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Cross-modal Auditory Cueing and Visual Processing: An fMRI Study

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Abstract

Spatial attention prioritizes behaviourally relevant information and can be oriented across sensory modalities. This study investigated whether lateralized auditory cues influence visual processing during a dual-Gabor contrast-discrimination task using fMRI. Thirty-four healthy adults completed behavioural testing and fMRI scanning. Cueing improved tilt-discrimination accuracy on easy conscious trials, but no reliable benefit was observed on hard conscious trials. The psychometric analysis yielded a negative difference between fitted test and standard PSEs, which was not interpreted as a direct measure of cue-induced changes in perceived contrast. Whole-brain analyses revealed no cue-related effects at the prespecified voxel-level FWE-corrected threshold $p < .05$. Exploratory clusters were consistent with response-related motor activity rather than occipital visual cortex. No exploratory ROI effect survived correction, and PSE-parametric analyses revealed no reliable neural associations. Overall, the findings indicate a behavioural cueing benefit under relatively easy conditions but provide no robust corrected neural evidence for attentional modulation across visual cortex.

Keywords: cross-modal attention, auditory cueing, visual cortex, contrast perception, perceptual appearance.

Cross-modal Auditory Cueing and Visual Processing

Introduction

Spatial attention enables the visual system to prioritize processing of behaviourally relevant stimuli in a cluttered environment. A fundamental question in cognitive neuroscience is how attentional mechanisms influence neural processing in visual cortex, and whether these effects extend across visual and other sensory processing. This thesis examines the behavioural and neural evidence on the effects of spatial attention, beginning with the distinction between endogenous and exogenous attentional orienting, proceeding to the effects of transient attention on contrast perception and appearance, and then considering how cross-modal auditory cues can modulate visual processing. Finally, the study considers evidence for attentional modulation in retinotopic visual cortex and introduces the rationale for the present empirical investigation, in which functional magnetic resonance imaging (fMRI) is used to examine whether cross-modal auditory cueing produces BOLD enhancements in retinotopically organized visual cortex

Spatial Cueing and Attentional Effects on Visual Perception

This section reviews the theoretical foundations of visual attention, focusing on attentional orienting, transient exogenous attention, and their effects on visual perception. Emphasis is placed on evidence suggesting that attention alters not only behavioural performance but also subjective visual experience.

Visual Attention and Attentional Orienting

Visual attention is characterized as a set of mechanisms that limit processing to a subset of incoming stimuli, thereby reducing complexity and informational overload (Posner, 1980). Selective visual attention describes the tendency of visual processing to be confined largely to stimuli that are relevant to behavior (Moore & Zirnsak, 2017). It is regarded as one of the most fundamental cognitive functions, especially in primates where vision is the dominant sense (Moore & Zirnsak, 2017).

Attention acts as a gatekeeper, passing relevant stimuli to limited-capacity processes (Wolfe, 2000). This notion of a limited-capacity attentional system has been a central feature of cognitive theories of attention (Posner, 1980). Selective attention not only affects behavioral performance but also modulates neural activity, enhancing the processing of attended stimuli and improving the quality of visual representations (Moore & Zirnsak, 2017).

Posner's spatial cueing paradigm (described in detail in Section 'Transient (Exogenous) Attention') demonstrated that covert attention, the ability to shift attention to a peripheral location without moving the eyes, can be shifted independently of eye movements (Posner, 1980). This framework distinguishes orienting — that is the alignment of attention with a sensory input — from detecting, the conscious registration of a stimulus (Posner, 1980). Orienting can be either overt, accompanied by saccadic eye movements, or covert, occurring in their absence (Moore & Zirnsak, 2017; Posner, 1980).

Orienting is further dissociated into endogenous (goal-driven) and exogenous (stimulus-driven) modes (Moore & Zirnsak, 2017). Endogenous attention is generated by internal goals or strategies, whereas exogenous attention is captured by the physical salience of stimuli such as abrupt onsets (Moore & Zirnsak, 2017). Corbetta and Shulman (2002) proposed that these two modes are supported by partially segregated networks: a bilateral dorsal frontoparietal system for goal-directed selection and a right-lateralized ventral system that detects behaviorally relevant stimuli and serves as a circuit breaker for reorienting.

These distinctions are particularly helpful when it comes to paradigms investigating spatial orienting of attention. In the present study, attentional orienting is manipulated through lateralized auditory cues that direct covert attention toward a location in the visual field prior to target presentation, allowing the examination of attentional influences on visual perception.

Transient (Exogenous) Attention

Transient attention refers to the automatic, stimulus-driven capture of attention by a sudden peripheral event (Jonides, 1981). It rises and decays rapidly, peaking at around 100–120 ms after cue onset, and observers cannot easily ignore peripheral cues even when uninformative (Carrasco, 2011). In the classic Posner (1980) cueing paradigm, a peripheral cue improves performance for targets presented at the cued relative to uncued locations through the covert orienting of attention.

