compared to the invalid condition at both the encoding and retrieval intervals.

Note, we also pre-registered predictions in the domain of ERPs, related to replicating basic attentional effects, however this is not pursued here in favour of more specific predictions made for memory functioning in oscillations (see supplementary materials).

Method

Participants

We recruited 49 participants (33 females, 16 males, mean age 21 years ($SD = 3.1$, range 18 – 32), 3 left-handed) from Aston university for payment (£10/ hour, cash) or course credit. Planned recruitment of 60 participants was cut off by the 2020 coronavirus pandemic, however the study is sufficiently powered to detect behavioural and neurological effects of the cues if present; a within subjects design with 49 participants has 80% power (Westfall, 2016) to detect a small to medium effect (e.g. $d = 0.35$, Gregory & Jackson, 2017; $d \approx 0.5$, Kompatsiari et al., 2021). All participants reported having normal or corrected to normal vision. Consent was obtained in accordance with the Declaration of Helsinki and ethical approval was obtained from the Aston University Research Ethics Committee.

Apparatus

The study was programmed in Unity using the Unity experimental framework (Brookes et al., 2020). A Lenovo Legion Y540-17IRH laptop computer (Intel Core i7-9750H Processor, 33GB RAM, NVIDIA GeForce RTX 2060 graphics card) ran the programme and communicate triggers wirelessly to the EEG (LSL4Unity; <https://github.com/labstreaminglayer/LSL4Unity>). Participants viewed the study through the Oculus Rift S PC-Powered VR Gaming Head-Mounted Display (HMD) and responded using a touch controller. Study and materials can be downloaded here: <https://osf.io/s9xmu/files/>.

Stimuli

Human avatar cue. Four male and four female identities with neutral facial expressions and plain grey clothing were created (see supplementary materials). Avatars were independently rated ($n = 61$, online study; see supplementary materials) for human personality traits (Oosterhof & Todorov, 2008), anthropomorphism, animacy, and likeability (Bartneck et al., 2009). Importantly, the ratings indicated that the avatars were seen as humanlike (see Table 1).

Table 1.

Table 1 shows average ratings for the avatars across all identities rated on general personality traits from Oosterhof & Todorov, 2008, as well as showing the results from the original study where 327 participants rated 66 different neutral faces on personality traits (data shown with permission). The scale ranged from 1 (not at all) - 9 (extremely) for each trait and results do not indicate that the avatars used were particularly strange, mean difference in rating = 0.6 points, though note the higher variability for the avatar ratings. Table 1 also shows the Godspeed ratings (9-point scale) for the human avatars and the robot avatar, ratings were significantly higher and thus more humanlike for the human avatars than for the robot to the $p < .001$ level.

Rating scale	Current study (Avatars) Mean (SD)	Oosterhof & Todorov, 2008 Table S1 Mean (SD)
Aggressive	3.67 (2.26)	4.68 (0.98)
Attractive	4.54 (2.36)	2.85 (0.78)
Caring	4.67 (2.04)	4.54 (0.72)
Confident	4.38 (1.98)	4.81 (0.68)
Dominant	4.25 (2.36)	4.81 (0.81)
Emotionally stable	4.16 (2.12)	4.74 (0.79)
Intelligent	5.31 (1.91)	4.88 (0.68)
Mean	4.23 (2.28)	4.94 (0.87)
Responsible	4.82 (1.88)	4.31 (0.77)
Sociable	4.20 (2.23)	4.58 (0.74)
Trustworthy	4.57 (2.09)	4.74 (0.85)
Unhappy	4.98 (2.47)	4.72 (0.82)
Weird	4.43 (2.55)	5.01 (1.05)
Threatening	3.61 (2.22)	Not included
Godspeed	Mean (SD) Avatars	Mean (SD) Robot
Amphropomorphism	5.04 (1.73)	2.16 (1.34)
Animacy	5.00 (1.64)	2.55 (1.48)
Likeability	5.22 (1.37)	3.25 (1.85)

Non-social stick cue. Created in Unity as a cylindrical game object which extended to a similar distance from the participant and table as the avatars (see Figure 1). Both cues have been shown to trigger typical cueing effects (Gregory, 2021).

Targets. Adapted from the Unity asset store (assetstore.unity.com/packages/3d/white-porcelain-dish-set-demo-82858), the cup and bowl were presented either empty or full by

adding coffee/ soup, the plate contained a pastry (assetstore.unity.com/packages/3d/props/food/croissants-pack-112263) that was bitten or whole and the teapot was presented cracked or not cracked. Items were presented in colour at encoding and grayscale at retrieval to avoid colour matching.

Procedure

A 5-trial familiarization session preceded the main experiment during which the HMD was configured prior to EEG set up. For the main study, cue condition was counterbalanced such that participants saw either the social avatar or the non-social stick condition first and all trials were completed before seeing the other cue condition. For both cue types there were 10 practice trials and 112 experimental trials. Breaks were encouraged every 28 trials and an enforced break was taken between the two cue type sessions. Participants could remove the HMD during breaks.

For both cue types, a trial proceeded as follows (Figure 1), a fixation cross was presented for 1000ms (inter trial interval), then replaced by the cue looking/ pointing at the table (1500ms). The cue then looked/ pointed at the participant (transition 500ms) and after 1000ms pointed/looked to the left or right (transition 500ms: for gaze, eyes also moved rapidly during the first 30ms of the 500ms head turn), targets were then presented (stimulus onset asynchrony (SOA) 500ms, calculated from the moment the cue began to shift). Four items were presented for encoding (500ms) in four of the six possible locations (Figure 1C) on either the valid or invalid side. Participants were instructed that the cue was not informative and should be ignored. After a blank maintenance interval (1000ms) a probe item was shown in grey scale either in the location in which it was initially presented, or in a different location (occupied previously by another object). Participants responded with a button press and received accuracy feedback. Next, the status of an item at encoding was probed using text (e.g. 'Did the bowl have soup in it?') and participants responded with a

button press and received feedback. The experiment was a free viewing study and there was no response-window cut off.

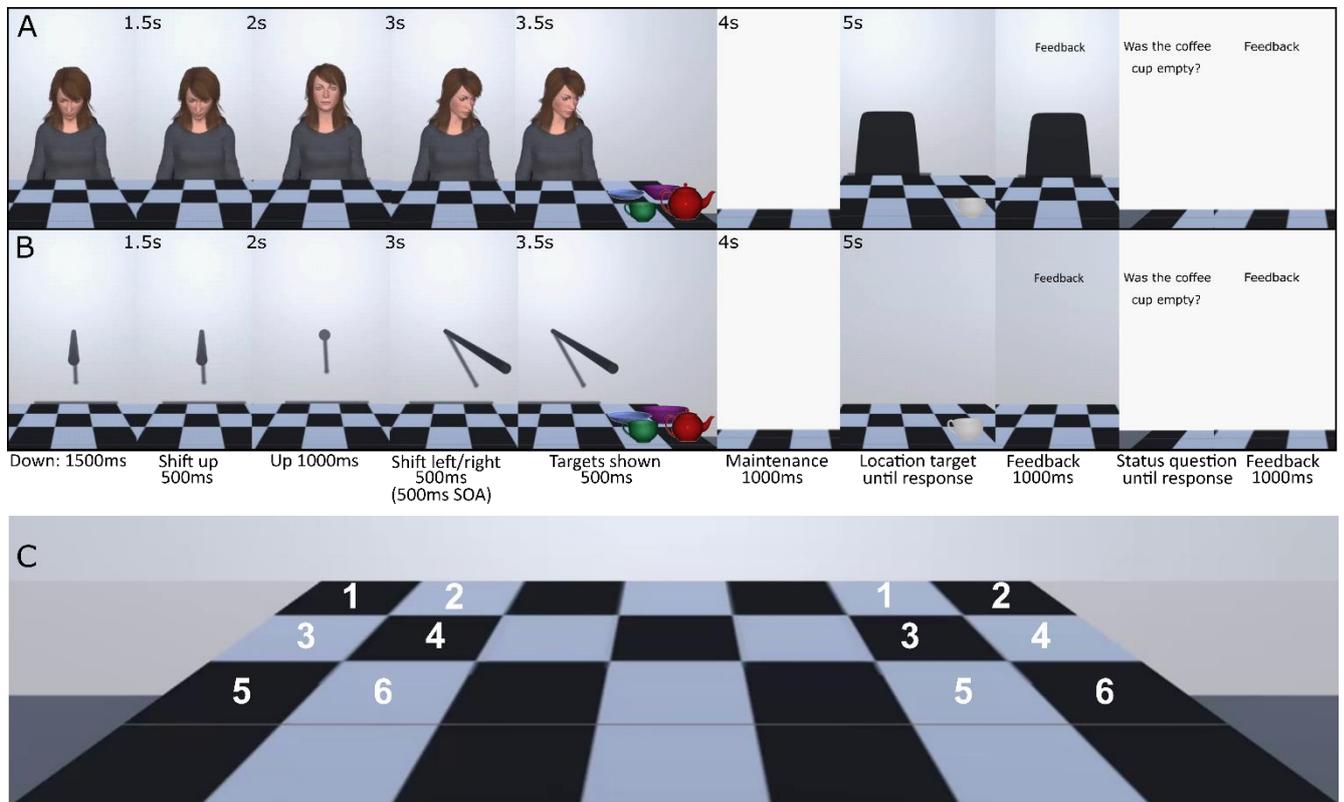


Figure 1. Illustration of the trial procedure (chequered pattern inspired by Harkin, Rutherford, & Kessler, 2011). Adopting the parameters of the traditional central cuing paradigm the cue remained on screen for the entire trial (e.g. Driver et al., 1999; Friesen & Kingstone, 1998). Panel A shows the social avatar cue and panel B shows the non-social stick cue. Timings, as shown in the figure, were matched across cue types. Note that the intertrial interval was 1000ms during which a fixation cross was presented. The experiment was a free viewing experiment; thus, participants could move their eyes as they wished. Panel C shows the 6 possible left and right locations for the 4 encoding targets.

