- Supplementary information -

Temporal dynamics of object location processing in allocentric reference frame

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1 The CAVE laboratory

Figure S1. The CAVE laboratory. The Experimenters are preparing a participant for the experiment in the picture. The CAVE is 3 by 3 meters wide and has a height of two meters. All persons in the picture consented to publish.

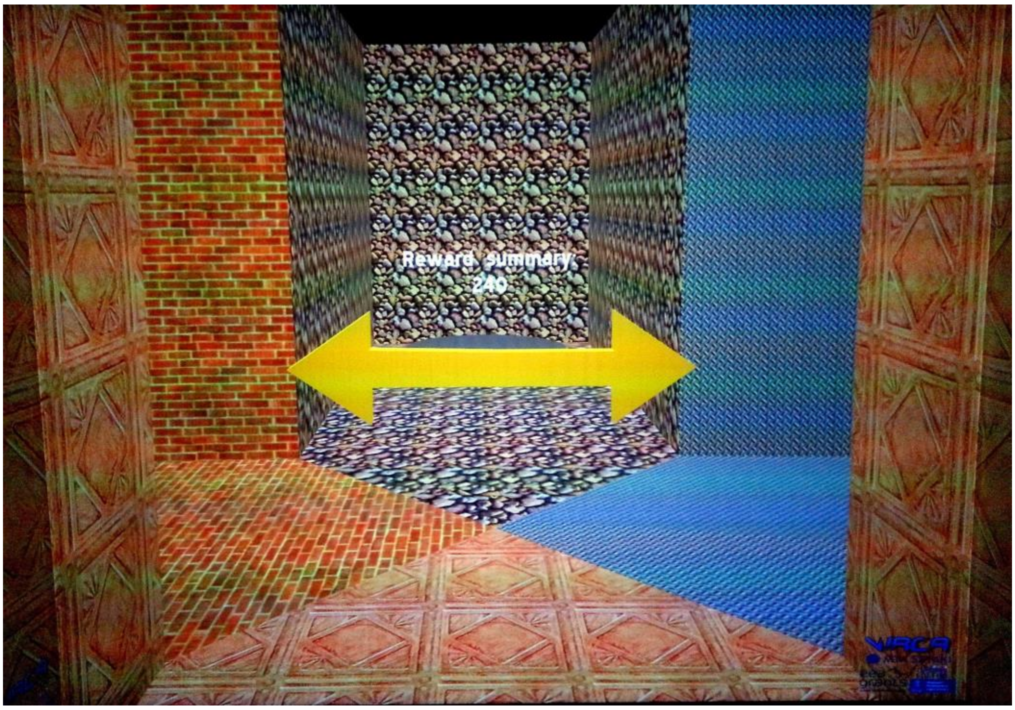


Figure S2. View of the experiment from the position of the participant. The participant saw a life-sized virtual maze in 3D using stereoscopic rendering. Note that in this picture the stereoscopic rendering is switched off for visibility of the scene without goggles.

2 Analysis of the practice phase

The electrode caps were mounted on the participants' head and we had recordings from the practice phase. The ERPs in the practice phase showed the same pattern as that of the experimental phase. The statistical analysis on PO8 revealed a significant difference between 90 and 128 ms both with FDR and Cluster Correction. The peak detection showed numerically the same difference as in the experimental phase but it did not reach significance ($t(33) = 1.92$, $p = .175$). The NT170 effect was not observable here either ($p > 0.9$). As observable in Fig S3, the data was noisier here. Although, in itself the analysis of the practice phase does not answer the question of whether the difference is attributable to processing of places in egocentric or allocentric reference frames, together with the results of experimental phase we can conclude that the participants were processing the alleys in allocentric reference frames from the beginning of the experiment. Similar to the results of the experimental phase, the behavioural responses of the practice phase showed a win-stay response strategy ($\beta = .36$, $z(33) = 8.41$, $p < .001$, $M_{prop\ win\ stay} = .59$).