Effects on Contrast Sensitivity, Spatial Resolution, and Appearance

Transient attention enhances contrast sensitivity. Carrasco et al. (2000) showed that a peripheral precue decreases contrast thresholds across spatial frequencies, indicating that transient attention enhances contrast sensitivity, and Cameron et al. (2002) confirmed that this reflects a genuine increase in perceptual sensitivity rather than a reduction in response uncertainty. Therefore, these findings support a signal enhancement model, whereby attention boosts the neural response to the attended stimulus, enhancing its perceptual representation (Carrasco, 2011). Ling and Carrasco (2006) further showed that this enhancement operates via a response gain mechanism: attention multiplies the neural response to a stimulus, with larger effects for higher contrast stimuli (Ling & Carrasco, 2006). Beyond contrast sensitivity, Yeshurun and Carrasco (1998) demonstrated that attention can enhance spatial resolution: in a texture segmentation task, attention improved performance at peripheral locations where resolution was too low but impaired performance at central locations where resolution was already too high for the task (Yeshurun & Carrasco, 1998). These findings suggest that attentional benefits depend on the interaction between task demands and the properties of the attended representation.

Carrasco et al. (2004) demonstrated that attention alters subjective appearance, not just performance. In their paradigm, observers viewed two Gabor patches presented simultaneously in opposite visual hemifields — one with a fixed contrast (standard) and the other with a variable contrast (test). A nonpredictive peripheral cue preceded the display,

summoning transient attention to one of the two locations. Observers judged the orientation of the Gabor patch that appeared higher in contrast, a task that dissociates subjective appearance from decision bias because the cue is uninformative about which patch has higher contrast.

The results showed that the cued patch was perceived as higher in contrast than an identical uncued patch, shifting the point of subjective equality by approximately 6% (Carrasco et al., 2004). Control experiments ruled out alternative accounts based on sensory interaction or response bias: the effect was eliminated at long cue–target intervals (consistent with the time course of transient attention) and persisted when observers were asked to report which stimulus was lower in contrast, a task that reverses any potential response strategy (Carrasco et al., 2004). These findings indicate that attention alters the perceptual representation itself rather than biasing post-perceptual decisions.

If attention alters appearance, an important question concerns its neural mechanisms, a question taken up in sections “Attentional Modulation in Early Visual Areas” and “Cross-modal Influences on Visual Cortex”.

Cross-modal Spatial Attention

Spatial attention is not restricted to a single sensory modality but can also be directed across modalities. McDonald et al. (2000) demonstrated that a nonpredictive auditory cue improves visual detection performance at the cued location. Using signal detection measures to dissociate perceptual from decision-level effects, they found that perceptual sensitivity (d'), a signal detection measure that dissociates perceptual sensitivity from response bias, was approximately 8–9% higher on valid in which the cue appeared on the same side as the upcoming target, than on invalid trials, in which the cue appeared on the opposite side, alongside faster reaction times and higher hit rates (McDonald et al., 2000). Critically, because the cue–target interval exceeded 100 ms, this facilitation cannot be attributed to passive multisensory integration and instead reflects an involuntary cross-modal orienting of

attention that enhances early perceptual processing of visual stimuli (McDonald et al., 2000).

Subsequent work extended these findings to visual experience. Using a lateralized nonpredictive auditory cue combined with an appearance-based contrast judgment task adapted from Carrasco et al. (2004), Störmer et al. (2009) showed that auditory cueing alters the perceived contrast of visual stimuli. Observers judged an auditory-cued Gabor patch as higher in contrast than an identical uncued patch, shifting the point of subjective equality by approximately 5% (Störmer et al., 2009). Importantly, because the cue was auditory rather than visual, the effect cannot be explained by low-level sensory interactions between cue and target — a concern that is raised in previous studies using visual cues (Störmer et al., 2009). Control conditions further ruled out a response bias account: the effect was eliminated at long cue–target intervals and persisted when observers reported the lower-contrast stimulus (Störmer et al., 2009).

Neural Mechanisms of Spatial Attention in Retinotopic Cortex

Having reviewed the behavioural, perceptual and experiential effects of attention, the following section examines the neural mechanisms underlying attentional modulation in visual cortex. Particular focus is placed on retinotopic organization and evidence from neuroimaging studies investigating attentional influences on early visual areas.

Retinotopic Organization of Visual Cortex

Early visual cortex is organized retinotopically, meaning that neighboring locations in visual space are represented by neighboring neuronal populations in cortex. Visual information from each hemifield is represented primarily in the contralateral hemisphere, forming systematic maps across areas such as V1, V2, V3, V3a, and hV4. The borders between these visual areas can be identified through reversals in polar-angle representations obtained using retinotopic mapping procedures (Liu et al., 2005). This organization enables researchers to localize neural responses to specific visual field locations and has made retinotopic cortex a central target in studies of spatial attention. Beyond sensory

representation, evidence suggests that spatial attention itself is closely linked to retinotopic coordinates.

Golomb, Chun, and Mazer (2008) demonstrated that attentional facilitation persists at previously attended retinotopic locations for approximately 100–200 ms after the eyes move away from those locations, even when the attended locations are no longer behaviorally relevant. The retinotopic organization of visual cortex therefore provides an ideal framework for examining how attentional orienting influences neural activity measured with fMRI.

