Efficiency of attentional allocation examined with lateralized EEG power spectra

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Abstract

Lateralized power spectra (LPS), introduced by Van der Lubbe & Utzerath (2013), are a new measure for the lateralization of oscillatory activity in the brain. In the Posner cueing paradigm, EEG measurements can be used to evaluate the influence of cue validity on attentional allocation, as well as the induced or evoked nature of endogenous attentional allocation. This thesis examines the potential of this new measure to detect differences in attentional allocation manifested as lateralized α-band power fluctuations in an endogenous Posner cueing task. An effect of cue validity on behavioral measure and LPS values was found over parietal and occipital cortical areas. Fully predictive cues caused a larger attentional shift and higher LPS values than cues with a low validity. This effect could not be found when LPS values were derived from ERPs, indicating an induced rather than evoked nature of this phenomenon.

Samenvatting

Lateralized power spectra (LPS) werden door Van der Lubbe & Utzerath (2013) geïntroduceerd als een nieuwe maat voor de lateralisatie van hersengolven in het brein. In deze studie werd de LPS toegepast op EEG metingen van een endogene Posner cueing taak. Ten eerste om te verkennen welk invloed de validiteit van de cue heeft op het richten van visuele aandacht, ten tweede om te bepalen of dit effect een directe reactie is op het verschijnen van de cue (evoked) of geinduceerd wordt door het bewuste richten van de aandacht (induced). Als maat voor het richten van aandacht werd gekeken naar α lateralisatie en gedragsdata. Proefpersonen werden meer door de cue beïnvloedt als deze volledig betrouwbaar was dan wanneer valide en invalide cues werden gebruikt. In beide gevallen werd er een cueing effect vastgesteld in de gedragsdata en in LPS waardes gemeten over parietale en occipitale corticale gebieden. Bij volledige cue validiteit was dit effect groter dan bij lage cue validiteit. Wanneer de LPS van ERPs werden afgeleid werden er geen significante resultaten gevonden. Deze bevinding suggereerd dat dit een geïnduceerd fenomeen is.

Introduction

Directing our mental focus to a specific target, be it a thought or a stimulus from the senses, is a very fascinating ability of our mind. A better understanding of the neural processes involved might help to inform the many models researchers have proposed to explain this phenomenon.

This bachelor thesis presents the outcome of a Posner cueing experiment conducted as a follow-up to the work of Van der Lubbe & Utzerath (2013), in which a new measure of spatial attention derived from electroencephalogram (EEG) data was proposed: the LPS (lateralized power spectra). LPS measurements from an endogenous Posner cueing task have been used in this thesis to examine the effect of cue validity on the allocation of visual spatial attention and to determine if those effects were evoked by the cue or induced by top-down attentional control. LPS have been applied to the full EEG to study the changes in α-band activity elicited by the cue as a measure of attentional allocation.

The next two paragraphs will provide an overview of the endogenous Posner cueing paradigm and of the role of α-band activity in the allocation of visual attention, emphasizing the role of cue validity in Posner cueing task and the influence of top-down control on the allocation of attention. This thesis will then explain how the LPS is derived from EEG data and how it was used to study these two phenomena.

The cue validity effect in the Posner cueing paradigm

According to Posner, visual attention can be compared to a spotlight that can be directed away from the point on which the eyes are fixated through exogenous or endogenous influences. This model entails that attention is a limited cognitive resource that facilitates processing of stimuli in the area of the visual field that it is directed to (Posner, Snyder, & Davidson, 1980). Consciously directing one's attention should therefore have a measurable impact on the perception of visual stimuli. The Posner cueing paradigm (Posner, 1980) demonstrates this:

In an endogenous Posner cueing task, participants have to fixate their eyes on a point while their attention is diverted to a different location in the visual field by cues presented at the fixation point. These cues are followed by a target stimulus somewhere in the visual field, which has then to be responded to. Posner has argued that reaction times and identification of the target stimulus are influenced by endogenous cue as follows: valid cues shift attention to the area of the visual field where the target will occur, thereby reducing reaction times and improving target identification. Invalid cues on the other hand require an attentional shift to be performed from the location where the target was expected to occur to where it actually appeared. This has a detrimental effect on reaction times (Posner, 1980) as well as target identification (Bashinski & Bacharach, 1980).

Studies that employ the Posner cueing paradigm typically demonstrate this cueing effect by contrasting performance in validly cued trials with that in a smaller number of invalidly cued trials. A cueing effect on reaction times can be found even when cue validity was as low as ten percent above chance (Vossel, Thiel, & Fink, 2006). Higher levels of cue validity lead to bigger cueing effects in behavioral results as well as neural correlates of covert attention shifts (Gould, Rushworth, & Nobre, 2011; Vossel et al., 2006).

When cue validity is low however, there is little incentive to always consciously direct attention to the cued side, because one could also try a guessing strategy instead. As the reaction to endogenous cues is subject to top-down control, the mechanism by which attention is allocated when cues are not fully reliable might differ from that suggested by Posner (Van der Heijden, 1992). Probabilistic models of attentional allocation predict that humans match the likelihood of attending to a cued location to the cue validity level (Eckstein, Shimozaki, & Abbey, 2002). This probability matching strategy could be prone to undermatching, i.e. disregarding the cue more often than the cue validity level would suggest (Fisher & Mazur, 1997). It is therefore of interest to examine if there is a measurable difference in how the brain responds to cues in different cue validity settings.

Attention and α-band oscillations

Such changes in cortical activity can be measured with EEG to examine whether they are related to the cueing effect. In the case of the allocation of visual attention, the predominant view is that the fronto-parietal attentional control network causes a change in activity in the sensory areas involved, but this process is not yet fully understood (Grent-'t-Jong, Boehler, Kenemans, & Woldorff, 2011).

A growing body of EEG research acknowledges the role that such changes in the synchronization and desynchronization of neural firing patterns in the α-band (approximately 8-12 Hz) might play in the allocation of attention (Grent-'t-Jong, Boehler, Kenemans, & Woldorff, 2011). When a cortical area is involved in the execution of a cognitive task, neural firing desynchronizes in the α-band, which can be measured as a decrease in α power in EEG recordings from that area. At the same time, a synchronization of α activity (an increase in α power) can be found in cortical areas not involved in that task (Sauseng et al., 2005).

Shifting attention away from the fixation point following an endogenous cue causes enhanced α-band activity in parietal cortical areas ipsilateral to the attended side of the visual field (Cosmelli et al., 2011). Also, when attention is endogenously directed to one side of the visual field by a cue, several studies found that the oscillations in the α band desynchronize in occipital cortical areas contralateral to the cue (Sauseng et al., 2005; Thut, Nietzel, Brandt, & Pascual-Leone, 2006) and synchronize in the ipsilateral occipital areas (Kelly, Lalor, Reilly, & Foxe, 2006; Worden, Foxe, Wang, & Simpson, 2000).