EEG acquisition and preprocessing

We recorded EEG using a 64 channel eego™ sports mobile EEG system (ANT Neuro, Enschede, The Netherlands; Ag/AgCl electrodes, international 10–10 system), digitised at a sampling rate of 500 Hz. Electrode CPz served as online reference and AFz as

the ground electrode. Mastoids and EOG electrodes were not used and impedance was kept below 20 k Ω during task.

EEG data were pre-processed using Fieldtrip toolbox version 20191028 (Oostenveld et al., 2011) in MatlabR2019b®. Data was detrended and then bandpass filtered between 0.5 - 36.0Hz. The data was epoched from 1second pre cue onset to 1 second post probe response, such that cue onset = time 0. Trials were inspected for artefacts and trials with large artefacts were removed (average 221 total trials/ participant in final analysis) and corrupted electrodes were interpolated using the average method (5 in total; max 2/ participant), data was re-referenced using the average refence method (post interpolation). Independent component analysis (fastica) was used to identify noise, eye-blink, saccade, heartbeat and muscle components (average 11 components removed per participant, range 2 – 23, see Figure 3 in supplementary materials for example components).

Data analysis and results

Behavioural data

Due to programming error (see supplementary materials) the preregistered use of d' as a measure of WM accuracy was not possible, instead percent accuracy was used. Repeated-measures ANOVAs were conducted on percent accuracy separately for the location and status data with cue type (social, non-social) and cue validity (valid, invalid) as within-subjects variables. Conforming to the preregistered analysis plan, results are reported using standard null hypothesis significance testing with supporting analysis conducted with Bayesian statistics using JASP (Version 0.12.2.0; Love et al., 2015) using default priors (Wagenmakers et al., 2018) and ANOVA effects across matched models only (see Van Den Bergh et al., 2020). Bayesian analysis allows us to make inferences about the strength of findings as well as about the nature of any null findings.

Time frequency analysis

Time-frequency analysis was carried out by applying a Morlet wavelet transform on each trial from 2-30Hz (for every 1Hz), with three cycles per time-window in steps of 50ms. For each participant trials were then averaged within each condition and a decibel (db) baseline correction was applied at 500ms to 100ms pre cue onset. Time-frequency representations were generated for the full time-frequency spectrum, and statistical analysis focussed on alpha (8 - 12 Hz) and theta (3 – 7 Hz) bands separately, averaging across the frequency band. Analysis was data-driven (no pre-selected time intervals or electrodes) and multiple comparisons across time points and electrodes were corrected using non-parametric cluster-based permutation tests implemented in the Fieldtrip Toolbox (Maris & Oostenveld, 2007), with 5000 permutations (cluster alpha = $p < .05$, critical alpha, $p < .05$). Analysis compared valid and invalid conditions separately for each cue type. In addition, to understand potential interactions between cue validity and cue type (person/stick) for each participant we subtracted the invalid condition from the valid condition for both cue types separately and then compared the magnitude of the difference. This statistical approach is recommended on the Fieldtrip website and has been implemented in previous work (Bögels et al., 2015; Huizeling et al., 2020; Wang et al., 2016), analysis scripts and data are available from OpenNeuro (<https://openneuro.org/datasets/ds003702>)

Results

Behavioural

Location accuracy was not statistically different for the social ($M = 0.89$, $SD = 0.11$) and non-social ($M = 0.90$, $SD = 0.09$) cuing conditions, $F(1,48) = 0.959$, $p = .332$, $\eta_p^2 = .020$, $BF_{incl} = 0.398$. There was also no difference in location accuracy between the valid ($M = 0.90$, $SD = 0.10$) and invalid ($M = 0.90$, $SD = 0.09$) condition, $F(1,48) = 0.398$, $p = .531$, $\eta_p^2 = .008$, $BF_{incl} = 0.175$. However, there was a significant interaction between cue type and validity, $F(1,48) = 8.958$, $p = .004$, $\eta_p^2 = .157$, $BF_{incl} = 0.464$. For the social cue, there was no

significant difference in location accuracy between the valid ($M = 0.90$, $SD = 0.10$) and invalid ($M = 0.89$, $SD = 0.12$) conditions, $t(48) = 1.102$, $p = .315$, *Cohen's d* = 0.145, $BF_{10} = 0.68$. For the non-social cue however, there was a significant difference with location accuracy being worse in the valid condition ($M = 0.90$, $SD = 0.10$) compared to the invalid condition ($M = 0.91$, $SD = 0.09$), $t(48) = -2.251$, $p = .029$, *Cohen's d* = -0.322, $BF_{10} = 1.54$ (Figure 2 panel A, see also supplementary materials Figure 1 for individual differences data).

Status accuracy was not statistically different for the social ($M = 0.67$, $SD = 0.09$) and non-social ($M = 0.68$, $SD = 0.08$) cuing conditions, $F(1,48) = 0.058$, $p = .811$, $\eta_p^2 = .0001$, $BF_{incl} = 0.16$. There was a significant main effect of validity, $F(1,48) = 6.196$, $p = .016$, $\eta_p^2 = .114$, $BF_{incl} = 1.99$ here status accuracy was better in the valid ($M = 0.69$, $SD = 0.07$) compared to the invalid condition ($M = 0.66$, $SD = 0.09$). There was a non-significant interaction between cue type and validity, $F(1,48) = 0.142$, $p = .798$, $\eta_p^2 = .003$, $BF_{incl} = 0.22$ indicating that the effect of cue validity on status accuracy was not modulated by cue type (Figure 2, panel B, and supplementary materials Figure 1).

Due to the unpredicted and disparate effects of the stick cue, (i.e., better memory for invalidly cued items in the location task, and better memory for the validly cued items in the status task) we ran an online follow up to test the effects of the two cues in a simpler memory task; participants indicated if a probe item had been one of five items presented at encoding (see supplementary materials). This 60-participant study replicated the status memory effects showing a significant main effect of validity, $F(1,59) = 33.331$, $p < .001$, $\eta_p^2 = .361$, $BF_{incl} > 100$ with validly cued items ($M = 0.63$, $SD = 0.09$) being recalled more accurately than invalidly cued items ($M = 0.58$, $SD = 0.07$) items for both the social and non-social cue (Figure 2, panel C).

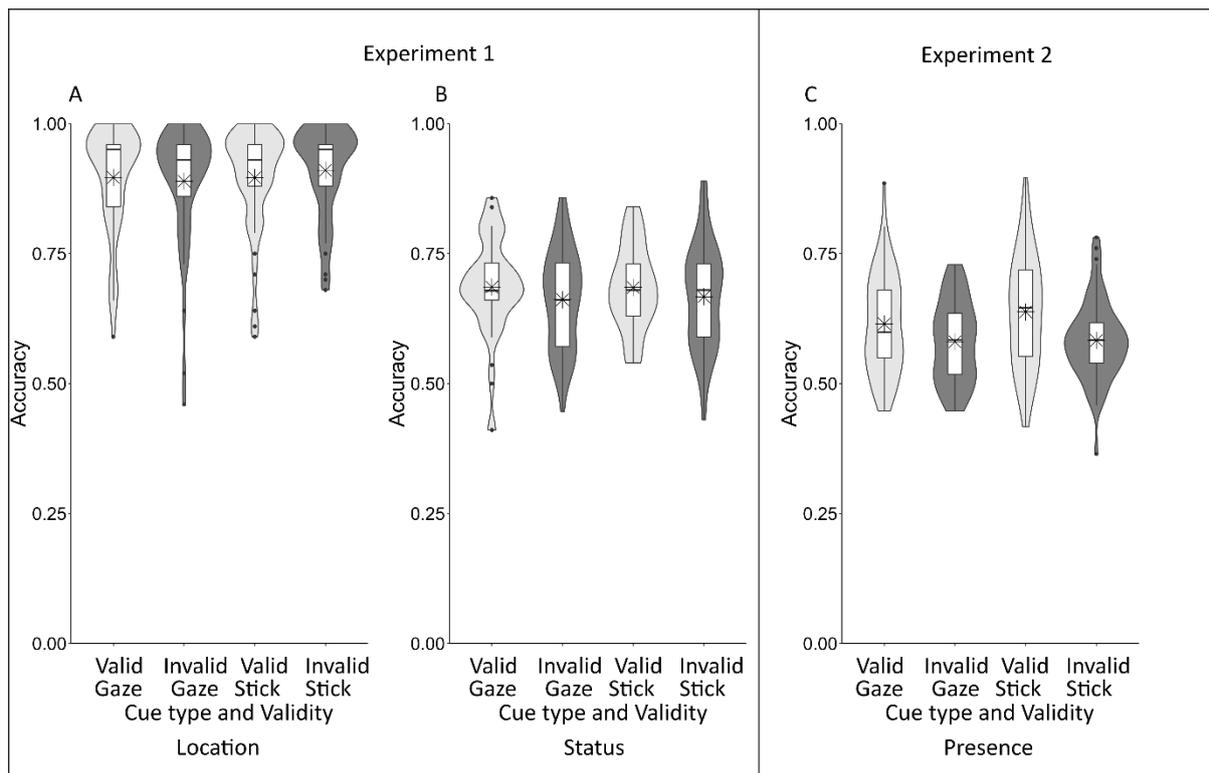


Figure 2. Results from experiment 1 and 2 showing location accuracy (A) and status accuracy (B) for experiment 1, and presence accuracy for experiment 2 (C) plotted as a function of cue validity. Boxplots indicate the median and quartiles (whiskers 1.5 times interquartile range), violin overlay shows the full distribution of the data (kernel probability density), mean is marked by an asterisk.