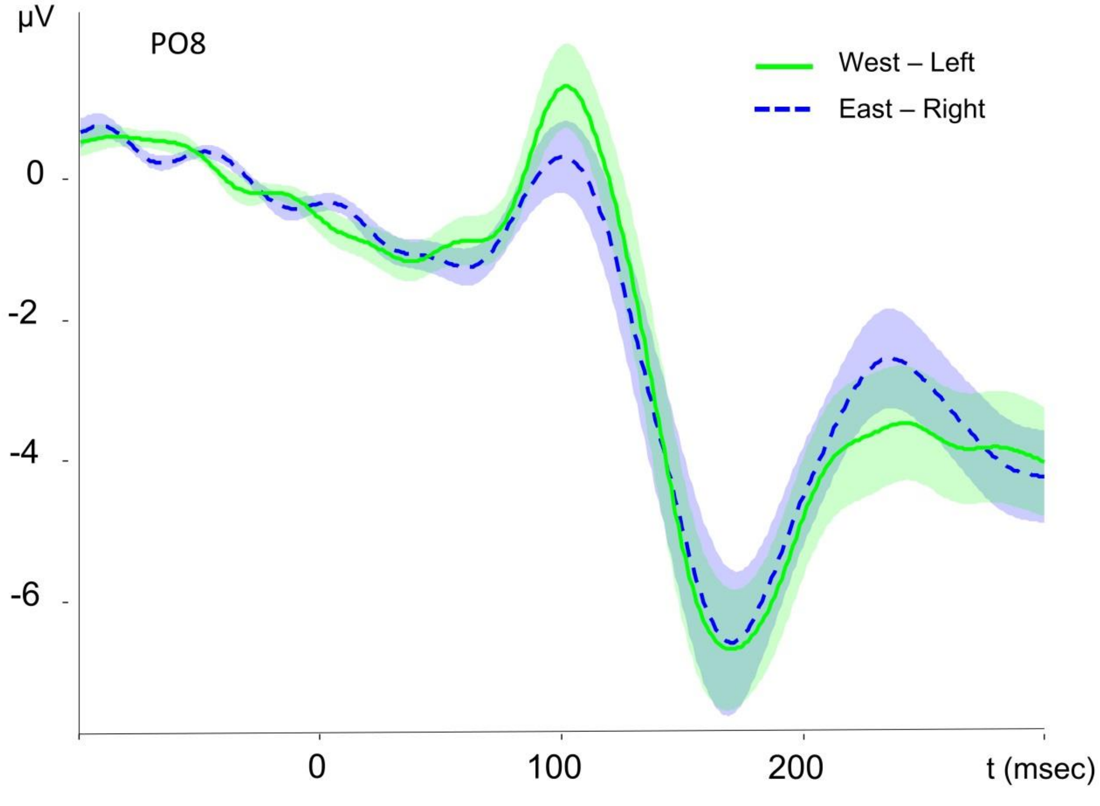


Figure S3. ERPs in the practice phase. The pattern of P1 amplitudes observable in the practice phase is similar to that of the experimental phase.

3 Comparison of the two halves of the Experimental phase

We statistically compared the first and second half of the experiment to investigate whether there is any shift from egocentric to allocentric reference frame use or vice versa during the experiment. We found a slight increase in preference for the same rewarded place in the second half of the experiment ($t(33) = -2.2348$, $p = 0.032$). This effect is not very strong but could be an indicator of strategy consolidation. It is possible that first, participants were experimenting more with different strategical choices, and later stuck to a more reward oriented strategy (i.e., the analysis only checks if there is higher chance for the same allocentric place after a reward). In contrast, there is no ERP difference in the effects between the first and second halves (see Fig S4 and S5). To note, both the P1 ($F_{Allo}(1,33) = 5.99$, $p = .020$, $\eta^2_p = .15$; F_{Ego} $(1,33) = 5.76$, $p = .022$, $\eta^2_p = .15$) and the NT170 latencies ($F_{Allo}(1,33) = 13.71$, $p = .001$, $\eta^2_p = .29$; $F_{Ego}(1,33) = 18.69$, $p < .001$, $\eta^2_p = .36$) differed between the first and second half. We hypothesize that this difference is due to a learning effect: The texture-alley association became more automatic during the task, and hence the spatial context related information was easier to retrieve.