It is not yet clear if these changes seen in the α-band are truly induced by conscious top-down control on attention or if they are involuntarily evoked by the cue. If the changes occur time-locked to the cue, this would suggest an evoked origin among the stimulus processing that takes place after the cue. A less direct connection to the cue would point to an induced origin (Van der Lubbe & Utzerath, 2013). The use of LPS also offers a way to investigate this, as will be explained below.

Lateralized power spectra

The LPS builds upon older ways of analyzing EEG data and offers a number of advantages to detect such changes in oscillatory neural firing.

Earlier work on the allocation of attention in the Posner cueing paradigm has employed electrophysiological measures such as event related potentials (ERPs) (Eimer, Velzen, & Driver, 2002; Van der Lubbe & Utzerath, 2013). ERPs represent the average electrophysiological activity following a certain event (such as the presentation of a stimulus), recorded at a specific site on the scalp by an EEG electrode. ERPs from electrodes on contralateral sites on the scalp can be used to compute event related lateralizations (ERLs) to compare cortical activity between contralateral cortical areas (Wascher & Wauschkuhn, 1996).

Lateralized power spectra as defined by Van der Lubbe and Uzerath (2013) combine earlier work on event related lateralizations (ERLs) (Van der Lubbe, Neggers, Verleger, & Kenemans, 2006) with a lateralization index of α power (Thut et al., 2006). They are calculated according to this formula:

$$LPS(\omega_p)_t = \left(\left(left\ cues\ \frac{(\omega_p(PO7) - \omega_p(PO8))}{(\omega_p(PO7) + \omega_p(PO8))}\right) + \left(right\ cues\ \frac{(\omega_p(PO8) - \omega_p(PO7))}{(\omega_p(PO7) + \omega_p(PO8))}\right)\right) \times \frac{1}{2}$$

It can be applied to EEG data gathered from pairs of electrodes on opposing locations on the scalp after performing wavelet analysis to extract the power of the frequency band of interest (for example electrode locations PO7 and PO8). First, the difference in power is computed by subtracting one value from the other. The result is then scaled by the sum of both values, resulting in the lateralization index described by Thut et al. (2008). Then, a double subtraction is applied to the result, analogous to the method of calculating an ERL. Measurements for left and right cue locations are thus combined in this measure. This is done to remove influences on the LPS index that arise from hemispherical differences in neuronal activity that do not depend on the cue (Verleger, Śmigasiewicz, & Möller, 2011), making the LPS highly specific to changes in attentional allocation.

The resulting LPS index will have a value between -1 and +1. Positive values correspond to higher power values measured on the hemisphere ipsilateral to the cue in relation to the hemisphere contralateral to the cue. Negative values indicate higher relative α power in the contralateral hemisphere. For example, a positive LPS value for electrodes PO7 and PO8 measured 200ms after the cue onset would indicate that α band activity is greater in the left hemisphere relative to the right hemisphere for trials where the cue pointed to the left side. The same is true for the right hemisphere when the cue points to the right side. A negative LPS value on the other hand would indicate that relative α power is higher on the contralateral relative to the ipsilateral hemisphere. A value of zero would indicate no difference in α power between the two electrodes. It is also possible to apply the above formula to ERP data. This results in the LPS-ERP, a lateralization index based on EEG data that has been averaged between trials before wavelet analysis is applied.

Research questions

To test whether LPS can offer new insights on the allocation of visual attention and the origin of the cueing effect, two research questions were formulated for this thesis.

This thesis is part of a larger research project that recorded EEG and behavioral data during two endogenous Posner cueing tasks. The experimental parameters that were manipulated included the cue validity level (full vs low cue validity), the target side and the duration for which the target was visible. The experimental setup will be described in more detail in the methodology section.

The first question was: Does cue validity influence behavioral and LPS measures in the Posner cueing paradigm? Previous research (Gould et al., 2011) suggests that larger cueing effects on behavioral measures and EEG results should be found in the full cue validity condition compared to the low cue validity condition of this experiment. It was thus predicted that a cueing effects on behavioral measures would be present in both conditions and that this effect would be stronger under full cue validity than under low cue validity. Taking into account the right hemispherical bias, an advantage for targets in the left visual field was predicted. It was also assumed that targets presented for only a short duration would be harder to detect and thus negatively impact reaction times and the percentage of correct responses.

Different levels of cue validity were expected to lead to more pronounced α-power lateralizations under full cue validity. Low cue validity was expected to reveal a weaker pattern. Strong differences in α-power lateralizations between full and low cue validity levels would suggest that attention might be allocated differently at low cue validity levels, casting doubt on the verity of Posner`s model at low cue validity. The initial paper that introduced the LPS (R. H. Van der Lubbe & Utzerath, 2013) suggested that this new measure should be capable of detecting the expected hemispherical differences in α-band activity in the Posner cueing task used here.

The second question concerned the cause of α-power lateralization in the cue-target interval: Are α-power lateralizations in the cue-target interval of an endogenous Posner cueing task induced or evoked phenomena?

A comparison of LPS versus LPS-ERP results is expected to offer new insights on this question. When the inhibition of stimulus processing is seen as an internally generated and ongoing process which is not directly caused by external events but by top-down control, most of it should be relatively independent of the timeframe for ERP and ERL measurements and averaged out of the signal (Başar, Schürmann, Demiralp, Başar-Eroglu, & Ademoglu, 2001).

Comparing LPS derived directly from raw EEG data and LPS derived after calculating ERPs first might help to determine whether or not this is the case: When changes in α-power lateralizations in the cue-target interval measured with LPS are also present in LPS-ERPs, these changes can be interpreted as an effect evoked by the cue. But when α-power lateralizations show up only in LPS but not in LPS-ERP measurements, this points to an induced rather than evoked origin of these changes (Van der Lubbe & Utzerath, 2013).

Van der Lubbe & Utzerath found no evidence for an induced origin of α-power lateralizations in the cue-target interval. This might be due to the low number of participants used in their experiment. To improve statistical confidence in the results, a larger number of participants was recruited to participate in the experiment (twenty-one versus twelve in the original experiment). Additionally, cortical activity related to the processing of the cueing stimulus might have overshadowed induced activity in the short-target interval that they examined. The experiment used for this study improves upon this by using a longer cue-target interval of 1400 ms, as recommended by the authors. Due to these changes, a difference between LPS and LPS-ERP findings was predicted.