EEG

EEG analysis was performed on trials where the location question was answered correctly. For both cues, the TFRs in Figure 3 show the expected increase in theta power at 3.5s when the targets are presented for encoding as well as expected decreases in alpha power.

Cue shift window

The first crucial comparison focuses on whether alpha and theta oscillatory effects are modulated by cue type during the initial cue shift. The window of interest is a 1000ms period (see Fig. 1) where the cue proceeds from pointing/ looking at the participant to looking/ pointing at a side of the table (2.5 – 3.5 seconds, shift to left/ right begins at 3 seconds), thus

containing a 500ms period of eye contact in the social avatar condition. Cue validity was currently unknown to the participant.

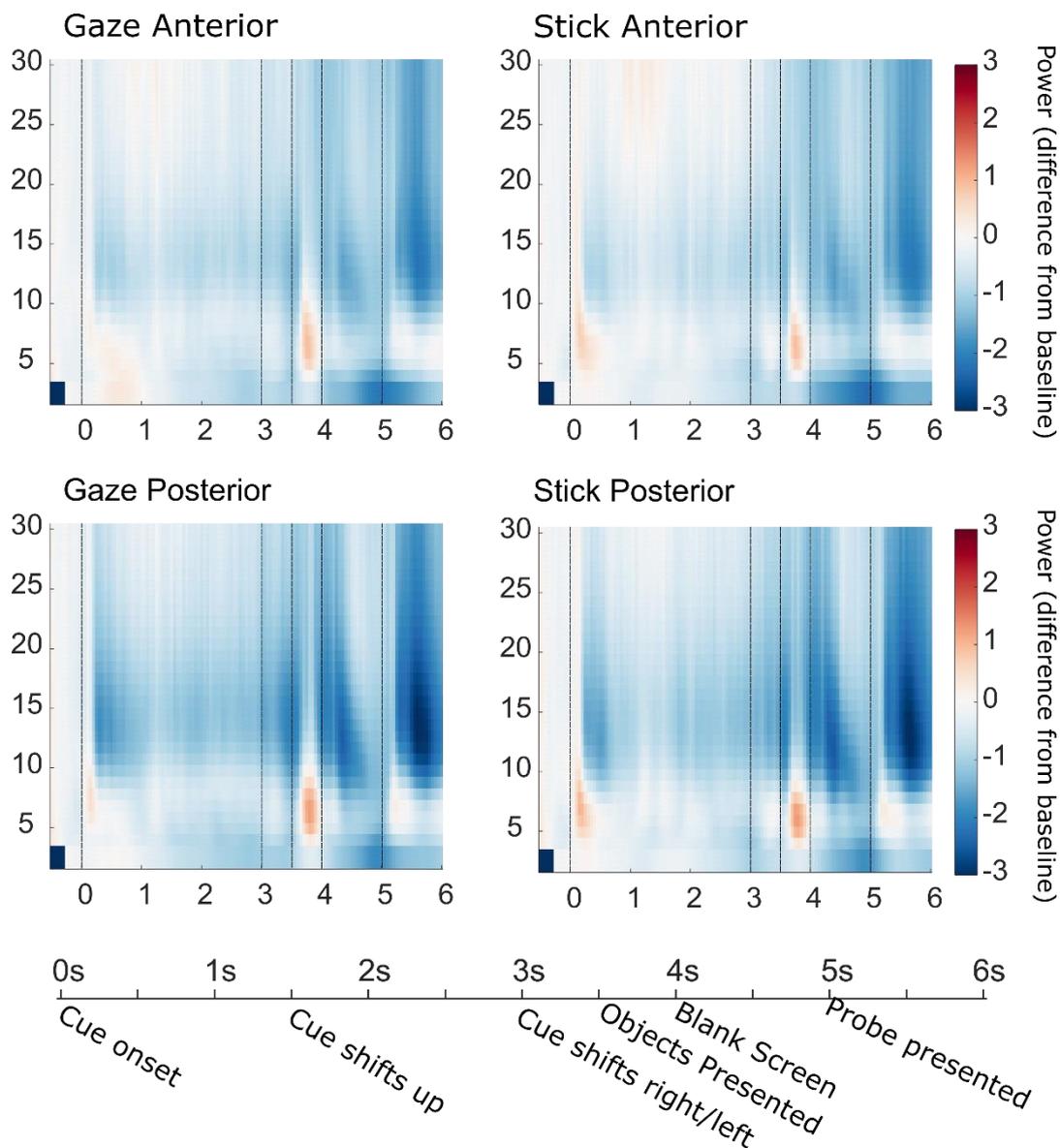


Figure 3. Figure shows time frequency (TFR) plots for oscillatory power (decibel (db)) baseline corrected (-500 - -100ms) during the social avatar and the non-social stick condition, collapsed across validity conditions for anterior (Fp1, Fpz, Fp2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8) and posterior (TP7, CP5, CP3, CP1, CP2, CP4, CP6, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO7, PO5, PO3, POz, PO4, PO6, PO8, O1, Oz, O2) electrodes separately. Timeline shows key experimental events and the crucial time points indicated on the TFRs are the trial start at 0ms, cue shift at 3s, the target onset at 3.5s, target offset at 4s and the probe onset at 5s.

Results show no significant differences in alpha power changes between cue types in this interval, with both cues showing the expected reduction in alpha power (Figure 4, panel A). However, during the cue shift, there was an apparent decrease in theta power for both cues, with this being larger for the social than the non-social cue ($p = .023$, Figure 4, panel A).

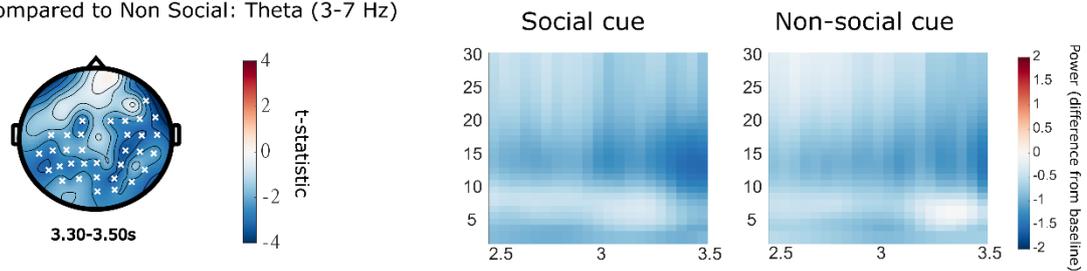
Because no differences were observed in the eye contact period, we conducted a second exploratory analysis to determine if any eye contact effects are present when the cue initially moved to point/ look at the participant, i.e., when eye contact is engaged in the gaze condition. Thus, we compared effects in alpha and theta between the social and non-social cue at the 1.5s (shift up starts) – 2.5s interval. Results show no significant differences in alpha or theta power changes between cue types in this interval.

Encoding window

The next comparison investigated whether changes in alpha and theta power were modulated by cue validity during the 500ms encoding period (3.5s – 4s; see Figure 1). Looking first at theta power, for the social cue there was a significantly smaller increase in theta power (in relation to baseline) for the valid compared to the invalid condition ($p = .012$, Figure 4, panel B). Contrastingly, for the non-social cue there was a significantly larger increase in theta power for the valid compared to the invalid condition, ($p = .044$, Figure 4, panel C). Comparing these validity differences across the two cue types across all electrodes revealed a non-significant difference ($p > 0.10$). However, for the non-social cue, effects appear to be located over occipital electrodes, while for the social cue effects are more dispersed both in time and location. Performing a more focussed post hoc cluster-based permutation analysis on the occipital electrodes that make up the significant clusters (see Figure 4 caption) during the encoding window indicates that the changes in theta power at this location are significantly different between the two cue types, ($p = .046$).