Attentional Modulation in Early Visual Areas

Liu et al. (2005) used rapid event-related fMRI to investigate the neural effects of transient attention in retinotopic visual cortex. On each trial, a peripheral cue appeared either at the same location as the upcoming target (valid trial) or at the opposite location (invalid trial), directing covert exogenous attention to one visual hemifield. In a critical control condition, the cue was presented after the target (postcue) rather than before it (precue), equating physical stimulation while preventing attentional orienting. This design isolates attentional modulation from sensory confounds.

Valid precues increased BOLD responses in early visual cortex relative to invalid cues, confirming that transient attention enhances neural activity at the attended location (Liu et al., 2005). The attentional modulation increased linearly from V1 to hV4, with marginal effects in V1 but robust enhancement in V2, V3, V3a, and hV4. The postcue condition ruled out sensory summation: valid precues produced greater activity than valid postcues even though the visual input was identical, demonstrating that the BOLD increases reflect attentional orienting rather than low-level cue–target interactions (Liu et al., 2005).

This progressive enhancement along the visual hierarchy is consistent with a response gain mechanism: attention multiplies the neural response to a stimulus, with the multiplication factor increasing at each successive stage of cortical processing (Carrasco, 2011). Under response gain, the effect of attention is largest for high-contrast stimuli, which is relevant for the present study where all stimuli were clearly above threshold. Importantly,

because the cue and target were spatially separated (above and below the horizontal meridian), the observed BOLD differences reflected genuine attentional modulation rather than sensory overlap in V1 through V3 (Liu et al., 2005).

Cross-modal Influences on Visual Cortex

As described in the section “Cross-modal Spatial Attention”, Störmer et al. (2009) showed that a nonpredictive auditory cue enhances neural responses, measured by EEG, in ventral occipito-temporal visual cortex contralateral to the cued target. Source localization placed this modulation in the fusiform gyrus, extending from the ventral occipital lobe to the temporal lobe. Critically, the magnitude of this enhanced neural response correlated positively with observers' reports of perceived contrast: participants with stronger cue-induced neural modulation were more likely to judge the cued target as higher in contrast (Störmer et al., 2009).

The same ventral regions modulated by auditory cueing were also sensitive to physical differences in contrast (Carrasco, 2009; Störmer et al., 2009), suggesting that cross-modal attention and contrast intensity engage overlapping neural populations in ventral visual cortex. This overlap, together with the response gain pattern observed in visual cueing studies (section “Attentional Modulation in Early Visual Areas”), supports the view that attention boosts early sensory representations of attended stimuli. The present study extends this line of inquiry by using fMRI to examine whether cross-modal auditory cueing produces analogous BOLD enhancements in retinotopically defined visual cortical areas.

The Present Study and Rationale

The present study extends previous work on transient attention by examining whether attentional modulation of visual cortex can be elicited through cross-modal auditory cueing and whether such modulation can be observed in retinotopically organized visual cortex using fMRI. To investigate this question, fMRI data were collected at the University Hospital of Umeå while participants performed a contrast appearance judgment task.

Whereas previous studies have demonstrated that visual transient attention enhances BOLD responses along the visual hierarchy (Liu et al., 2005) and that auditory cues modulate neural activity in visual cortex and alter perceived contrast (Störmer et al., 2009), to our knowledge, no studies have examined whether cross-modal auditory cueing produces analogous BOLD enhancements in retinotopically organized visual cortex using fMRI. Based on the neurophysiological and behavioral evidence reviewed above, it is hypothesized that valid auditory cues will elicit greater BOLD responses than uncued targets in retinotopically organized visual cortex, with stronger effects in extrastriate areas (V2–hV4) than in V1. The study further examines how neural responses relate to subjective awareness and perceived contrast under conditions of cross-modal attentional orienting.

Given that previous investigations of transient attention have primarily relied on predefined visual cortical regions, the present study combines exploratory whole-brain analyses with anatomically informed region-of-interest (ROI) analyses focusing on posterior visual cortex, while also investigating possible effects in other parts of the brain. This approach allows for the investigation of potential attentional effects throughout the brain, while increasing sensitivity to detect attentional modulation within visual areas that have been implicated in previous studies. Given the methodological differences between the present study and the original Liu et al. (2005) paradigm, exact replication of previous findings should not necessarily be expected. Nevertheless, examining whether comparable patterns emerge may provide insight into the robustness and generalizability of attentional modulation effects across different sensory modalities and experimental paradigms.

Methods

Participants

Participants were recruited through advertisements at Umeå University and other public venues in Umeå, Sweden. All participants reported normal or corrected-to-normal vision, were right-handed, and were screened for MRI compatibility. Exclusion criteria included a history of neuropsychiatric or neurological disorders, serious mental illness, or

medication affecting the central nervous system. A total of 42 participants were recruited. Eight participants were excluded because they did not exhibit the expected cueing effect, resulting in a final sample of 34 participants. After the fMRI session, participants completed a handedness inventory and a short personality questionnaire.

All participants provided written informed consent. The study was approved by the Swedish Ethical Review Authority (Reference No. 2024-04689-01).