Method

Participants

Twenty one participants with no history of neurological disease and normal or corrected to normal vision were recruited for our experiment. One participant had to be excluded from our data analysis because he did not comply with the instructions of the researchers. 12 female and 8 male participants remained, their mean age being 21 years, ranging from 18 to 25 years. With one exception, all were undergraduate students of either Psychology or Communication Sciences at the University of Twente who received course credit for participation. One male participant who was no longer a student volunteered without receiving compensation. Before the experiment all participants signed informed consent and were assessed with the complete Ishihara test for color-blindness (Ishihara, 1976) which all participants passed. Using Annet's Handedness Inventory (Annett, 1970), 18 participants were found to be right-handed, one ambidextrous, and one left-handed.

Experimental procedure

The experiment consisted of two versions of the Posner endogenous spatial cueing paradigm similar to the task used by Van der Lubbe and Uzerath (2013) but using different sorts of cues. One variant (the full cue validity condition) used valid cues intermixed with inward or outward pointing neutral cues. The other variant (low cue validity condition) used cues which always pointed to one side or the other, but were valid in only two out of three trials.

At the start of the experiment every participant signed an informed consent and were assessed for colorblindness and handedness, followed by the application of the EEG and EOG electrodes. Each participant was then subjected to both conditions of the experiment, separated by a 10 minute break. Before trials were run, either blue or yellow was designated as the relevant color to indicate an upcoming target. Participants were instructed to react as fast and as accurate as possible without guessing. Both conditions began with a training block of 24 practice trials, followed by 7 runs of 48 trials with one minute breaks between the runs. The chronological order of the conditions as well as the relevant cue color were randomized and counterbalanced between participants. The total duration of the experiment was approximately 90 minutes. The experimental procedure was approved by the ethics committee of the Faculty of Behavioral Sciences.

Stimuli

Figure 1 illustrates the order of stimuli making up one trial: A central white fixation dot between two white circles was used as the default display. Trial onset was indicated after 700 ms by slightly enlarging the fixation dot for 200 ms. After 600 ms the fixation dot was replaced by a diamond-shaped cue for 600ms.

This cue was composed of two triangles which could be either yellow or blue in color. Three different versions of this cue were used. A diamond with the relevant color present on one side was meant to signal that the target will appear on that side of the visual field. A diamond made of two triangles both sharing the same color represented neutral cues. Outward pointing cues had the relevant color in both triangles to direct attention to both sides. Inward pointing cues featured only the irrelevant color.

The default display was presented for another 800ms following the cue. 1400 ms after cue onset, a target was presented for either 44 ms or 176 ms inside one of the circles: horizontal stripes required pressing a button with the left index finger, while vertical stripes required pressing a button with the right index finger. During target presentation, the other circle was filled with pixel noise. The targets were immediately followed by a checkered mask covering both circles for 500ms, after which the default display was shown either until a response was received by the participant or until 1000ms had passed. When the participant did not respond or if the response was incorrect, feedback was given by enlarging and coloring the fixation dot red for 500 ms.

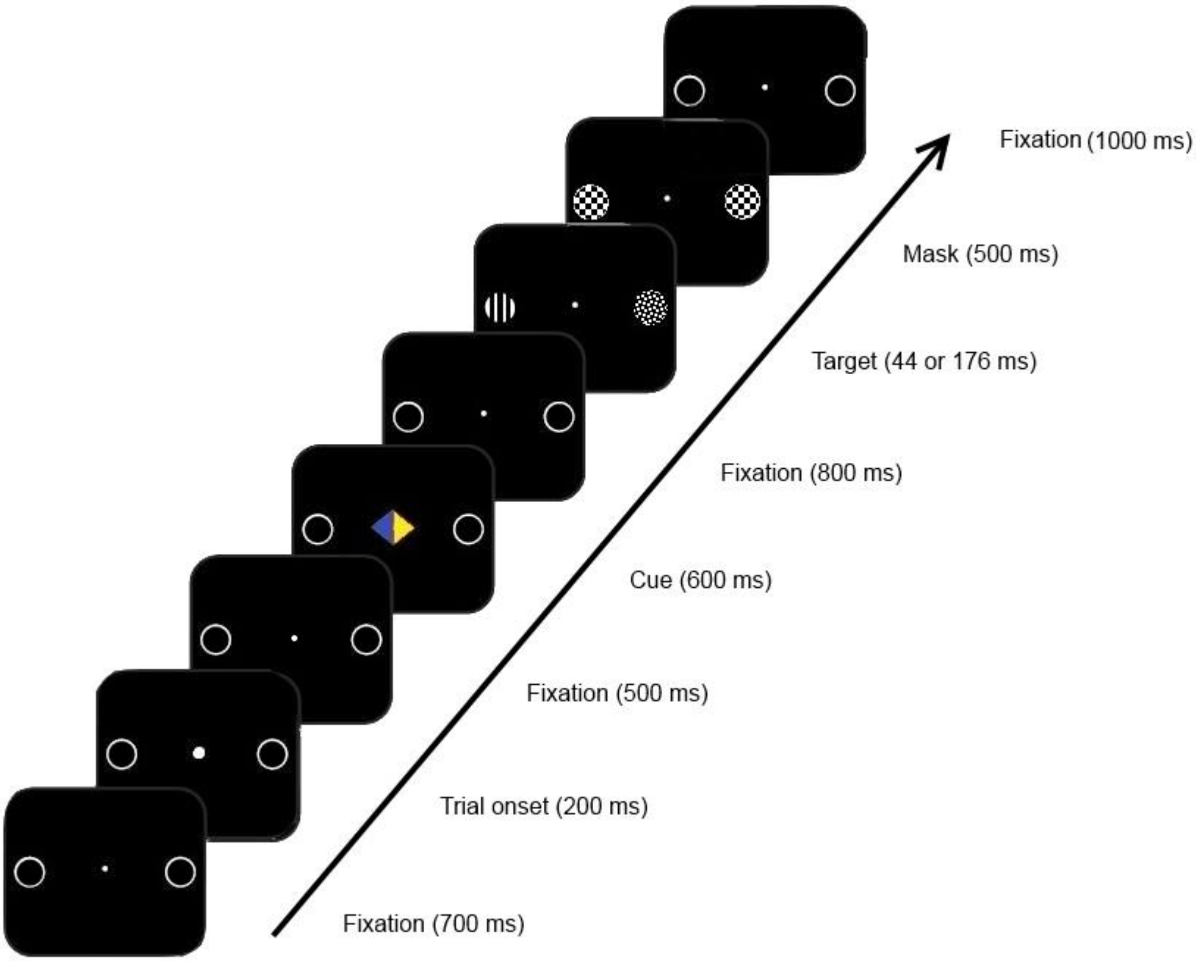

Figure 1 Overview of a single trial

Apparatus

Participants were seated on a chair in a darkened room at approximately 60cm viewing distance from a 17 inch CRT screen. Presentation software (Neurobehavioral Systems, Inc., 2012) was used to display the stimuli. Participants responded by pressing either the left or right "Ctrl" key on a QWERTY keyboard. Stimulus-related events and key presses were sent to a separate data acquisition computer and captured with BrainVision Recorder software alongside the EEG data.