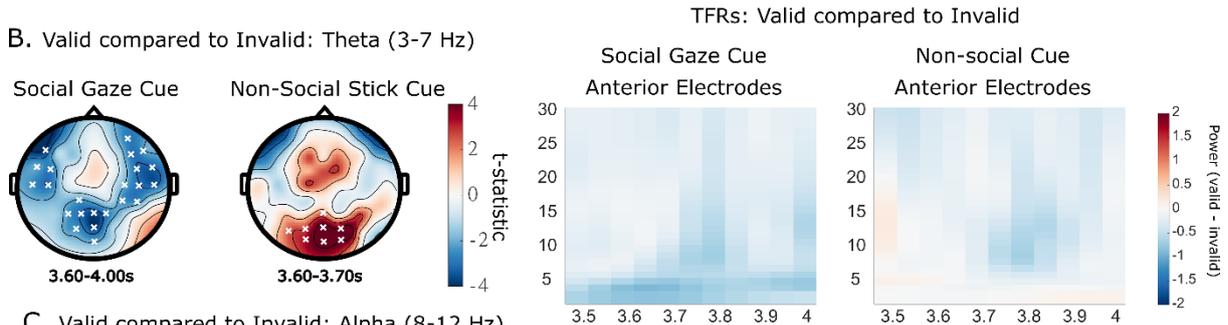
Cue shift interval (2.5s - 3.5s)

A. Social compared to Non Social: Theta (3-7 Hz)



Encoding interval (3.5s - 4s)

B. Valid compared to Invalid: Theta (3-7 Hz)



C. Valid compared to Invalid: Alpha (8-12 Hz)

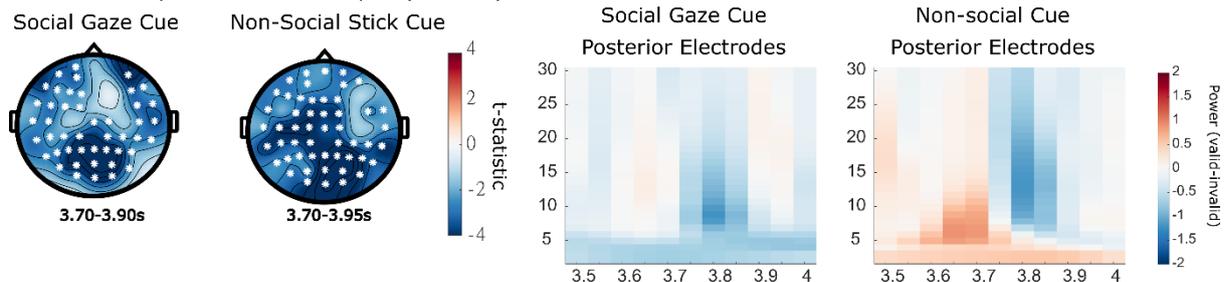


Figure 4. The left side of the figure shows representative cluster plots, full plots of effects across the time window are in the supplementary materials (Figure 1). The right side shows associated TFRs (decibel (db) baseline corrected -500 - -100ms). In plot A the social gaze and non-social stick cue are contrasted during the initial cue shift window (Theta effects only), the associated TFR is plotted over all electrodes. Valid and invalid conditions are contrasted for each cue separately in the encoding window, B shows theta band effects and C shows Alpha band effects. In associated TFR plots, in the upper plots data shows a snapshot of the anterior electrodes (Fp1, Fpz, Fp2, AF7, AF3, AF4, AF8, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC5, FC3, FC1, FCz, FC2, FC4, FC6, FT8), and in the lower plots data is plotted over the electrodes that make up the significant posterior clusters in B (Social: CP1, P3, Pz, POz, P1, P2, PO3, Oz, Non-social: Pz, POz, O1, O2, PO5, PO3, PO4, PO6, Oz). Note that these plots are created by subtracting the invalid from the valid power-spectrum data, thus they show the difference between the conditions. Cluster significance levels from a two-tailed test are indicated as x $p < .05$, * $p < .01$.

Looking now at changes in alpha power, there was a significantly stronger decrease in alpha power in the validly cued compared to the invalidly cued condition for both the social ($p = .002$) and non-social cue ($p < .001$, Figure 4, panel C;). Comparing the validity differences across the two cue types across all electrodes revealed a non-significant difference in the magnitude of this alpha power change ($p > 0.20$).

Probe window

Finally, we investigated changes in alpha and theta power during the probe interval (retrieval; 5s – 6 s). Results for both cue types showed that cue validity at encoding did not modulate alpha and theta power at retrieval, all $p > .1$.

Discussion

Here we examined the behavioural and neural effects of virtual social and non-social cues on working memory for the status and location of presented objects. We predicted that the social gaze cue would influence working memory, while the non-social cue would not. Further, we predicted that the social cue would have a stronger effect on alpha and theta oscillations than the non-social cue.

Contrary to predictions, working memory for status information was modulated by both the social and non-social cues, with objects in the valid location being recalled more accurately than those in the invalid location for both cue types. This finding was replicated in experiment 2 using a different task. This is contrary to previous work conducted using arrows as the non-social cue, where no effects of the non-social cue were seen on working memory (Gregory & Jackson, 2017), long term memory (Dodd et al., 2012) or object appraisal (Bayliss et al., 2006). Due to its size and motion, in the studies presented here the non-social cue is much more potent than the traditional arrow. It is therefore possible that arrow cues are easier to ignore if required, such as when doing complex higher order tasks, than eye gaze, and here this potent moving stick.

The social cue had no effect on working memory for the location information, however, for the non-social cue, surprisingly memory was better in the invalid than the valid condition. Location accuracy was high across participants, with some achieving accuracy of 100%, therefore gaze cue effects may have been lost to ceiling effects, and so it is unknown if gaze cues would influence location accuracy in a more difficult task. The non-social cue result may reflect inhibition of return (Klein, 2000), however this is unlikely because this cue has been found to show facilitative cuing at this 500ms SOA (Gregory, 2021). Further, the result is reversed for the status condition, where memory is better for items in the valid condition. This is therefore possibly a spurious effect, likely driven by ceiling effects. However, to speculate briefly, evidence suggests that visuo-spatial working memory works as a distributed network, processing visual appearance (i.e. status) information separately from spatial location information (see Zimmer, 2008). It is possible that the presence of the stick cue increased overall attention to the cued objects enhancing visual appearance processing while adding an extra spatial element to be processed which disrupted spatial processing. For the gaze cue the head of the avatar was attached to a body giving it a more distinct and fixed spatial location compared to the moving stick.

There was no difference between the two cue types in their influence on alpha power during the cue shift, which incorporated a period of eye contact (social cue only) as well as the left/ right cue shift movement, nor were there any differences during the earlier period where eye contact was established. This is contrary to the results of Kompatsiari and colleagues (2021) who found that eye contact modulated alpha power, with a greater decrease in power found in an eye contact condition compared to a no eye contact condition. Here both the social gaze cue and the non-social stick cue engaged the participant prior to cue shift either by looking or by pointing at them. It is therefore possible that prior findings that eye contact and joint attention modulated alpha power (Chapman et al., 1975; Kompatsiari et al.,

2021; Lachat et al., 2012) are related to the participant attending more when the stimulus is more engaging, either through looking at them, or looking where they look, rather than the specific social nature of the stimuli. However, it is possible that differences could be found when focussing analysis on specific regions of interest. There was also no difference in the alpha effects between the two cues during the encoding interval. For both cues there was a significantly stronger decrease in alpha power in the validly cued condition compared to the invalidly cued condition, with no difference in the magnitude of the effect. This reflects the memory findings and indicates that the cues had similar influences on attention.

During the cue shift there was no clear theta synchronisation and instead significantly stronger theta desynchronisation for the social cue compared to the non-social cue. This indicates that there was a general ignoring of the cues that did not require effortful processing. The significant decrease in the social condition may be due to the apparent automatic nature of level-1 perspective taking (Samson et al., 2010).

Theta power during the encoding interval was also modulated by cue type. For the social cue there was a significantly smaller increase in theta power (in relation to baseline) for the valid condition, where working memory for the status information was better than in the invalid condition. Theta oscillatory power increases reflect effort (Gevins et al., 1997; Jensen & Tesche, 2002; Klimesch, 1999), therefore this result indicates that less effort was needed for encoding of status information when cued by gaze. Contrastingly, for the non-social cue there was a significantly larger increase in theta power for the valid condition where again working memory was better for the status information compared to the invalid condition. This indicates that more effort was made for the validly cued location, leading to better encoding of status information.

The effects in the social condition may be explained by the tendency for humans to automatically track another's perspective (e.g. Kessler et al., 2014; Kessler & Rutherford,

2010; Michelon & Zacks, 2006; Samson et al., 2010). It is possible that less effort is required in the valid gaze condition due to this ease of (level-1) perspective taking. Indeed, it has been stated that ‘...objects falling under the gaze of others acquire properties that they would not display if not looked at’ (p. 254 Becchio et al., 2008) and research by Shteynberg (2010) indicates that stimuli experienced as part of a social group are more prominent due to what is termed a “social tuning” effect. Alternatively, it is possible that due to tracking the perspective of the avatar, yet, without a target, it is more difficult to disengage from the invalid location, leading to greater theta power required in that condition.

In contrast to our expectations, there were no effects of cue validity on alpha and theta power during the retrieval interval, indicating that effects are specific to encoding. Research has shown stronger theta power at parietal-to-central electrodes during successful encoding (Khader et al., 2010), though generally memory related theta power changes tend to occur in anterior sites, (Jensen & Tesche, 2002). For the gaze cue effects appear across temporal, parietal and occipital electrodes, with some differences in anterior electrodes, whereas for the stick cue the differences occur posteriorly. Parietal theta may promote successful memory encoding, while frontal theta may mediate general attentional processing (Khader et al., 2010). Due to the nature of the study, we do not have clear information about the sources of the power changes, however the differences in the nature and location of effects suggest that there are differences in how social and non-social cues influence memory processes during encoding.

Here we aimed to understand the influence of social cues on working memory, expanding on previous work in this area (Dodd et al., 2012; Gregory & Jackson, 2017). Using a realistic immersive environment and dynamic social and non-social cues we found that social and non-social cues had similar effects on working memory performance, but that this was underpinned in differences in neural activations. While alpha oscillations were

comparable in their modulation of effects, theta oscillations during encoding told a different story. Results therefore indicate that while attention cuing does impact working memory in a similar fashion for the social and non-social cues presented, the underlying neural mechanisms differ, with objects seen under joint attention appearing to require less processing power to be encoded. This provides further evidence for the idea that eye gaze offers a specialised signal in human cognition (Becchio et al., 2008; Kamps & Southgate, 2020; Samson et al., 2010; Shteynberg, 2010).