Experimental Design and Procedure

The experimental design, data collection, and preprocessing procedures were carried out as part of the larger research project "Mapping out the neural correlates of consciousness at the intersection between consciousness and attention" at Umeå University. The project included a couple of experimental components, of which the present thesis focuses on the two-patch (2pAAA) paradigm. The analyses reported in the present thesis, including first-level, second-level, whole-brain, and ROI analyses, were conducted by the author. The backward mask and Perceptual Awareness Scale (PAS) ratings were included in the original paradigm to address the research questions of the main experiment; their relevance to the current analysis is discussed below.

Participants completed two sessions within a seven-day period: a behavioral training session at the Department of Psychology, Umeå University, and an fMRI session at the University Hospital of Umeå.

The experiment employed a within-subject design. On each trial, a central fixation cross appeared for a variable interval (1–8 s), followed by a lateralized nonpredictive auditory cue (46 ms, snare-drum sound, panned 60/40). The target display appeared 119 ms after cue onset and consisted of two Gabor patches (sinusoidal gratings, 1.4° radius, 3.8 cycles per degree) presented simultaneously for 16.7 ms, one in each visual hemifield. The contrast of the standard patch was fixed at 131.1%, while the test patch contrast varied across six levels:

76.2, 96.0, 121.0, 152.5, 192.1, and 242.0% (corresponding to 58–185% of the standard). Stimulus position and orientation were counterbalanced across trials.

After an individually calibrated interstimulus interval (ranging from approximately 17 to 200 ms), a red backward mask was presented for 50 ms. While this mask was an ancillary component included to ensure consistency with the research questions of the main experiment (for which the present study served as an ancillary run), it was irrelevant to the current analysis. Participants first indicated the location and orientation of the Gabor patch perceived as higher in contrast, then rated their subjective awareness using the Perceptual Awareness Scale (PAS), a four-point scale ranging from "no experience" to "clear experience" (Ramsøy & Overgaard, 2004). The cue was spatially uninformative and therefore provided no information regarding the location, contrast, or orientation of the upcoming targets. This ensured that any cueing effects reflected involuntary exogenous attentional orienting rather than strategic allocation of attention. The experiment was programmed in E-Prime 3; stimulus generation and preprocessing used MATLAB.

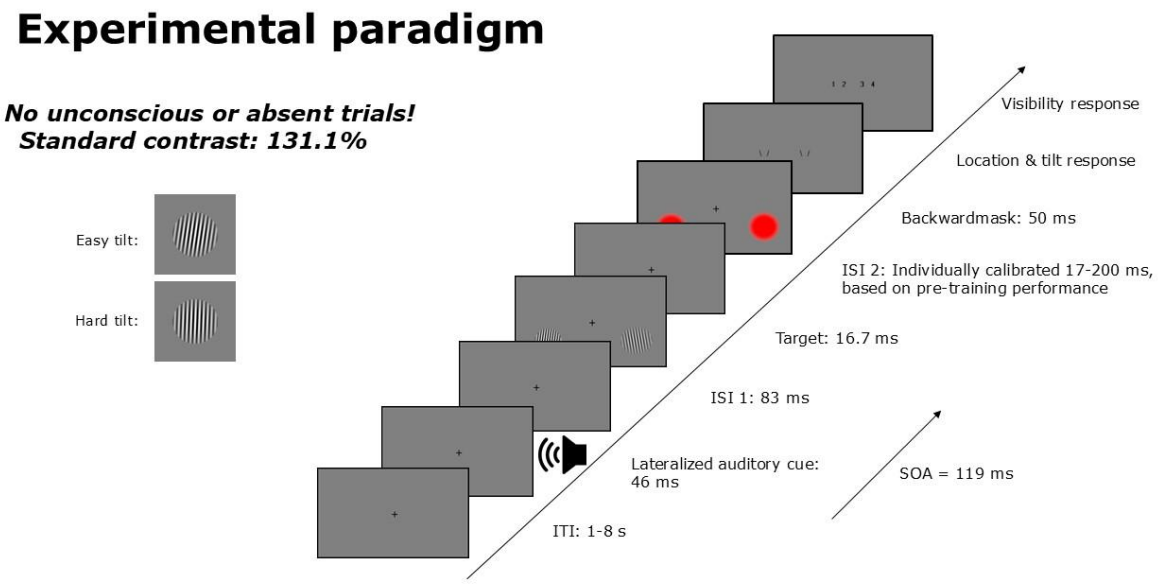

Figure 1. *Schematic illustration of the experimental paradigm.*

Each trial began with a central fixation cross (ITI: 1–8 s), followed by a lateralized nonpredictive auditory cue (46 ms), a brief ISI (83 ms), and a bilateral Gabor display (16.7 ms). After an individually calibrated interstimulus interval (16.7–200 ms), a backward mask (50 ms) was presented. Participants first indicated the location and tilt orientation of the higher-contrast Gabor patch, then rated their subjective awareness of the patches using the Perceptual Awareness Scale (PAS; Ramsøy & Overgaard, 2004). Like the backward mask, the inclusion of the PAS rating was necessitated by the research objectives of the main experiment—for which the present study served as an ancillary run—rather than being a primary focus of the current analysis. Total stimulus onset asynchrony (SOA) between cue and target was 119 ms.