EEG was measured with 61 average-referenced, passive Ag/AgCl ring electrodes fixated with a Braincap (Brain Products GmbH) on the following positions: Fpz, Fp1, Fp2, AFz, AF3, AF4, AF7, AF8, Fz, F1, F2, F3, F4, F5, F6, F7, F8, FCz, FC1, FC2, FC3, FC4, FC5, FC6, FT7, FT8, Cz, C1, C2, C3, C4, C5, C6, T7, T8, CPz, CP1, CP2, CP3, CP4, CP5, CP6, TP7, TP8, Pz, P1, P2, P3, P4, P5, P6, P7, P8, POz, PO3, PO4, PO7, PO8, Oz, O1, O2. Vertical and horizontal electro-oculogram was recorded with bipolar electrodes placed above and below the left eye (vEOG) and at the outer canthi of both eyes (hEOG). A ground electrode was placed on the forehead. Electrode resistance was kept below 10 kΩ. All Electrodes were connected to a 72-channel QuickAmp amplifier (Brain Products GmbH). The EEG signal was recorded at a sampling rate of 1000 Hz, with a low pass filter at 200 Hz and a notch filter at 50 Hz.

Behavioral data analysis

Responses outside the time interval of 100 to 3000 ms after target onset were discarded. Averages were then computed for the reaction times and the percentage of correct responses for both experimental conditions apart. These behavioral measures were then analyzed with a three-way repeated measures ANOVA to check for the influence of the following factors: cue type (valid or invalid in the low cue validity condition or valid, all or none in the full cue validity condition), the side of the visual field on which the target appeared (left or right) and for how much time the target was present (44 ms or 176 ms). All statistical analysis was done using IBM SPSS Statistics version 22 (IBM Corporation).

EEG data analysis

BrainVision Analyzer (Brain Products GmbH) software was used to process the EEG data. After applying a low pass filter at 30 Hz the data was cut into segments of 4500 ms, starting 1000 ms before cue onset. A baseline was set from 100 ms to cue onset. Segments including hEOG amplitudes exceeding +/- 40 µV in the cue-target interval were excluded from further analysis to avoid effects of overt attention. Then, artifact rejection was applied, flat EEG channels were removed from the data and EOG correction was used.

After these preparations, Complex Morlet wavelet analysis was conducted on all segments for a range of frequencies. Gabor normalization was used. The frequency bands of relevance for our analysis were α_1 with a central frequency of 8.9 Hz and upper and lower borders at 7.2 and 10.7 Hz and α_2 with a central frequency of 11.7 Hz and upper and lower borders at 9.4 and 14.0 Hz. On the basis of these values, lateralized power spectra were computed for all 26 symmetric electrode pairs depending on the direction of the cue. These were then averaged across trials to give one value per participant for each 50 ms time window in the cue – target interval (24 in total). Values were averaged in two ways: before applying wavelet analysis to get the ERP-LPS indices and after wavelet analysis to get LPS indices.

Two-tailed t-tests were performed on all results gathered between 200ms and 1400ms after cue onset to check whether the lateralization indices deviated significantly from zero. All

26 symmetrical electrode pairs were included in the analysis. Since this required a large number of t-tests to be performed, the heightened risk for a type I statistical error had to be accounted for. The correction applied here is based on a formula used by Van der Lubbe in earlier work, $p < \sqrt{\alpha \div ((time\ windows - 1) \times eletrode\ pairs)}$, which yields a critical p value that has to be crossed at two consecutive time windows (Van der Lubbe, Bundt, & Abrahamse, 2014). The significance level was chosen to be α = .05 and measurements were taken in 24 time windows for 26 electrode pairs. The significance criterion for this analysis was therefore lowered to $p < 0.009144$ in two consecutive 50 ms time windows.

Results

Behavioral measures

To determine whether or not a cueing effect was present, the percentage of correct responses was examined in both cueing conditions. It was found that the percentage of correct responses was most affected by following short targets was very low, ranging from 42 % to 67 % (see tables 1 and 2 below). This indicates that participants mostly guessed which target appeared as it was too hard to discern in that short amount of time even after a valid cue. Trials with short target duration were therefore excluded from further analysis after reporting the main ANOVA results.

Table 1

Estimated marginal means for the reaction times and the percentage of correct responses in the full cue validity condition as a function of cue type, target side and target duration.

Cue type	Target side	Target duration	RT (ms)		PC (%)	
			Mean	SE	Mean	SE
valid	left	short	881	55	57	6
		long	813	53	86	3
	right	short	878	72	67	5
		long	795	64	93	3
outward	left	short	987	84	45	6
		long	890	71	84	3
	right	short	940	70	62	6
		long	825	59	87	3
inward	left	short	955	71	41	6
		long	894	54	84	4
	right	short	886	58	52	6
		long	866	74	91	4

Note: RT = reaction time, PC = percentage of correct responses. SE = standard error.

Table 2

Estimated marginal means for reaction times and the percentage of correct responses in the low cue validity condition as a function of cue type, target side and target duration.

Cue type	Target side	Target duration	RT (ms)		PC (%)	
			Mean	SE	Mean	SE
valid	left	short	944	50	53	6
		long	840	44	91	2
	right	short	891	48	62	6
		long	820	45	94	2
invalid	left	short	980	47	47	6
		long	898	51	70	6
	right	short	922	51	49	7
		long	938	63	76	6

Note: RT = reaction time, PC = percentage of correct responses. SE = standard error.

See table 3 for an overview of the results of the repeated measures analysis of variance. It should be noted that when the reaction times were analyzed, some participant´s data had to be excluded from the analysis because they did not achieve a correct response for some combinations of variables (for example: missing all invalidly cued short targets on the left yields no reaction time to contribute to the ANOVA). The big influence of target duration compared to the other independent variables is also apparent here, with by far the largest estimated effect on the percentage of correct responses in both conditions as measured by η_p^2.

Table 3

Main effects and significant interaction effects of cue type, target duration and target side on reaction times and the percentage of correct responses.