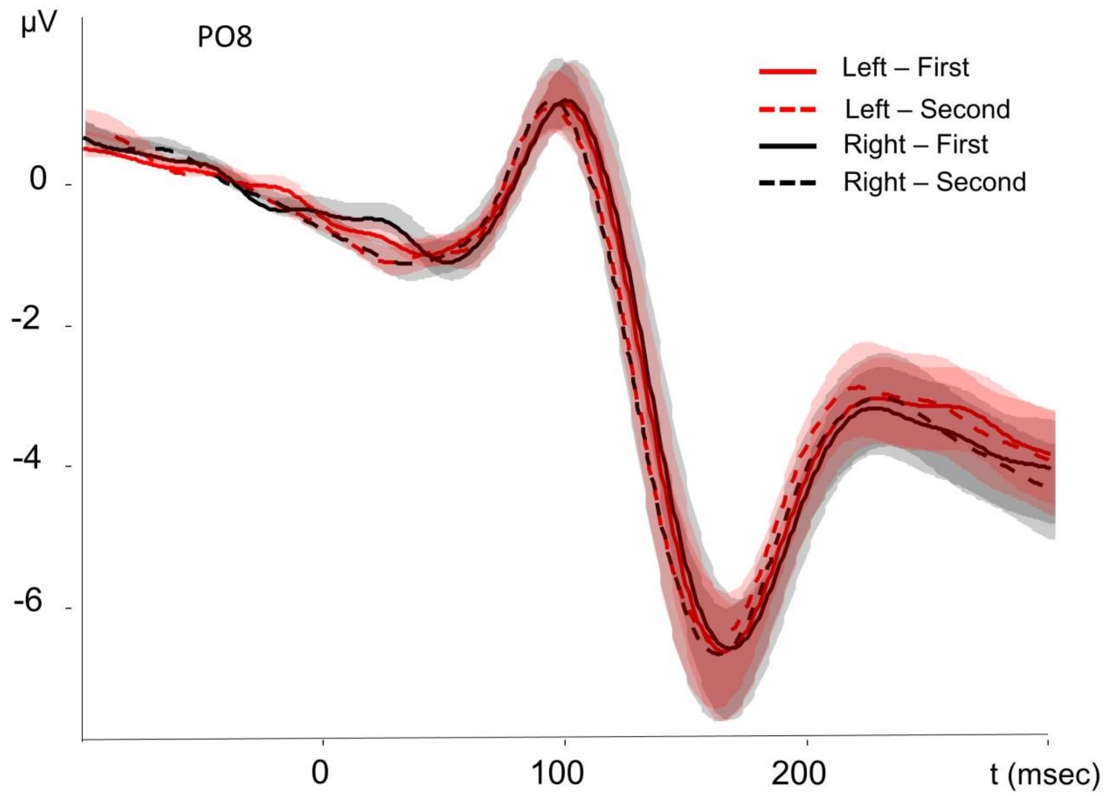
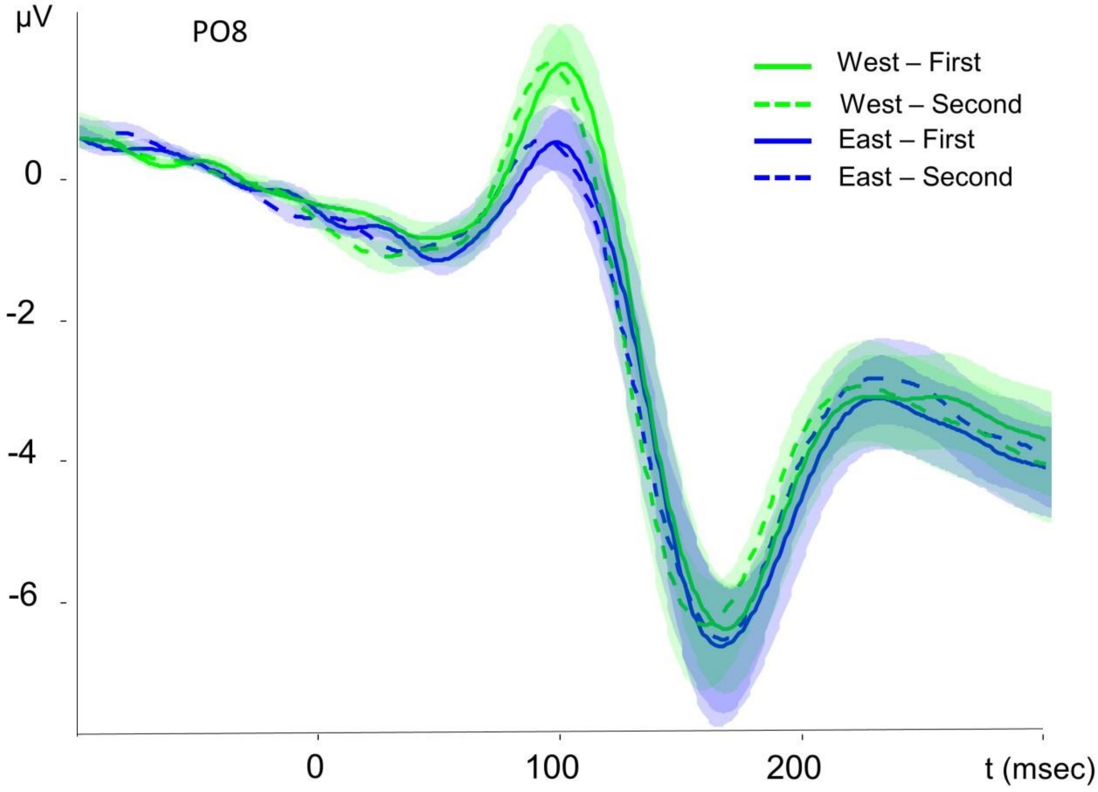