MRI Data Acquisition

Functional images were acquired at Umeå University Hospital using a GE Sigma Premiere 3T scanner with a 48-channel head coil (T2*-weighted EPI, TR = 2 s, 37 axial slices, 2.67 mm thickness). Structural T1-weighted images were also acquired for anatomical reference. The fMRI session lasted 20 minutes. The number of completed trials varied across participants due to the self-paced responses.

Preprocessing

Prior to first-level analysis, the functional images had been preprocessed using SPM12 as part of the larger research project. Preprocessing included: (1) slice timing correction; (2a) coregistration of B0 field map to T1; (2b) coregistration of slice-timing-corrected volumes to T1; (3) realignment and unwarping; (4) segmentation of T1 and generation of a group-specific DARTEL template using data from all 42 participants; (5) normalization to MNI space and smoothing with an 8 mm FWHM Gaussian kernel; and (6) ArtRepair to identify and correct outlier volumes.

FMRI Data Analysis

First-level analyses were conducted separately for each participant using a general linear model (GLM) implemented in SPM12. The model included regressors representing trials in which the target patch appeared in the left or right lower visual field and was either cued or uncued. Condition-specific onsets were convolved with the canonical hemodynamic response function, and only trials associated with conscious perception (PAS ≥ 3) were included in the analysis. To assess group-level attentional cueing effects, four first-level contrasts (Cued vs. Uncued for each visual field) were computed and entered into second-level random-effects analyses using one-sample t-tests. Whole-brain analyses were performed for each contrast, followed by region-of-interest (ROI) analyses within predefined visual cortical regions corresponding approximately to V1, V2/V3, and extrastriate cortex. The ROIs were defined using regions from the Brainnetome Atlas.

Results

Behavioral Results

Descriptive Statistics

Behavioural performance was examined in the final fMRI sample of 34 participants. For conscious trials, accuracy was higher in the Easy condition (M = 92.21%, SD = 5.84) than in the Hard condition (M = 71.23%, SD = 9.77). Mean participant-level median reaction times were 1071.94 ms (SD = 313.40) for Easy trials and 1340.82 ms (SD = 502.39) for Hard trials. Mean PAS ratings were 3.62 (SD = 0.24) for Easy trials and 3.52 (SD = 0.25) for Hard trials.

Cueing Effects on Tilt Discrimination Accuracy

To examine whether attentional cueing influenced tilt discrimination accuracy, participant-level cueing effects were calculated as the difference in accuracy between cued and uncued trials and tested against zero using one-sample t-tests.

For Easy conscious trials, accuracy was significantly higher in the cued compared with the uncued condition, with a mean cueing effect of 2.48 percentage points (SD = 4.56), $t(33) = 3.17$, $p = .003$, 95% CI [0.89, 4.07]. For Hard conscious trials, the mean cueing effect was −2.53 percentage points (SD = 7.86), and this difference did not reach statistical significance, $t(33) = -1.87$, $p = .070$, 95% CI [−5.27, 0.22]. Thus, cueing was associated with a significant improvement in accuracy for Easy trials, whereas no reliable cueing effect was observed for Hard trials.

Psychometric Analysis and Point of Subjective Equality

Individual points of subjective equality (PSEs) were estimated from the fitted psychometric functions for the final fMRI sample of 34 participants. The PSE difference was calculated as PSE Test – PSE Standard, with negative values indicating that the fitted PSE for the test stimulus was lower than the fitted PSE for the standard stimulus. Valid PSE differences were obtained for 33 participants. The PSE difference for participant 171 could

not be calculated because the corresponding test PSE was missing and was therefore excluded from the group-level descriptive analysis.

Across the 33 participants with valid PSE differences, the mean difference was −42.19 percentage points (SD = 32.48), with a median of −39.42 percentage points. Most participants showed a negative PSE difference, with 31 of the 33 valid values falling below zero. This distribution indicates a systematic difference between the fitted psychometric functions for the test and standard stimuli. However, because the PSE difference was calculated between the test and standard functions, it should not be interpreted by itself as a direct measure of the effect of attentional cueing.

fMRI Results

Whole-Brain Second-Level Analyses

Whole-brain second-level analyses were conducted to examine cue-related differences in neural activity for the right-lower-field and left-lower-field conditions. Four directional group-level contrasts were tested: RightLower Cued > Uncued, RightLower Uncued > Cued, LeftLower Cued > Uncued, and LeftLower Uncued > Cued. The analyses included the final fMRI sample of 34 participants, resulting in 33 degrees of freedom.

At the prespecified whole-brain voxel-level threshold of $p < .05$, corrected for family-wise error (FWE), none of the four contrasts produced suprathreshold clusters. Thus, the whole-brain voxel-level analysis did not provide statistically reliable evidence for cue-related differences in neural activity at the prespecified corrected threshold.