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Supplementary materials for: EEG alpha and theta signatures of socially and non-socially cued working memory in virtual reality

Creation of Avatars

Four male and four female identities were created using Adobe Fuse (discontinued software), showing neutral facial expressions and wearing plain grey clothing. The avatars were given a bone structure for movement and placed in a seated position using Adobe Mixamo (www.mixamo.com) and were then loaded into Unity where the inbuilt animator was used to add head movement animations, no other movements were used, and so the avatars were rigid except for the looking movement.

Avatar rating

A separate group of participants ($n = 61$) viewed the Avatar stimuli online and rated them using the Godspeed (Bartneck et al., 2009) questionnaire to acquire a standardized measure of anthropomorphism, animacy and likeability for the avatars, further they rated the avatars on human personality traits (Oosterhof & Todorov, 2008). Participants also rated a generic humanoid robot as a comparison (<https://osf.io/4amb6/>). Participants viewed the avatars and the robot first looking down at a table and then up to look at the participant. They were asked to rate the now stationary figures based on their initial impression during the movement. Participants first completed the traits ratings and then the Godspeed ratings, prior to seeing the Godspeed questions they again viewed the brief video showing the movement of the humanoid or robot avatar. They rated each identity on all points before moving on to the next identity and identities were shown in a random order for each participant. See table 1 (main paper) for the results, a full breakdown of results by avatar identity including the raw data is available on the OSF: <https://osf.io/h89tz/>. Importantly, the trait ratings were within the range seen for images of human faces showing neutral expressions and the Godspeed results were significantly more humanlike for the human avatars than the robot control. Videos of the stimuli can be viewed here: <https://osf.io/s9xmu/> and the stimuli can be downloaded for use in your own research.

E1: programming error

For the status question, while the accuracy of the answer was recorded, we did not record enough detail about the target at encoding, nor the response made by the participant at retrieval to be able to perform d' -prime sensitivity analysis as initially planned. Specifically, we did not have enough detail to know if a correct response could be counted as a hit or as a correct rejection or if an incorrect response was a miss or a false alarm.

This error has been fixed in the uploaded experiment so that if replicated using this, the data will be available. Also, as the error was caught during testing, some participants data does contain this detail.

Supplementary analysis for behavioural data Experiment 1: Reaction times

A repeated-measures ANOVA was conducted on reaction times from correct response trials only for the location and status data separately with cue type (Social vs Non-Social) and cue congruency (valid, invalid) as within-subjects variables.

For the Location data, reaction times were not statistically different for the social ($M = 1.029s$, $SD = 0.203s$) and non-social ($M = 1.032s$, $SD = 0.265s$) cuing conditions, $F(1,48) = 0.011$, $p = .917$, $\eta_p^2 < .001$, $BF_{incl} = 0.155$. There was also no difference in reaction times between the valid ($M = 1.028s$, $SD = 0.221s$) and invalid ($M = 1.034s$, $SD = 0.215s$) condition, $F(1,48) = 0.533$, $p = .469$, $\eta_p^2 = .011$, $BF_{incl} = 0.158$. There was also no significant interaction between cue type and validity, $F(1,48) = 0.005$, $p = .946$, $\eta_p^2 < .001$, $BF_{incl} = 0.219$.

For the Status data, reaction times were not statistically different for the social ($M = 1.495s$, $SD = 0.275s$) and non-social ($M = 1.456s$, $SD = 0.272s$) cuing conditions, $F(1,48) = 1.069$, $p = .306$, $\eta_p^2 = .022$, $BF_{incl} = 0.432$. There was also no difference in reaction times between the valid ($M = 1.476s$, $SD = 0.259s$) and invalid ($M = 1.475s$, $SD = 0.237s$) condition, $F(1,48) = 0.001$, $p = .972$, $\eta_p^2 < .001$, $BF_{incl} = 0.153$. There was also no significant interaction between cue type and validity, $F(1,48) = 1.589$, $p = .214$, $\eta_p^2 = .032$, $BF_{incl} = 0.274$.

Individual differences data for the behavioural task:

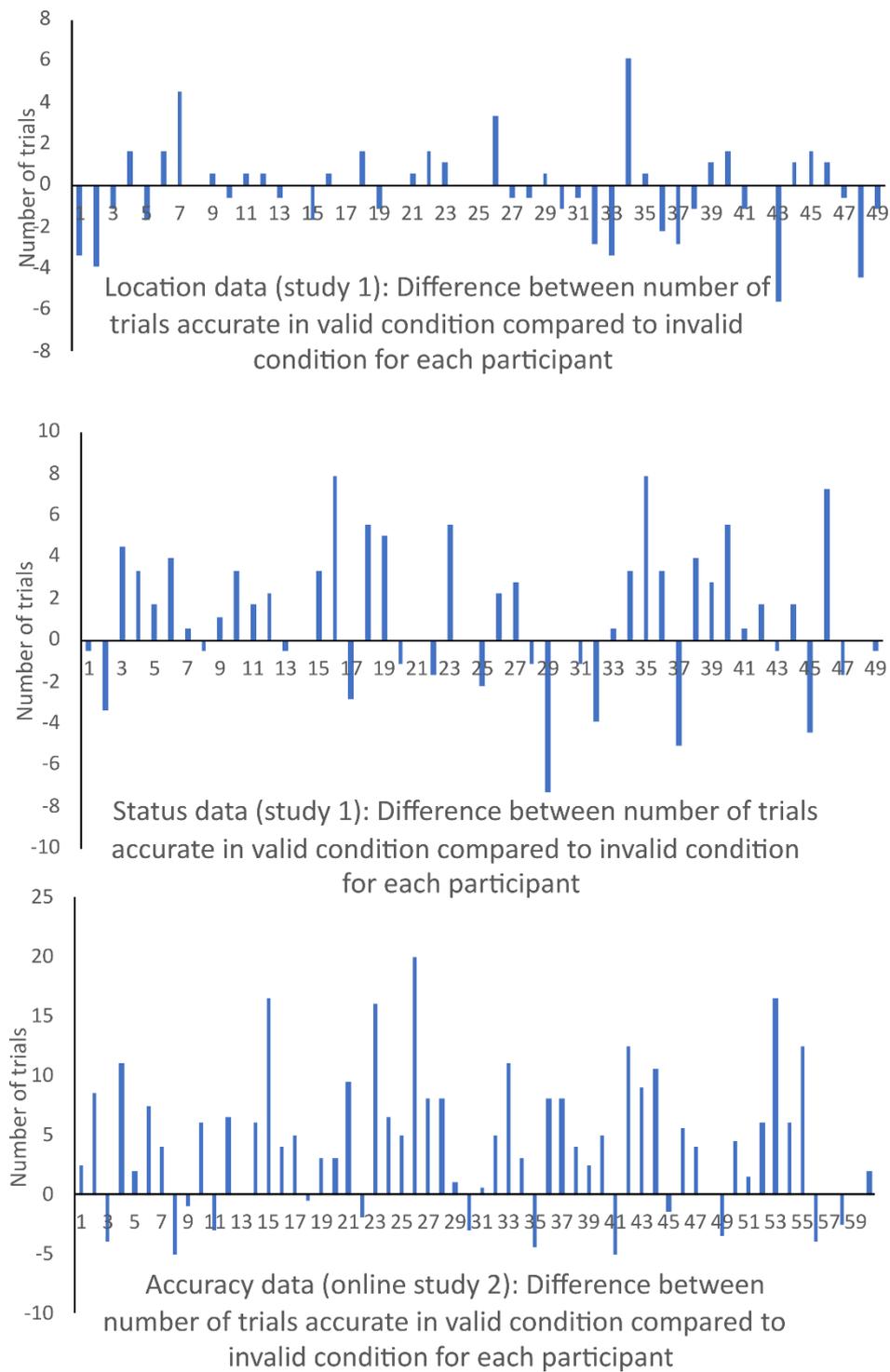
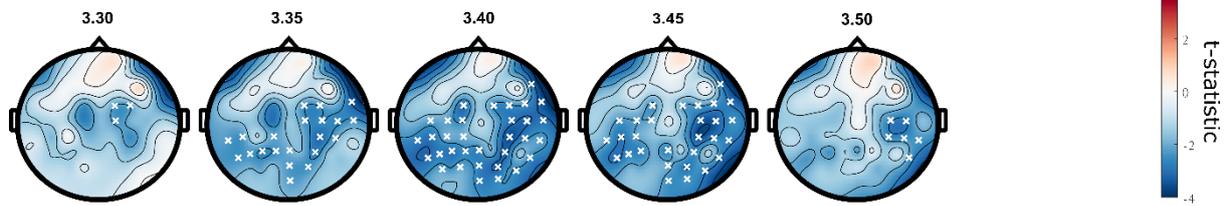


Figure 1. Figure shows the difference between the number of trials correct in the valid trials minus the number correct in the invalid trails for each participant for the location question in study 1, the status question in study 1 and for the task in study 2 across both cue types. A positive result indicates a facilitation effect.