Figure S4. ERP averages to left and right reward locations in the first and second half of the experiment. The egocentric location specific effect is lacking throughout the experiment.



Supplementary Figure 5. ERP averages to East and West reward locations in the first and second half of the experiment. The allocentric location specific effect is present throughout the experiment.

4 Analysis of the different strategy groups

We have conducted in-depth analysis to investigate the potential behavioural and electrophysiological correlates of the different strategy groups. In the analysis of the behavioural data, we found that participants were following often an allocentric win-stay strategy (see Section 3.1). This result can be used also to identify groups of participants expressing more allocentric and more egocentric win-stay responses. If we simply split the participants above 50 % of same alley choices after reward and after teleportation as allocentric and below 50 % percent as egocentric, we would get 26 participants following allocentric and 8 participants following egocentric strategy. However, in that case, we did not take into account that the ratio of same alley choices can be different of 50 % just by chance, which would bias our results. Therefore, we classified participants as egocentric or allocentric only when the preference score was more extreme than what one would expect if choices were made by random. To statistically asses this, we generated a null-distribution using 1000 Bernoulli series of length 100 (this is the expected number of trials fulfilling the criteria as being after reward and after teleportation). Then we calculated the p values for each participant's preference scores (probability of the value or any more extreme values in the null distribution). Based on this we identified 22, 7, and 5 participants following *allocentric*, *unknown*, and *egocentric* strategies, respectively (Fig S6).

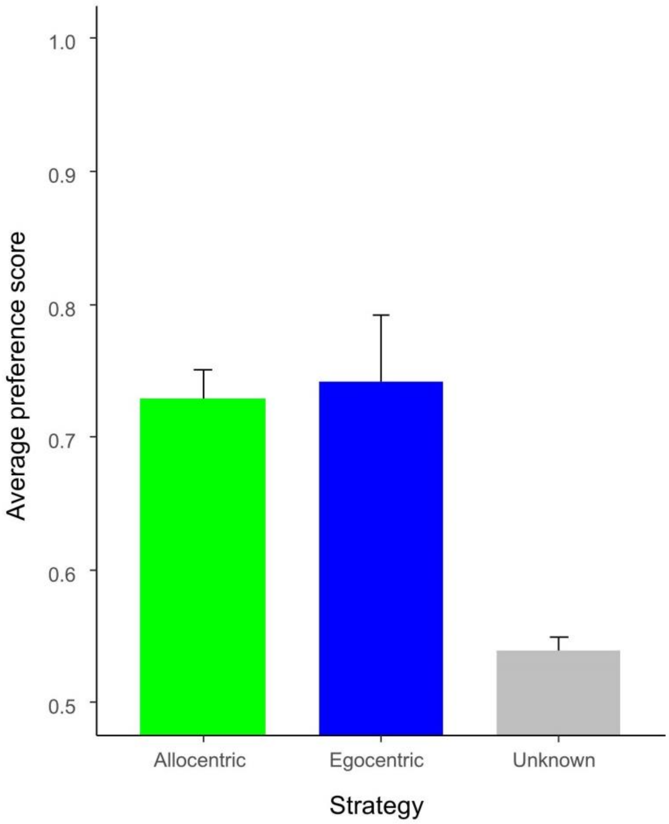


Figure S6. Average preference of win-stay responses in the three strategy groups.