Condition	Effect source	Variable	*df*	*F*	*p*	η_p^2
Full cue validity	Cue type	RT	2,32	8.25	.001*	.340
		PC	2,38	12.216	<.001*	.391
	Target side	RT	1,16	9.48	.007*	.372
		PC	1,19	21.24	<.001*	.528
	Target duration	RT	1,16	8.57	.010*	.349
		PC	1,19	40.00	<.001*	.678
	Cue type × target duration	RT	2,32	4.49	.019*	.219
		PC	2,38	8.33	.004*$^{+}$	.305
	Target side × target duration	PC	1,19	7.42	.013*	.281
	Cue type × target side × target duration	PC	2,38	4.06	.025*	.176
Low cue validity	Cue type	RT	1,16	10.31	.005*	.392
		PC	1,19	16.65	.001*	.467
	Target side	RT	1,16	1.328	.266	.077
		PC	1,19	10.813	.004*	.363
	Target duration	RT	1,16	5.82	.028*	.267
		PC	1,19	34.54	<.001*	.645
	Cue type × target duration	PC	1,19	5.84	.026*	.235
	Target side × target duration	RT	1,16	5.83	.028*	.267

Note. An asterisk (*) marks results significant at the p<.05 level. RT = reaction time, PC = percentage of correct responses. Partial eta squared (η_p^2) is reported as an estimate of effect size.

Full cue validity.

Table 1 shows the estimated marginal means for the full cue validity condition. The main effect of the cue type (valid, outward or inward) on reaction times was significant (F(2,32) = 8.25, *p* = .001. The effect of target side was significant (F(1,16) = 9.48, *p* = .007), as well as the main effect of target duration (F(1,16) = 9.48, *p* < .001). There was also a significant interaction between cue type and target duration (F(2,32) = 4.49, *p* = .019)

Pairwise comparisons revealed that validly cued targets were detected 69 ms faster than targets following outward cues (*p = .015*) and 58 ms faster than targets following inward cues

(p = .008). There was no significant difference in reaction times between outward and inward cues. Targets on the right side of the visual field were detected 38 ms faster than targets on the left side of the visual field (p = .007).

Significant main effects of cue type (F(2,38) = 12.213, p < .001), target duration (F(1,19) = 40.00, p < .001) and target side (19,1) = 21.24, p < .001) on the percentage of correct responses were found. There was a significant two-way interaction between target side and target duration (F(1,19) = 7.42, p = .013), as well as a three-way interaction between cue type, target side and target duration (F(2,38) = 4.06, p = .025).

The percentage of correct responses after valid cues was 6.3 % higher than after outward cues (p = .004) and 8.7 % higher than after inward cues (p < .001). After targets on the right side of the field, the percentage of correct responses was 9 % higher when compared to targets in the left side of the visual field ($p < .001$).

Low cue validity.

Table 2 contains the estimated marginal means for reaction times and the percentage of correct responses for the low cue validity condition. The main effect of cue type was significant for reaction times (F(1,16) = 10.31, p = .005): Reaction times were 60 ms faster for valid compared to invalid cues (p = .005). The main effect of target side on reaction times was not significant (F(1,16) = 1.328, p = .266), whereas the main effect of target duration was significant for reaction times (F(1,16) = 5.82, p = .028). There was also a two way interaction between target side and target duration (F(1,16) = 5.83, p = .028)

Significant main effects on the percentage of correct responses were found for cue type (F(1,16) = 10.31, p = .005), target side (F(1,16) = 10.813, p = .0040) and target duration ((F(1,19) = 34.54, p = .001). There was a significant interaction between cue type and target duration (F(1,19) = 5.84, p = .026. Pairwise comparisons revealed that the percentage of correct responses was 14.4 % higher for valid than for invalid cues (p < .001). The percentage of correct responses was 5 % higher for targets in the right vs left visual field.

EEG results

In this section, the LPS results derived from the raw EEG for both conditions will be summarized, followed by an examination of the LPS-ERP findings. The findings discussed below concern increases in ipsilateral α-power relative to the contralateral α power, since no α-power lateralizations of the opposite polarity came close to reaching the significance criterion.

All statistically significant changes in α-power that were found are listed in the Appendix to provide a complete view of the results.

Full cue validity.

Significant effects were found in the higher and lower α band across many electrode pairs in the full cue validity condition. They can be roughly divided into two patterns by their timing. The first pattern starts about 400ms after the cue and involves lateral temporal cortical areas as well as occipital areas, lasting for approximately 200ms in temporal areas and 400ms in occipital areas. The second pattern started around the 1000 ms mark and lasts until target onset. It had a more occipital focus. More and longer significant deviations of the LPS from zero were found in the lower α band. Significant lateralization was found at P3/P4 for 17 out of 24 50 ms intervals, more than at any other site. The lowest p-values were found at P7/P8, with $p < .001$ between 1100 – 1350 ms after the cue and at PO7/PO8, with $p < .001$ between 550 – 750 ms after the cue. Analogous to the low cue validity condition, strong lateralization was also observed at P5/P6. See figure 2 on the following page for a visual overview.