Cluster plots across full time window:

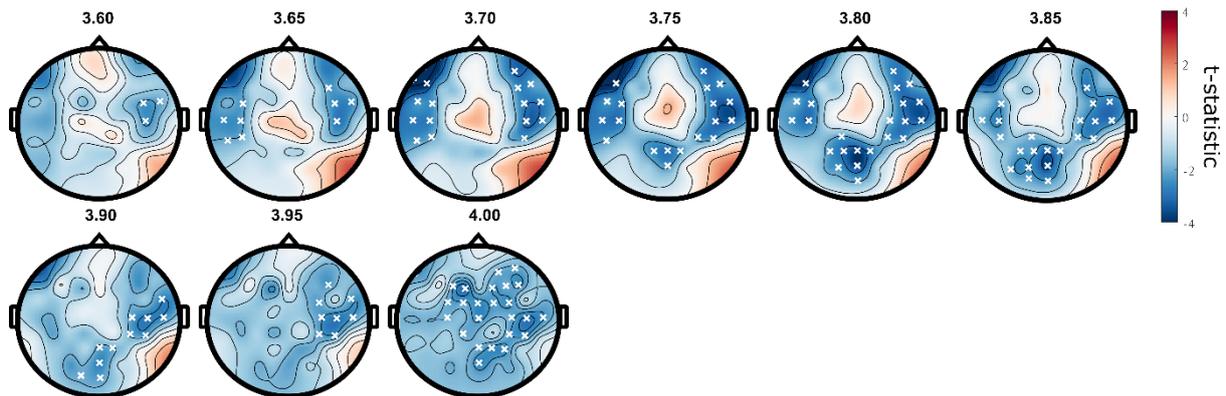
Cue shift interval (2.5s - 3.5s)

A. Social compared to Non Social: Theta (3-7 Hz)



Encoding interval (3.5s - 4s)

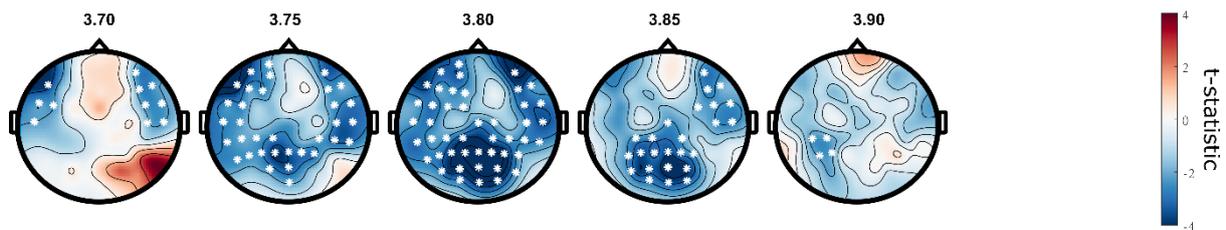
B. Social Gaze Cue: Valid compared to Invalid: Theta (3-7 Hz)



C. Non-Social Stick Cue: Valid compared to Invalid: Theta (3-7 Hz)



D. Social Gaze Cue: Valid compared to Invalid: Alpha (8-12 Hz)



E. Non-Social Stick Cue: Valid compared to Invalid: Alpha (8-12 Hz)

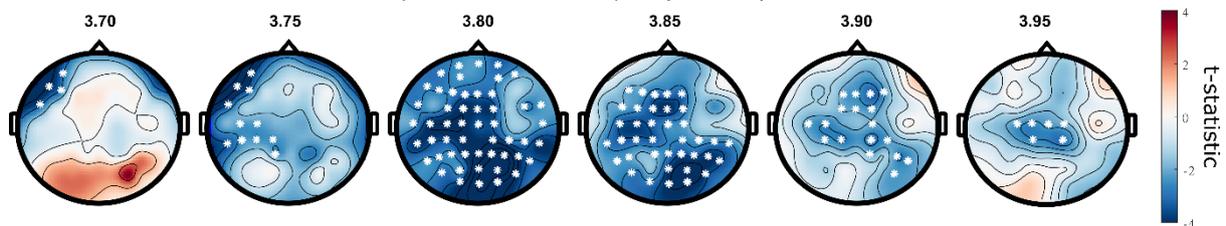


Figure 2. Figure shows the full cluster plots of the effects across the time window. The social gaze and non-social stick cue are contrasted during the initial cue shift window (Theta effects only, panel A). Valid and invalid conditions are contrasted for each cue separately in the

encoding window, theta band effects in gaze cues (B) and the stick cue (C), Alpha band effects in the gaze cue (D) and stick cue (C). Cluster significance levels from a two-tailed test are indicated as x $p < .05$, * $p < .01$.

EEG artifacts

Example eye blink artifact



Example eye movement (saccade) artifact



Example heart artifact



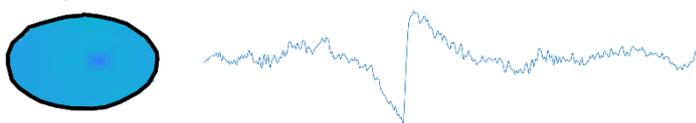
Example muscle artifact



Example electrical shift artifact



Example linear trend artifact



Example high frequency, high amplitude artifact

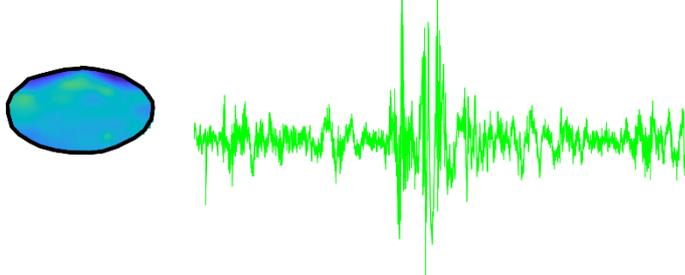


Figure 3. Figure shows example artifacts that were identified through the Independent component analysis (fastica)

ERP analysis

The pre-registration stated that we would look for known event-related brain potential (ERP) components, specifically, the early directing attention negativity (EDAN), a negative deflection over posterior scalp locations, elicited between 200 and 300 ms post-cue. This has been found previously for arrow cues but not gaze cues (Hietanen et al., 2008). In addition, we stated that we would also look for the anterior directing attention negativity (ADAN), an enhanced negativity over anterior scalp locations contralateral to the cued location, elicited between 300 and 500 ms post-cue, this component has been seen for gaze cuing (Holmes et al., 2010).

Note that during the time window investigated the cue was in motion which is different to previous studies of this component.

ERP analysis was performed on the same pre-processed data as the time frequency analysis. Data was baseline corrected in using `ft_timelockbaseline` from 200ms to 0ms pre cue shift using the average method. To get the EDAN/ ADAN data, the procedure was as stated in Holmes, et al., (2010). For the avatar and stick cues separate averages were computed for each laterality. For the EDAN the ipsilateral waveform was computed as the average of the left-sided electrodes (P7, PO7) to the leftward cues and the right-sided electrodes (P8, PO8) to the rightward cues, and the contralateral waveform was computed as the average of the left-sided electrodes to the gaze-rightward faces and the right-sided electrodes to the gaze-leftward faces over the 200-300ms post cue time interval. For the ADAN the same procedure was applied but using left electrode positions F5, F7, FC5, FT7 and right electrode positions F6, F8, FC6, FT8 over the 300-500ms post cue time interval. This data can be found on the OSF: <https://osf.io/s9xmu/>.

These mean amplitudes in each condition for the EDAN and ADAN analyses were entered into a 2 (Cue type) \times 2 (laterality) repeated measures ANOVA.

EDAN

There was no main effect of cue type, $F(1, 46) = 2.025$, $p = .162$, $\eta^2 = 0.042$, no main effect of laterality, $F(1, 46) = 0.078$, $p = .781$, $\eta^2 = 0.002$, and no interaction between cue type and laterality, $F(1, 46) = 3.968$, $p = .052$, $\eta^2 = .079$, meaning that there was no EDAN component present for either condition (see figure 4). However, see figure 5 for an extension of the time window to incorporate the encoding and maintenance interval. Please note that this data shows just the electrodes selected for the EDAN analysis and is based on the cue shift location and its laterality to the electrodes selected. This means that the data does not relate to the congruence effect at the encoding interval (i.e. whether the targets were in the cued or un-cued position).

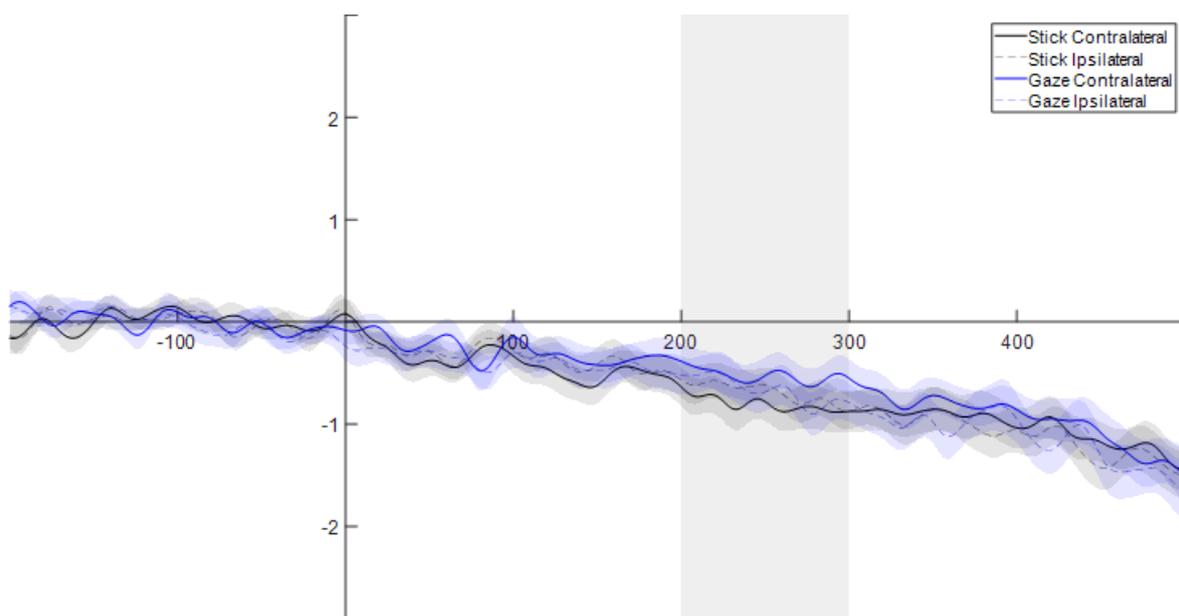


Figure 4. Figure shows the grand averaged ERP data for posterior electrodes: P7, P8, PO7, PO8, evaluated for EDAN effects for the avatar and stick cues separately. Shaded areas show 1 standard error above and below the mean. Time 0 is the time at which the cue started to shift, at 500ms the targets appeared on screen (500ms SOA).