The average size of difference was rather similar for the egocentric and allocentric subgroups (see Fig S6). We investigated also the average decision times for participants in both groups, and – although they did not differ significantly – decision times are numerically the longest in the unknown strategy group ($M_{unknown}$ = 937.86 ms, $SE_{unknown}$ = 104.33, $M_{egocentric}$ = 785.60 ms, $SE_{egocentric}$ = 186.83, $M_{allocentric}$ = 68436 ms, $SE_{allocentric}$ = 59.17, F (2) =1.946, p = .16; see Fig S7), suggesting that these participants were not just picking randomly but rather followed some more complex strategy which was not revealed by this score.

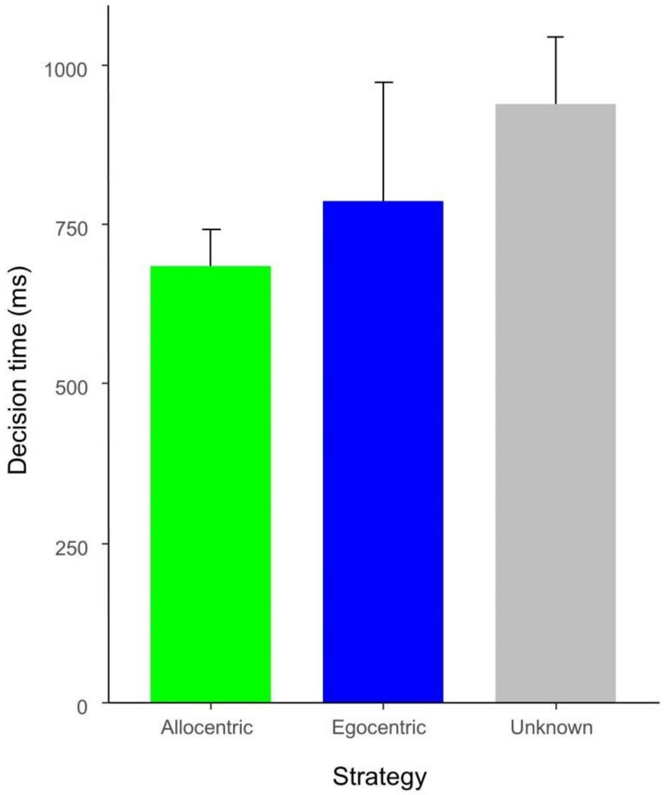


Figure S7. Average decision times in the three strategy groups. It can be seen that the unknown strategy group did not show low decision times, which would have been expected if they were choosing randomly, instead, their seemingly longer reaction times suggest that they were following some strategy that was likely more complex than the simple win-stay pattern.

Analysis of the ERPs of different strategy groups on the PO8 electrode did not reveal Strategy X Allocentric place interaction, only a significant P1 amplitude modulation of Allocentric place from 93 to 112 ms (significant after FDR and Cluster correction) which was present in measured P1 peak amplitudes ($F(1,31) = 6.73$, $p = .014$, $\eta^2_p = .18$). We did not find any other significant differences and all Strategy-wise effects had $p > .1$, also there is no intriguing visual difference either (see Figure S8 and S9). Therefore, although visually it seems that the allocentric P1 modulation is less pronounced in the unknown strategy group (see Figure S8), we cannot conclude that the P1 modulation is in direct relation with the strategy used to solve the task.