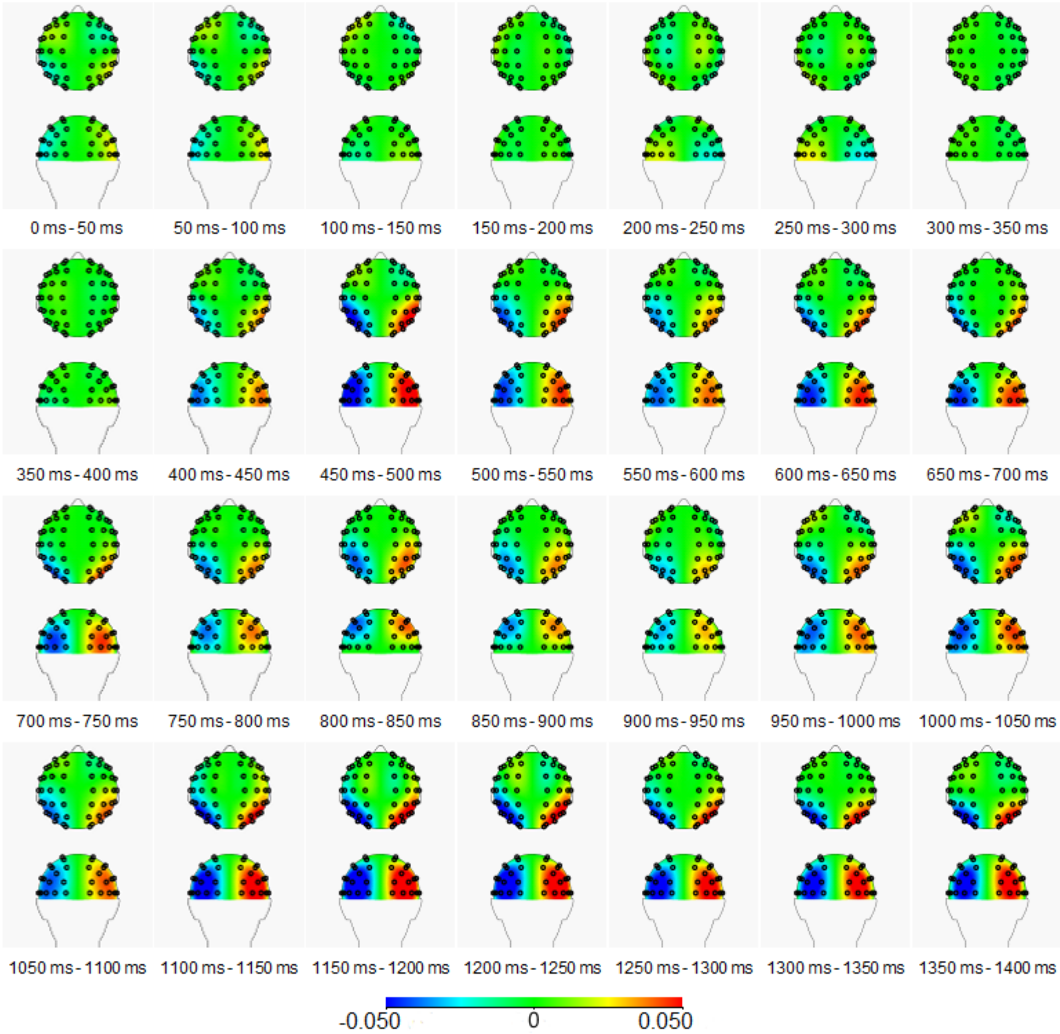

Figure 2. Topographical representation of LPS deviations from zero in the $\alpha_1$band for the full cue validity condition. LPS values are plotted on the right hemisphere and their inverse on the left. Positive values displayed in red indicate higher ipsilateral to contralateral α power.

In this visualization of LPS indices for the α_1 band, the two patterns are clearly visible, including the decreased lateralization of α power in between them and the shift from lateral parietal areas to medial posterior occipital areas. At electrodes T7/T8, the significance criterion was crossed between 500 and 600 ms in the α_1 band. At the neighboring medial electrode pair C5/C6, a significant effect was found between 400 and 700 ms. The significance criterion was crossed again at 1150ms, but only for 100ms. At electrodes above the occipital cortex such as PO3/PO4 and PO7/PO8, significant effects lasted for a longer duration in the first pattern (from 450 ms to 800 ms for PO3/PO4 and 400 ms to 800 ms for PO7/PO8). Significant effects were found again at these sites starting 1100 ms after the cue and lasting until target onset. At P1/P2, an effect was only seen for the last 100 ms of the cue target interval (1300 ms to 1400 ms). At the adjacent lateral electrode P3/P4 however, significant lateralization of α power occurred from 400 ms after the cue until target onset, with the exception of only two 50 ms intervals starting 650 ms and 1150 ms after the cue.

Low cue validity.

In the low cue validity condition fewer significant effects were found in comparison with the full cue valitidy condition (see the appendix). The most pronounced deviation from zero of the LPS was found at electrodes F1/F2 in the lower α band. The significance criterion was crossed between 300 and 500 ms after the cue and also between 750 and 1000 ms after the cue. A significant result was also found above the frontal cortex (FC5/FC6) from 800 to 950 ms after the cue. All of the effects mentioned above were found in the lower α band. Two more statistically significant results were found in this condition between 550 ms and 650 ms: at P5/P6 in the higher α band and at PO7/PO8 in the lower α band. See also figure 3 on the following page.

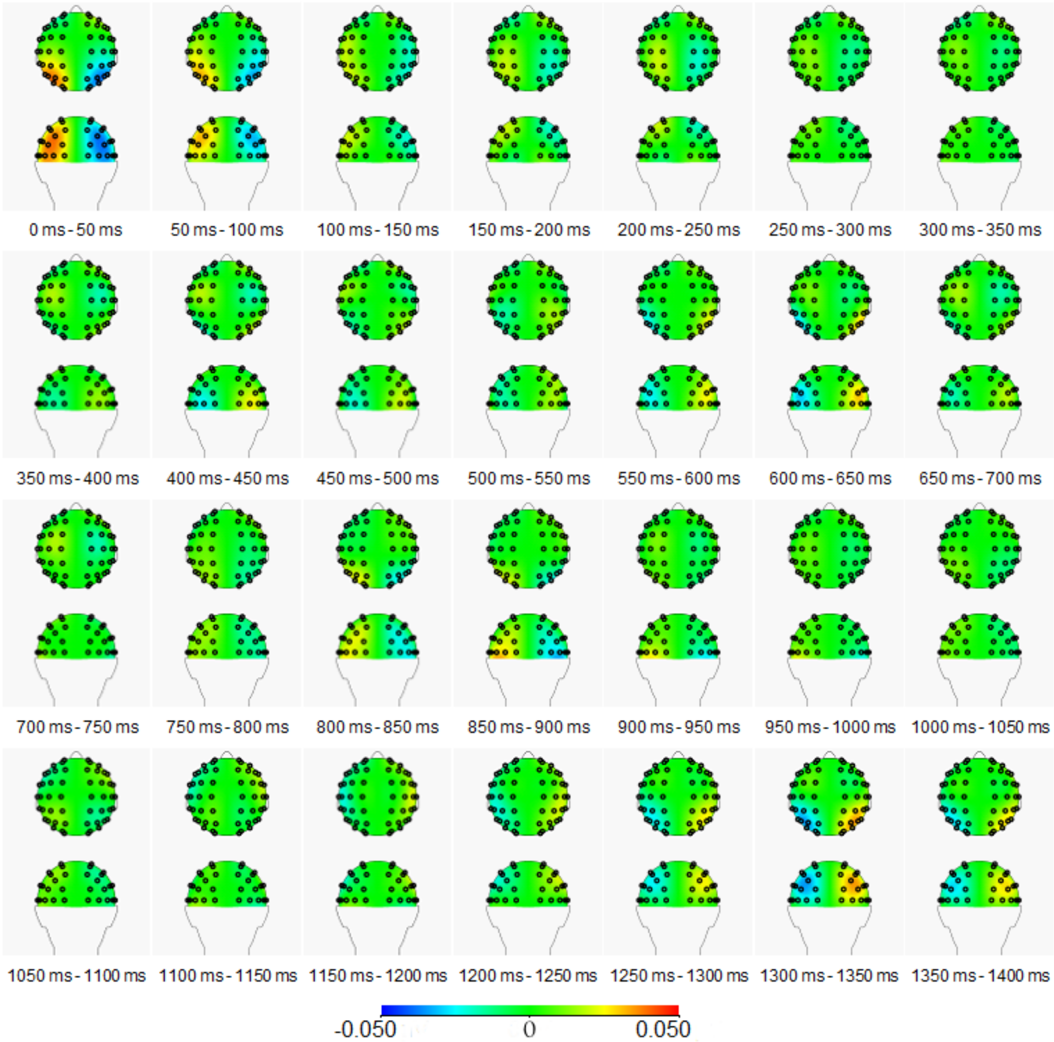

Figure 3 Topographical representation of LPS deviations from zero in the $\alpha_l$band for the low cue validity condition. LPS values are plotted on the right hemisphere and their inverse on the left. Positive values displayed in red indicate higher ipsilateral to contralateral α power.