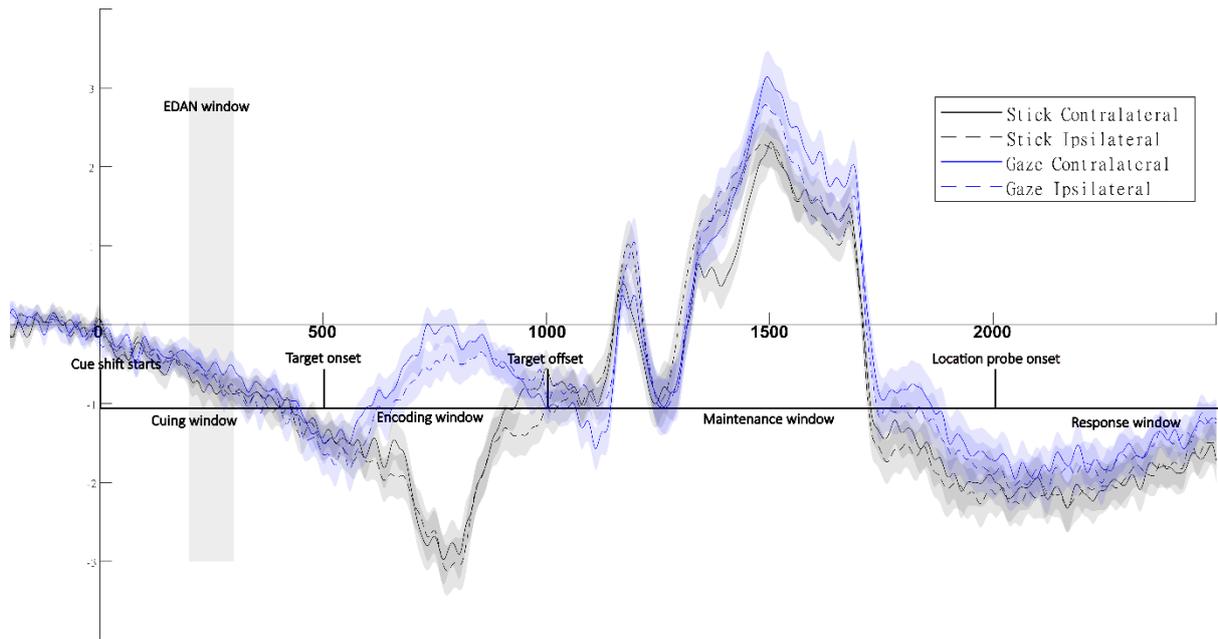


Figure 5. Figure shows the same data as in figure 2 over an extended time window. Figure shows the grand averaged ERP data for posterior electrodes: P7, P8, PO7, PO8, evaluated for EDAN effects for the avatar and stick cues separately. Shaded areas show 1 standard error above and below the mean. Time 0 is the time at which the cue started to shift, at 500ms the targets appeared on screen (500ms SOA). Other key time points are labelled: 1000ms: target offset, 1000ms-2000ms: maintenance window, 2000ms: probe onset (response window). Note that this data does not relate to the congruence effect, however, it is interesting to note the difference between gaze and stick cueing conditions during the encoding window. This is likely to reflect the marked difference observed in theta oscillations reported in the main text, where there was a significant effect between the two conditions during encoding with a central-posterior topography.

ADAN

Repeated measures ANOVA, main effect of cue type, $F(1, 46) = 10.817$, $p = .002$, $\eta^2 = 0.190$. This was due to a more positive mean amplitude in the stick condition ($M = 0.4105$) compared to the gaze condition ($M = 0.0815$).

There was a main effect of laterality, $F(1, 46) = 63.688$, $p < .001$, $\eta^2 = 0.581$, this was not in the expected direction with mean amplitudes being more positive at contralateral ($M = 0.6450$) than ipsilateral electrode locations ($M = -0.1532$) thus not showing the ADAN component in the data

There was no interaction between cue type and laterality, $F(1, 46) = 2.773$, $p = .103$, $\eta^2 = .057$, showing that there was no significant difference in the ADAN component between the stick and gaze conditions.

The findings show that a lateralized component appears to be present for both gaze and stick, but that the component does not appear to be the ADAN component (see figure 6). Further see figure 7 for an extension of the time window which again incorporates the encoding and maintenance intervals. Again, please note that this data shows just the electrodes selected for the ADAN analysis and is based on the cue shift location and its laterality to the electrodes selected. This again means that the data does not relate to the congruence effect (i.e. whether the targets were in the cued or un-cued position).

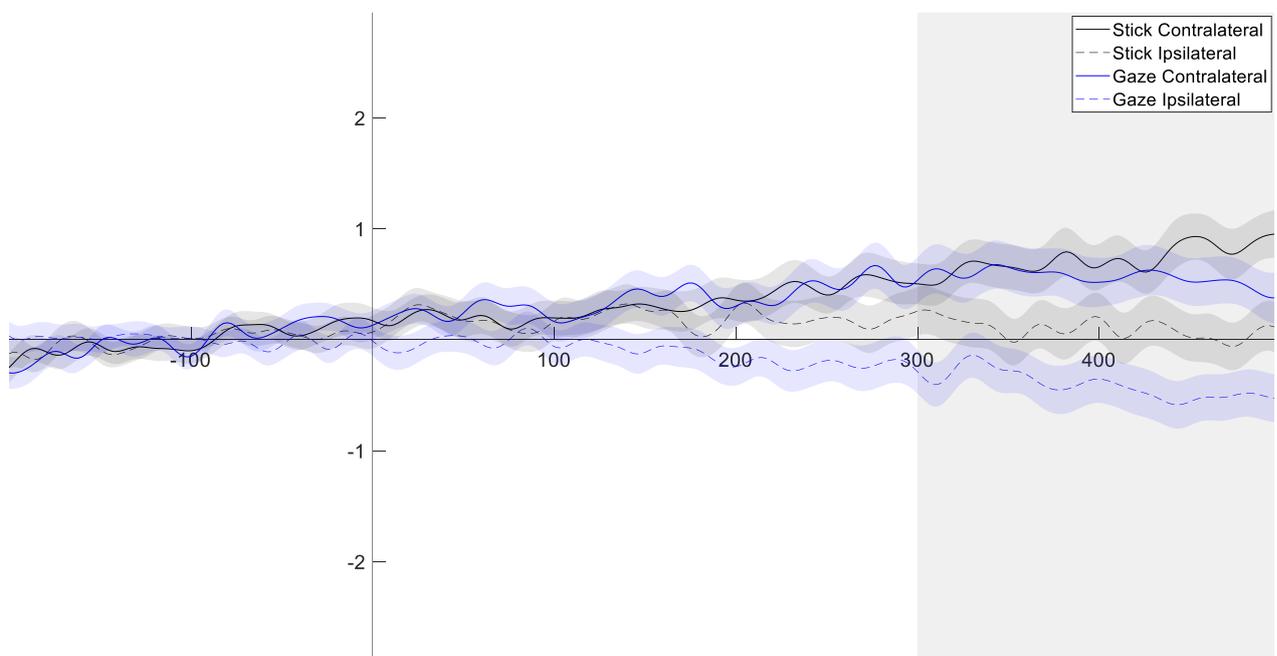


Figure 6. Figure shows the grand averaged ERP data for anterior electrodes: F5, F6, F7, F8, FC5, FC6, FT7, FT8 evaluated for ADAN effects for the avatar and stick cues separately.

Shaded areas show 1 standard error above and below the mean. Time 0 is the time at which the cue started to shift, at 500ms the targets appeared on screen (500ms SOA).