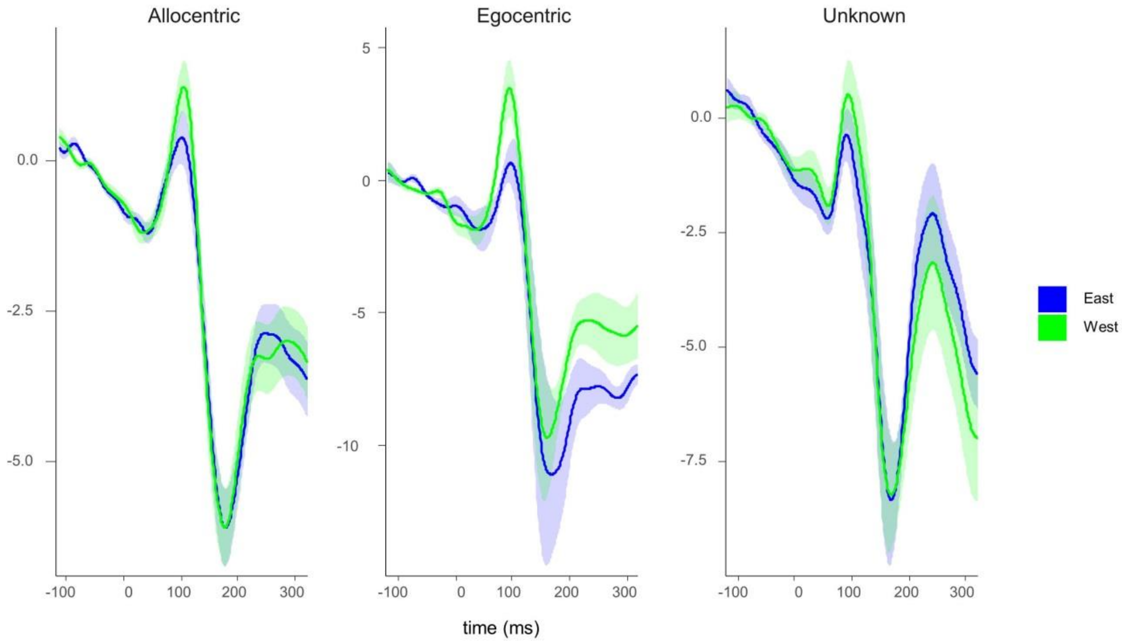


Figure S8. Allocentric P1 modulation in the three strategy groups. The P1 modulation is consistently present for the different strategy groups.

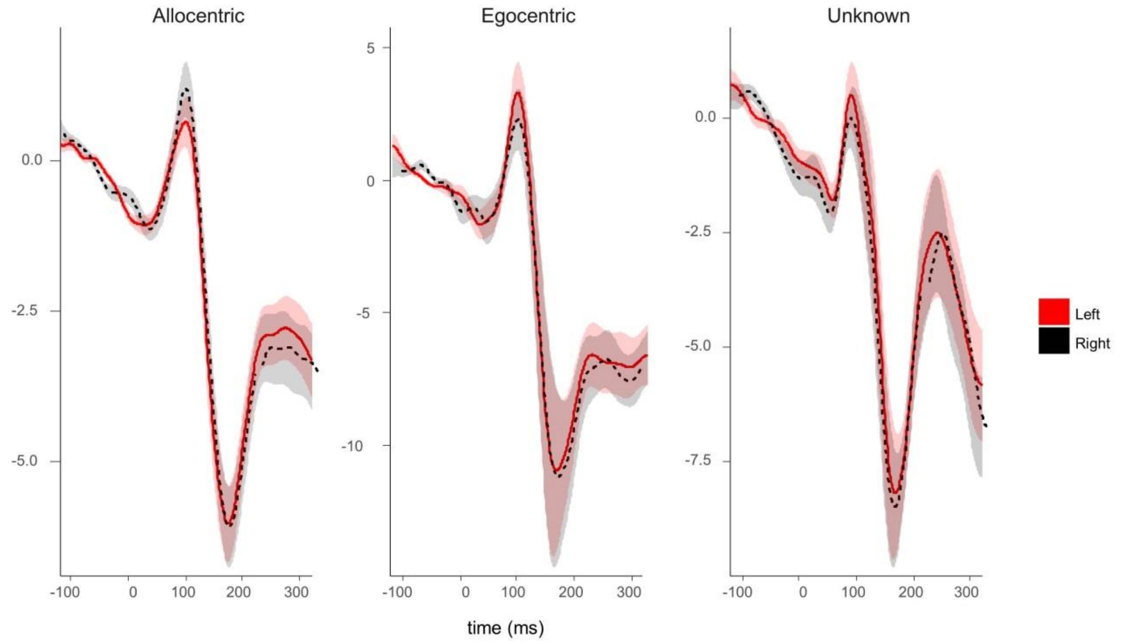


Figure S9. Egocentric ERP contrasts in the three strategy groups. Visual observation of the ERPs did not reveal any potential differences between the ERPs of the strategy groups.