Exploratory analyses were subsequently conducted using a voxel-level threshold of $p < .001$, uncorrected, with cluster-level FWE correction applied across the whole-brain search volume. The RightLower Cued > Uncued contrast produced a cluster of 101 voxels, which did not survive cluster-level FWE correction, $p_{FWE-corr} = .409$. The RightLower Uncued > Cued contrast produced a cluster of 1,396 voxels that survived cluster-level FWE

correction, $p_{FWE-corr} < .001$. The peak of this cluster was located at MNI coordinates [36, −24, 54], with a peak T-value of 5.24.

The LeftLower Cued > Uncued contrast produced a cluster of 399 voxels that survived cluster-level FWE correction, $p_{FWE-corr} = .034$. Its peak was located at MNI coordinates [40, −28, 62], with a peak T-value of 4.65. The LeftLower Uncued > Cued contrast produced a small cluster of 10 voxels that did not survive cluster-level FWE correction, $p_{FWE-corr} = .943$.

Coordinate inspection of the two prominent clusters suggested that their peak locations were consistent with primary motor regions associated with finger responses rather than with occipital visual cortex. This pattern is compatible with response-related activity entering the stimulus-related regressors because button presses followed stimulus presentation at a relatively consistent interval. These clusters were therefore not interpreted as evidence of cue-related modulation within visual cortex.

Overall, the whole-brain analyses did not provide reliable evidence for cue-related modulation of visual cortex at the prespecified voxel-level FWE-corrected threshold. The cluster-level findings observed at the exploratory threshold were treated as exploratory and were not interpreted as confirmatory evidence for the predicted visual attentional effect.

Table 1. Summary of exploratory whole-brain second-level results at a voxel-level threshold of p<.001, uncorrected.

Contrast	**Cluster size, k**	**Peak T**	**Peak MNI coordinates**	**Cluster-level FWE**
RightLower Cued > Uncued	101	4.39	[−50, −30, 8]	.409
RightLower Uncued > Cued	1,396	5.24	[36, −24, 54]	< .001

LeftLower Cued > Uncued	399	4.65	[40, −28, 62]	.034
LeftLower Uncued > Cued	10	3.74	[6, −66, 30]	.943

Note. Cluster sizes and peak statistics are reported for an uncorrected voxel-level threshold of p<.001. Cluster-level probabilities are FWE-corrected across the whole-brain search volume. The prominent clusters were not interpreted as visual attentional effects because their peak locations were consistent with response-related motor activity.

PSE-Parametric Whole-Brain Analysis

To examine whether individual differences in perceived contrast, indexed by the PSE difference, were associated with cue-related neural activity, PSE-parametric whole-brain analyses were conducted for the four cueing contrasts. For each contrast, both positive and negative associations with the PSE difference were tested, resulting in eight parametric analyses in total. The analyses included the 33 participants with valid PSE estimates. A positive association indicates that higher PSE-difference values were associated with higher neural activity, whereas a negative association indicates that higher PSE-difference values were associated with lower neural activity. These terms describe the direction of the statistical relationship between PSE difference and neural activity and do not indicate positive or negative attentional effects.

At the prespecified whole-brain voxel-level threshold of $p < .05$, corrected for family-wise error, none of the positive or negative PSE associations produced suprathreshold clusters. The statistical maps were therefore also examined using exploratory voxel-level thresholds of $p < .001$ and $p < .01$, uncorrected.

At the exploratory threshold of $p < .001$, uncorrected, some small clusters were identified across the positive and negative PSE analyses. However, none of these clusters survived cluster-level FWE correction. The same pattern was observed at the more liberal

threshold of $p < .01$, where larger and more numerous clusters were detected, but none survived cluster-level FWE correction.

Overall, the PSE-parametric analyses did not identify statistically reliable whole-brain associations between individual PSE differences and neural activity in any of the four cueing contrasts. Therefore, the present data do not provide evidence that individual differences in the behavioural PSE measure were reliably associated with cue-related neural activity at the whole-brain level.

Exploratory ROI Analysis

Because the study was motivated by a priori hypotheses concerning attentional modulation within visual cortex, an exploratory region-of-interest (ROI) analysis was conducted. Anatomically defined visual ROIs were derived from the Brainnetome atlas and were selected to approximate the visual regions examined in previous research. The ROIs were grouped into three regions: V1, V2/V3, and extrastriate visual cortex. V1 was represented by regions of the caudal lingual gyrus and caudal cuneus, V2/V3 by regions of the rostral lingual gyrus and rostral cuneus, and extrastriate cortex by medial and inferior occipital regions.

The same four cueing contrasts used in the whole-brain analysis were examined within each ROI. Statistical maps were inspected at a voxel-level threshold of $p < .001$, uncorrected, and at a more liberal exploratory threshold of $p < .01$, uncorrected. The analysis was intended to provide a spatially restricted examination of cue-related activity in visual cortex rather than a confirmatory test based on individually defined retinotopic maps.