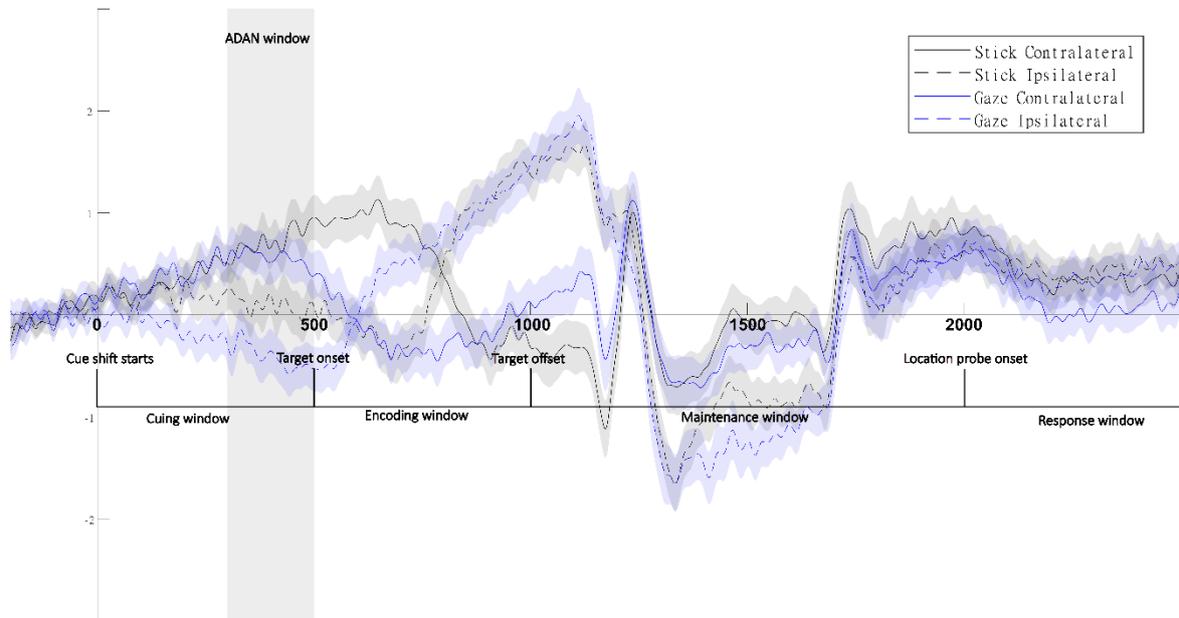


Figure 7. Figure shows the same data as in figure 4 over an extended time window. Figure shows the grand averaged ERP data for anterior electrodes: F5, F6, F7, F8, FC5, FC6, FT7, FT8 which were evaluated for ADAN effects for the avatar and stick cues separately. Shaded areas show 1 standard error above and below the mean. Time 0 is the time at which the cue started to shift, at 500ms the targets appeared on screen (500ms SOA). Other key time points are labelled: 1000ms: target offset, 1000ms-2000ms: maintenance window, 2000ms: probe onset (response window). Note that data does not relate to the congruence effect. While no ADAN effect was seen, there does appear to be a difference between the ipsilateral and contralateral waveforms during the encoding and maintenance windows. These times occur during or after memory item presentation and could reflect eye movement components, but importantly, the pattern appears to be similar for both cue types, therefore any oscillatory differences between cue types reported in the main text are unlikely to be due to eye movement components.

This absence of the ADAN and EDAN components are possibly due to the centralised nature of the cues. Further, here the cue was still in motion during the time tested and so this may also be why these components are absent.

Experiment 2: Behavioural follow up online

Experiment 1 showed an effect of both the social gaze cue and the non-social stick cue on working memory. While the effect of the gaze cue was predicted, the effect of the stick cue was not. Further, the stick cue had some disparate effects, showing better memory for the invalidly cued items in the location task, and better memory for the validly cued items in the status task. Therefore, here in Experiment 2, we test the effects of the two cues in a memory task more consistent with the task used previously with gaze and arrow cues, where only gaze cues showed an effect on memory (Gregory & Jackson, 2017). This task was presented online, thus not in 3D VR, therefore this also allows investigation of whether the effects of the non-social stick cue were due to its virtual presence.

Method

Participants

60 participants (30 females, 30 males, mean age 28 years ($SD = 9$), range 18 - 57 years) were recruited online through Prolific for payment. All participants reported having normal or corrected to normal vision. Ethical approval was obtained from the Aston University Research Ethics Committee.

Apparatus and stimuli

Stimuli were presented using PsychoPy3 through Pavlovia, an online study platform that has high timing accuracy (Bridges et al., 2020). The task was hosted in a web browser and so participants completed the task using their own desktop/ laptop computers. Chrome or Firefox browsers were recommended but it is unknown which were used. The study and

materials can be downloaded here: <https://osf.io/s9xmu/>, note that there is a 500 ms timing discrepancy between online and desktop-based presentation in the programmed study due to the use of java script for online presentation, this is explained in detail in the notes attached to the study. The avatar and the stick cue were recorded from unity, thus the movement matched that seen in experiment 1. Memory items were items typically found on a table, from experiment 1 we included the teapot, bowl, cup and plate and added a banana, an apple and an orange. Each item was displayed in colour at encoding, however at retrieval items were presented in greyscale so that memory for the object identity and not presence of a specific colour was probed. These objects were made into png images with transparent backgrounds to impose over the top of the cue video, on either the left or right side of the table (see figure 8).

Design

Within subjects' independent variables were cue type (avatar, stick), cue target validity (50% valid, 50% invalid) pseudorandomised. Other manipulated variables were, item presence (50% present, 50% absent), items location (50% left, 50% right). The avatar seen in each condition (8 identities) were pseudorandomised as were objects shown. There were 192 trials per cue type divided equally such that there were 48 trials per condition (valid present, valid absent, invalid present, invalid absent). The experiment was separated into two cue type sections, within which there were two blocks of 96 trials. The programme randomly selected which cue type would be shown first and participants were informed of the cue type before beginning each section. The dependent variable was accuracy to correctly identify whether the probe item had been present in the previous array.

Procedure

To become familiar with the task an 8-trial practice session preceded the main experiment containing examples of both cue types and validity conditions. As in Experiment

1, cue condition was blocked so that the participants saw either the social avatar condition or the non-social stick condition first. Participants were encouraged to take breaks. The cue movement replicated experiment 1, however, here the task was to remember the items presented, rather than status or location. A trial proceeded as follows, a fixation cross was presented at the centre of the screen for 1100ms, then replaced by the video of the cue. The cue was initially presented looking/ pointing at the table (500ms), then up to the participant (1000ms), and then either to the left, right. After the cue had finished shifting (500ms SOA from start of shift) 5 memory items were presented either on the left or right of the table for 100ms (as seen in Gregory & Jackson, 2017), after a 1000ms maintenance they saw 1 item and responded with whether this was one of the items seen in the previous display. There was no response window cut off. As with experiment 1, feedback was presented throughout to keep participants engaged. Figure 8 illustrates an example trial sequence for each cue type.

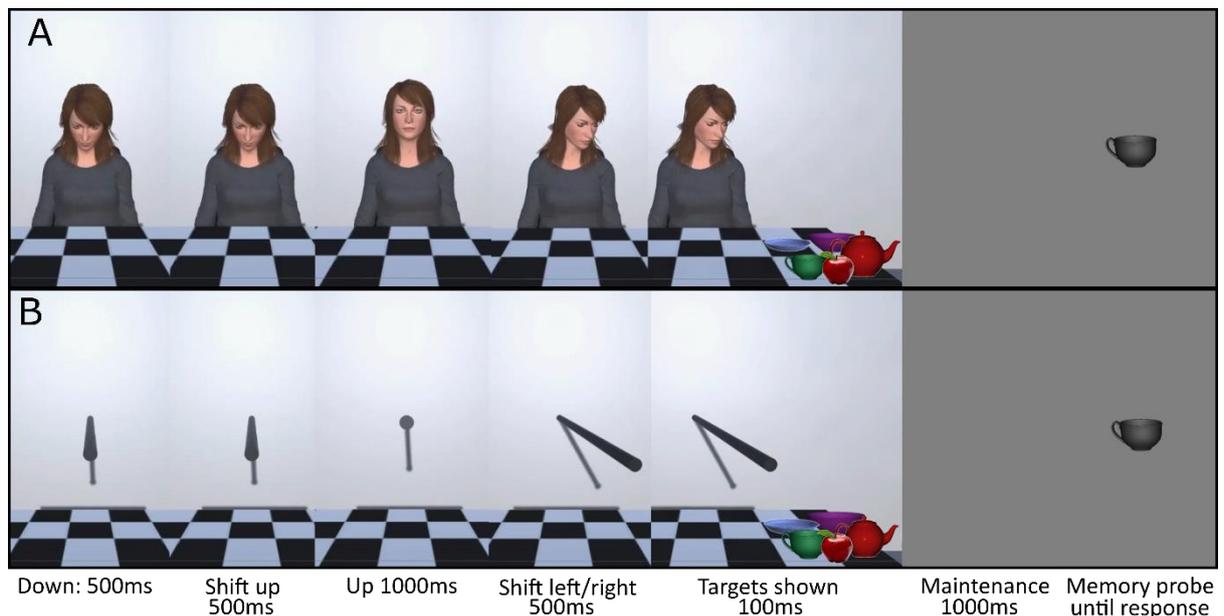


Figure 8. Illustration of the trial procedure, adopting the parameters of the traditional central cuing paradigm the cue remained on screen for the entire trial (e.g. Driver et al., 1999; Friesen & Kingstone, 1998).

Results

While it is possible to calculate d' for these data, to be consistent with experiment 1, we again present accuracy data for accurately reporting that the probe item was present or absent in the previous display. Running the analysis with d' values results in equivalent findings. We conducted a repeated measure ANOVA with cue type (social avatar, non-social stick) and validity (valid, invalid) as within subject factors. This showed a non-significant main effect of cue type, $F(1,59) = 2.612$, $p = .111$, $\eta p^2 = .042$, $BF_{\text{incl}} = 0.70$ meaning that memory accuracy was not statistically different for the social ($M = 0.60$) and non-social ($M = 0.61$) cuing conditions. There was a significant main effect of validity, $F(1,59) = 33.331$, $p < .001$, $\eta p^2 = .361$, $BF_{\text{incl}} > 100$ with validly cued items ($M = 0.63$) being recalled more accurately than invalidly cued items ($M = 0.58$) items. There was no significant interaction between cue type and validity, $F(1,59) = 2.666$, $p = .108$, $\eta p^2 = .043$, $BF_{\text{incl}} = 0.39$ meaning that the effect of cue validity on memory was not modulated by cue type (see Figure 2 in main paper).

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