Because the experiment was designed to facilitate the use of an allocentric reference frame, and hence the number of participants following egocentric (5/34) and unknown strategies (7/34) was rather small, these results are useful to facilitate further research but in themselves enable only limited space for interpretation.

5 Analysis of ERP after reward and no-reward trials

We found that participants showed a small lose-shift and a large win-stay tendency in their behavioural responses (see Section 3.1). If the allocentric P1 difference was directly related to the strategy, one could expect difference in the P1 modulation after trials which were rewarded and after trials which were not rewarded. Therefore, we split the EEG data to these two parts and compared ERPs after reward vs. no-reward trials. The analysis did not reveal any difference between reward and no-reward trials ($p > .3$). Consistently with all previous results, the P1 modulation was significant between West and East alleys, here from 100 – 115 ms (after FDR and Cluster correction, see Figure S10) the P1 peak amplitudes differed also on tendency level ($F(1,33) = 3.68$, $p = .064$, $\eta^2_p = .10$).

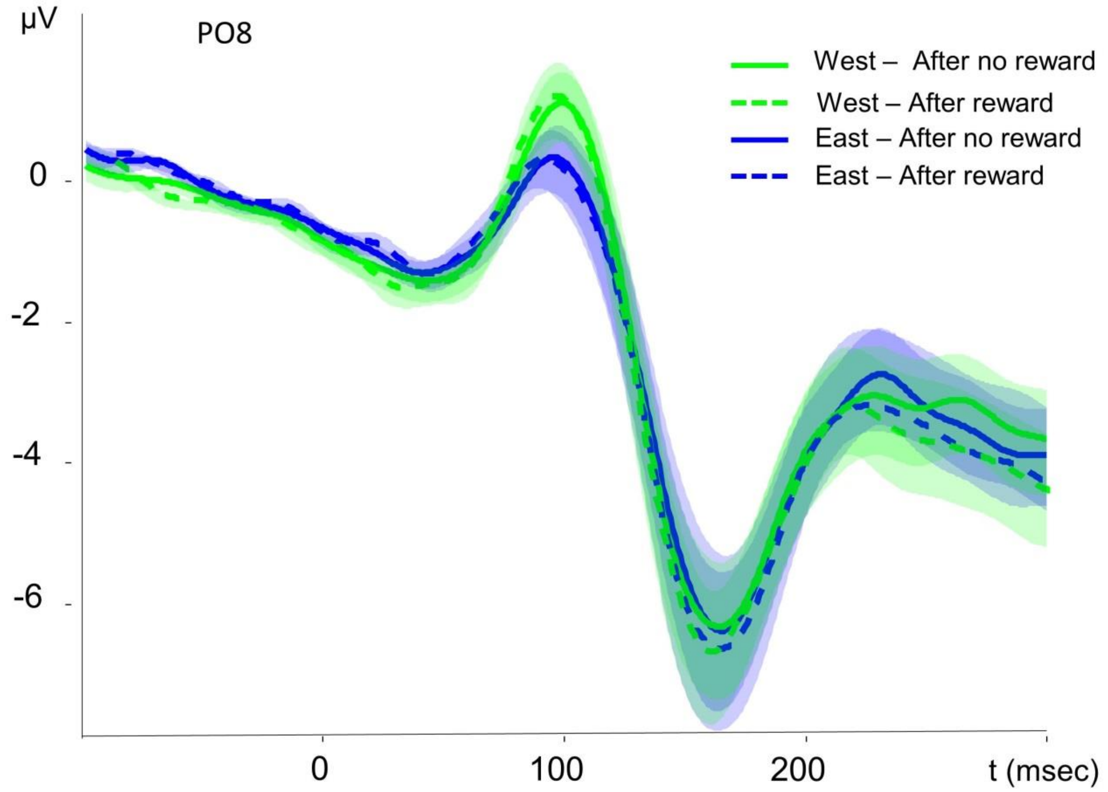


Figure S10. ERP for object in the West and East alleys in trials after reward and after no-reward trials. P1 amplitude modulation is not affect by reward value of the preceding trial.