At the voxel-level threshold of $p < .001$, uncorrected, no suprathreshold clusters were identified for any of the four cueing contrasts within any of the predefined visual ROIs. At the more liberal exploratory threshold of $p < .01$, uncorrected, small clusters were observed for the RightLower_Uncued > RightLower_Cued contrast in extrastriate cortex, V1, and V2/V3. An additional small cluster was observed within V2/V3 for the LeftLower_Uncued >

LeftLower_Cued contrast. None of these exploratory effects survived correction for multiple comparisons and they were therefore not interpreted as reliable evidence of cue-related modulation within visual cortex.

The cluster extent, peak T-value, and MNI coordinates of the exploratory ROI findings are reported in Table 2.

Table 2. Summary of exploratory ROI findings at p < .01, uncorrected

Note. All ROI findings are exploratory and are reported at an uncorrected voxel-level threshold of $p < .01$. None survived correction for multiple comparisons.

Contrast	**ROI**	**k**	**Peak T**	**x**	**y**	**z**
RightLower Uncued > Cued	Extrastriate	18	2.96	-12	-98	-18
RightLower Uncued > Cued	V1	12	2.90	-2	-88	-16
RightLower Uncued > Cued	V1	3	2.73	8	-88	-14
RightLower Uncued > Cued	V2/V3	23	2.91	12	-48	-6
LeftLower Uncued > Cued	V2/V3	19	2.91	2	-72	32

Discussion

Summary of Main Findings

The present study examined whether cross-modal auditory cueing modulates visual processing and attentional effects within visual cortex. Behaviourally, attentional cueing was associated with improved tilt-discrimination accuracy for easy conscious trials, whereas no reliable cueing effect was observed for hard conscious trials. The psychometric analysis produced a negative mean PSE difference, indicating that the fitted PSE for the test stimulus was generally lower than the fitted PSE for the standard stimulus. However, this PSE difference should not be interpreted by itself as a direct measure of the effect of attentional cueing.

At the neural level, none of the four whole-brain contrasts survived the prespecified voxel-level FWE-corrected threshold of $p < .05$. At the exploratory voxel-level threshold of $p < .001$, uncorrected, two clusters survived cluster-level FWE correction. However, coordinate inspection suggested that the prominent clusters were located in primary motor regions associated with finger responses rather than in occipital visual cortex. These exploratory clusters were interpreted as possible response-related activity captured by the design and were not treated as evidence of attentional modulation in visual cortex.

The exploratory ROI analysis did not identify effects that survived correction for multiple comparisons. Thus, the present study did not provide reliable corrected neural evidence for the predicted attentional modulation within visual cortex. The PSE-parametric whole-brain analyses also did not identify reliable associations between individual PSE differences and neural activity.

Behavioral Findings and Attentional Modulation of Appearance

The behavioural results provided evidence that attentional cueing influenced performance under some task conditions. For easy conscious trials, accuracy was significantly higher in the cued than in the uncued condition, with a mean cueing effect of 2.48 percentage points, $t(33) = 3.17$, $p = .003$, 95% CI [0.89, 4.07]. In contrast, the cueing

effect for hard conscious trials was not statistically significant, with a mean difference of −2.53 percentage points, $t(33) = -1.87$, $p = .070$, 95% CI [−5.27, 0.22].

This pattern suggests that the behavioural effect of cueing was not uniform across task difficulty. Cueing was associated with improved discrimination accuracy when the task was relatively easy, whereas no reliable benefit was observed under the harder condition. The reduced or absent cueing benefit for hard trials may reflect the greater difficulty and variability of performance in this condition.

Neural Correlates of Attentional Modulation

The whole-brain analyses did not provide confirmatory evidence for cue-related neural modulation at the prespecified voxel-level FWE-corrected threshold of $p < .05$. None of the four directional contrasts produced a sufficiently strong effect to survive voxel-level correction across the whole-brain search volume.

Exploratory cluster-level analyses identified two clusters that survived cluster-level FWE correction when using an uncorrected voxel-forming threshold of $p < .001$. However, the prominent peaks of these clusters were located in regions consistent with primary motor or finger-response cortex rather than occipital visual cortex. Because the button press followed stimulus presentation at a relatively consistent interval, motor-related activity may have overlapped with the stimulus regressors through the temporal spread of the haemodynamic response.

Accordingly, these exploratory clusters should not be interpreted as reliable evidence that auditory cueing enhanced or suppressed activity in visual cortex. Instead, they may reflect response-related activity captured by the design and should not be used to draw conclusions about attentional modulation in visual cortex. Taken together, the whole-brain results did not provide confirmatory evidence for the predicted pattern of attentional enhancement in visual cortex. The absence of reliable ROI effects further supports a cautious interpretation of the neural findings.

PSE-Related Neural Activity

The behavioural psychometric analysis revealed a negative mean PSE difference, indicating that the fitted PSE for the test stimulus was, on average, lower than the fitted PSE for the standard stimulus. This finding demonstrates a systematic difference between the two fitted psychometric functions. However, the PSE difference was not itself a direct comparison between cued and uncued conditions. It should therefore be interpreted as a measure of the relationship between the test and standard psychometric functions, rather than as conclusive evidence that auditory cueing altered perceived contrast.

The PSE-parametric whole-brain analyses did not identify reliable positive or negative associations between individual PSE differences and neural activity. No association survived voxel-level FWE correction at $p < .05$, and none of the exploratory clusters identified at the uncorrected thresholds of $p < .001$ or $p < .01$ survived cluster-level FWE correction.