LPS-ERP results.

The LPS derived from the ERP never crossed the significance criterion for two consecutive time intervals. Figure 4 shows that there were clear deviations from zero at a number of sites and in both polarities, but these phenomena were much shorter induration and less stable than the LPS values. This section describes the occasions were the measured LPS-ERPs came closest to our criterion by reaching a value of $p < 0.009144$ in one 50ms interval

In the low cue validity condition, this occurred twice in the higher α-band: At FC5/FC6 between 250 – 300 ms after the cue and at CP1/CP2 between 550 – 600 ms. In the lower α-band the significance criterion was crossed at FC3/FC4 from 650 ms to 700 ms after the cue.

At none of these sites was there a significant result in the LPS derived from raw EEG data around those times.

In the full cue validity condition the significance criterion was crossed once at the frontal site of F1/F2 (1300 – 1350 ms) while no significant lateralization was found in the LPS derived from raw EEG at that time and site. At P7/P8 however, non-significant deviations of the LPS-ERP were found crossing the significance criterion between 550 - 600 ms and staying below p = .05 for the following 200 ms. The significance criterion was also crossed once at PO7/PO8 (650 – 700 ms) and in the lower α-band at P3/P4 (700 – 750 ms). These spurious results do coincide with significant LPS results derived from the raw EEG.

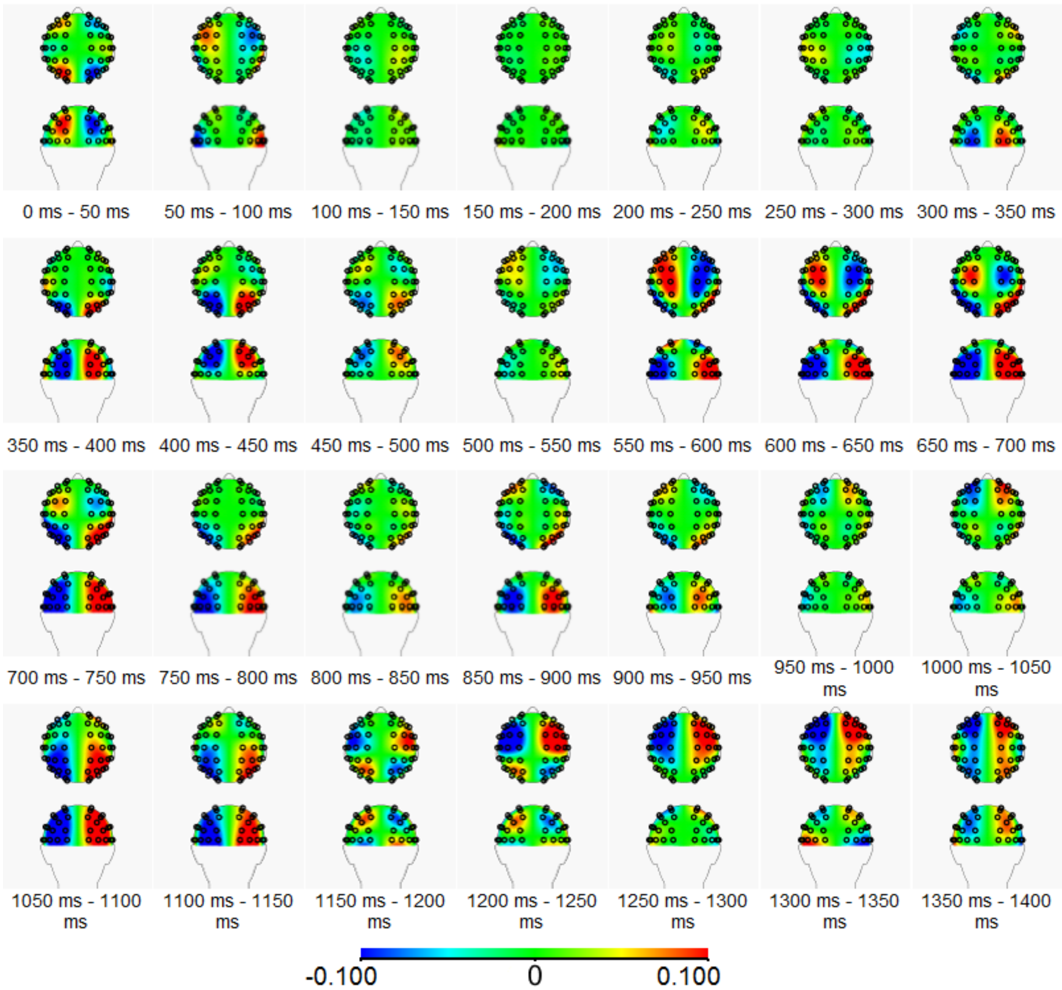

Figure 4 Topographical representation of LPS-ERP deviations from zero in the α_2 band for the low cue validity condition. LPS values are plotted on the right hemisphere and their inverse on the left. Positive values displayed in red indicate higher ipsilateral to contralateral α power.

Discussion

Cue validity and the allocation of attention

The goal of the first research question was to determine if different levels of cue validity in an endogenous Posner cueing task lead to differences in behavioral and LPS measures. It was predicted that cueing effects would be found on reaction times and the percentage of correct responses in both the full and low cueing condition, but that these effects would be stronger in the full cue validity condition. It was further predicted that the LPS results would show stronger α-power lateralizations in the high cue validity condition.

The behavioral results presented above support the view that a cueing effect was present in both cue validity conditions, but a difference in the magnitude of the cueing effect is not easily deducible from these results. The cueing effect on the percentage of correct responses was largest in the low cue validity condition while the biggest difference in reaction times was found between valid and outward cues in the high cue validity condition.

An influence of target duration was also predicted, but it was surprisingly large and produced a number of unexpected interaction effects. The percentage of correct responses following short targets was comparable to chance. The 44 ms targets were so hard to identify even when validly cued that they were excluded from further analysis.

The influence of the side of the visual field in which the target appeared was also unexpected. Prior research indicated an advantage for targets in the left side of the visual field (Kiefer et al., 2011; Verleger, Śmigasiewicz, & Möller, 2011), yet here an opposite effect was found. Reaction times and the percentage of correct responses were better for targets in the right visual field in the high cue validity condition. In the low cue validity condition, an advantage of targets in the right side of the visual field was found in the percentage of correct responses only.

The behavioral results thus do not provide a clear picture of the influence of the level of cue validity on the allocation of visual attention. When the LPS results are examined, however, this is clearly visible: In line with the predictions, the patterns of α-power lateralizations differ between the high and the low cue validity condition.

More evidence for α-power lateralizations was found in the full cue validity condition than in the low cue validity condition, implying a positive correlation between cue validity and α-power lateralization. These results support the hypothesis that cueing effects and the cognitive processes that are related with them depend on the predictive value of the cue. The most significant α-power lateralizations found in this study were measured over occipital and parietal cortical areas in the high cue validity condition. This supports the findings of Gould et al. (2011), who first demonstrated that graded changes in the spatial allocation of visual attention in an endogenous cueing task were correlated to graded α-power lateralizations over occipito-parietal areas. The findings presented here therefore add evidence to the view that there is a connection between cue validity, the allocation of visual attention and α-power lateralizations.

The very low amount of significant α-power lateralizations could either mean that the effect was too small to be detected in this study, or that the allocation of visual attention follows a different mechanism under low cue validity, as suggested by Van der Heijden (1992).

LPS do not distinguish between ipsilateral increases or contralateral decreases in power. The two patterns of α-power lateralizations observed in the high cue validity condition of this experiment might therefore have a separate origin: The longer cue-target interval used in this experiment (1400 ms as opposed to 1000 ms in the original study) revealed two distinguishable peaks in α-power lateralization, the first one with a more parietal focus than the second one, which had a more occipital focus.

The reason for this could be that two separate cognitive processes have been observed. Parietal α-power fluctuations could correspond to the shifting of attention in response to the central cue, as described by Cosmelli et al. (2011) while occipital α-power changes might reflect ipsilateral inhibition of stimulus processing as described by Kelly et al (2006) or contralateral enhancement of stimulus processing in anticipation of the target in line with the findings of Sauseng et al. (2005).

Induced or evoked α-power lateralization

The second research question was to determine if α-power lateralizations in the cue-target interval are time-locked to the cue or not, in order to understand whether they are evoked by the cue or induced by top-down processes.

Statistically relevant lateralization effects were only found when LPS derived from raw EEG data were analyzed. Some spurious LPS-ERP results coincided with LPS findings between 550 ms to 800 ms after cue onset, therefore there might be a relationship between evoked processes and α-band activity that failed to be detected here due to the very conservative significance criterion used in this study. In the initial study by Van der Lubbe & Utzerath (2013), LPS-ERPs largely matched the LPS, suggesting an evoked rather than induced origin.

At least for the LPS findings late in the cue-target interval, however, it can be concluded that the findings presented here point to an induced rather than evoked origin of α-power lateralization, because an evoked response should have shown up clearly in the LPS-ERPs. Cueing effects were found in the behavioral data and in the LPS, which means that the allocation of visual attention is not a process that is time-locked to the cue. This suggests that the allocation of spatial visual attention in the endogenous Posner cueing paradigm is not an evoked but an induced process, in line with the findings of Grent-´t-Jong and Woldorff (2007).

Recommendations

Cue validity manipulation resulted in distinctively different patterns of α-power lateralization between the two experimental conditions. If α-power lateralization is indeed necessary for attentional allocation, then more attention has to be paid to the level of cue validity in future research. Low levels of cue validity might make research participants use guessing strategies or simply diminish the cueing effect to levels where it is difficult to measure.

The participants had widely differing opinions on the perceived difficulty of the two experimental conditions. All reported fatigue towards the end of the experiment. These influences might have lead them to alter their attention shifting strategies over time, which might have contributed to the high variance in performance found between participants. Our behavioral data also show the importance of fine-tuning the difficulty of target discrimination to avoid the disappearance of the cueing effect when the task becomes too easy or too hard.

The analysis of the behavioral data also revealed that participants responded faster and more accurately to targets on the left side of the visual field under certain conditions, contrary to what the literature has suggested. Follow-up research should investigate whether this was a fluke or if there is a real reason for this.

All in all, the LPS and LPS-ERPs results performed very well as tools to investigate the processes of interest in this study and are therefore recommended for use in future research on the allocation of visual attention.

Conclusion

The results of this study support the view that the allocation of visual attention is linked to processes in the α-band and that α-waves are specifically involved in the voluntary direction of visual attention. The way in which endogenous visual attention is allocated could be very different depending on the uncertainty of the cue directing it.

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Appendix

Statistically significant α-power lateralizations sorted by condition, frequency band and time of occurrence.

	α_1 frequency band		*α_2 frequency band*	
Condition	Time (ms)	Electrode pair	Time (ms)	Electrode pair
Low cue validity	300 – 500	F1/F2	550 – 650	TP7/TP8
	550 – 650	P7/P8	800 – 950	CP5/CP6
	750 – 1000	PO7/PO8		
High cue validity	400 – 700	C5/C6	400 – 500	AF7/AF8
	400 - 800	PO7/PO8	400 – 500	PO7/PO8
	400 – 850	P7/P8	400 – 550	CP5/CP6
	450 – 600	C3/C4	400 – 650	P7/P8
	450 – 600	CP3/CP4	450 – 550	TP7/TP8
	450 – 600	CP5/CP6	450 – 600	CP3/CP4
	450 – 600	TP7/TP8	450 – 600	P5/P6
	450 – 650	P3/P4	600 – 750	PO3/PO4
	450 – 800	PO3/PO4	1050 – 1400	P7/P8
	450 - 850	P5/P6	1100 – 1400	P5/P6
	500 – 600	T7/T8	1150 – 1300	CP5/CP6
	550 – 750	O1/O2	1150 – 1300	P3/P4
	700 - 1000	P3/P4	1150 – 1300	PO3/PO4
	900 – 1000	C3/C4	1150 – 1300	PO7/PO8
	900 – 1000	CP3/CP4		
	1000 – 1300	TP7/TP8		
	1000 – 1350	CP5/CP6		
	1050 – 1400	P5/P6		
	1050 – 1400	P7/P8		
	1100 – 1400	PO3/PO4		
	1100 – 1400	PO7/PO8		
	1150 – 1250	C5/C6		
	1200 – 1400	P3/P4		
	1300 – 1400	P1/P2		

Note. Time is measured relative to cue onset. Results were considered significant when $p < .009144$ for at least two consecutive 50 ms time windows.