These findings provide no reliable evidence that individual differences in the behavioural PSE measure were reflected in cue-related whole-brain neural activity. The absence of a significant PSE-neural association should not be interpreted as evidence that perceived contrast and neural activity are unrelated in general. It indicates only that the present sample and analysis did not detect a reliable association under the applied statistical criteria.

ROI Findings and Visual-Cortical Hierarchy

The exploratory ROI analysis did not provide corrected evidence for cue-related modulation within the predefined visual regions. Although small clusters were observed at the more liberal uncorrected threshold, none survived correction for multiple comparisons. The ROI analysis therefore did not support a reliable region-specific attentional effect across the examined visual areas.

The absence of reliable ROI-level effects contrasts with the progressive attentional modulation across visual areas reported by Liu et al. (2005). Several methodological factors may account for this difference. First, the present study used anatomically defined ROIs

derived from the Brainnetome atlas rather than individually defined retinotopic maps. Anatomical ROIs may provide less precise correspondence between the analysed voxels and the cortical representation of the stimulated visual locations. Second, the present study used auditory rather than visual cues, and cross-modal attentional effects may be weaker or more variable than effects produced by cues within the visual modality. Finally, the number of observations available for each participant may have limited the sensitivity of the ROI analyses.

These findings do not demonstrate that auditory cueing has no effect on visual cortex. Rather, they indicate that the present data did not provide sufficiently strong or consistent evidence for cue-related modulation within the predefined visual regions under the applied statistical criteria.

Comparison with Previous Literature

The present neural findings differ from the pattern reported by Liu et al. (2005), who observed attentional modulation across retinotopic visual areas, with the magnitude of the effect increasing from V1 to extrastriate cortex. In the present study, none of the four cue-related contrasts survived the prespecified whole-brain voxel-level FWE correction, and the exploratory ROI analysis did not identify effects that survived correction for multiple comparisons.

This discrepancy should not be interpreted as evidence against attentional modulation in visual cortex in general. The two studies differed in several important respects. Liu et al. (2005) used visual peripheral cues, whereas the present study used auditory spatial cues. Visual cues directly stimulate the same sensory system in which attentional modulation is subsequently measured and may therefore produce stronger or more spatially specific modulation of visual cortex. Auditory cues, in contrast, require attentional orienting across sensory modalities and may produce weaker, more variable, or differently distributed neural effects.

The apparent directional asymmetry in the whole-brain results should also be interpreted cautiously. Coordinate inspection suggested that the prominent clusters were more consistent with response-related activity in primary motor regions than with occipital visual cortex. The present data therefore do not allow strong conclusions about lateralized cue-related modulation within visual cortex.

The behavioural findings nevertheless indicate that cueing influenced performance under at least some task conditions, particularly for easy conscious trials. The absence of corresponding reliable ROI-level effects may indicate that behavioural benefits of auditory cueing can occur without sufficiently strong or consistent modulation within the specific visual regions examined in the present study.

Taken together, the whole-brain and ROI findings do not provide reliable neural evidence for the predicted progressive enhancement across visual cortex. Rather, they suggest that the neural consequences of auditory spatial cueing may be weaker, more variable, or differently distributed than those observed following visual cueing.

Limitations

Several limitations should be considered when interpreting the present findings. First, the number of usable observations available for each participant was relatively limited. This may have reduced the sensitivity of both the behavioural and neuroimaging analyses, particularly the ROI and PSE-parametric analyses. Consequently, the absence of statistically reliable neural effects should not be interpreted as evidence that cross-modal cueing has no influence on visual processing.

Second, the ROI analysis was based on anatomically defined regions derived from the Brainnetome atlas rather than on individually defined retinotopic maps. Although this approach provided an independent and anatomically motivated definition of the visual regions, it may not have captured individual differences in the precise organisation of visual cortex or the exact cortical representations of the stimulated visual locations. In addition, V2

and V3 were analysed as a combined ROI, which limited the anatomical specificity of the analysis.

Third, the ROI findings were exploratory and included statistical inspection at an uncorrected threshold of $p < .01$. None of the observed ROI effects survived correction for multiple comparisons. The ROI results should therefore be regarded as descriptive exploratory findings rather than as confirmatory evidence for region-specific attentional modulation.

A further limitation concerns the interpretation of the exploratory whole-brain clusters. Because button presses followed stimulus presentation at a relatively consistent interval, response-related motor activity may have overlapped with the stimulus-related regressors through the temporal spread of the haemodynamic response. Coordinate inspection suggested that the prominent clusters were more consistent with primary motor regions associated with finger responses than with occipital visual cortex. These clusters were therefore interpreted cautiously and were not treated as reliable evidence of cue-related modulation within visual cortex.

Finally, the present study used auditory spatial cues, whereas much of the relevant previous literature, including Liu et al. (2005), examined attentional modulation using visual cues. Auditory and visual cues may engage attentional orienting through partly different mechanisms, and cross-modal effects may be weaker, more variable, or differently distributed across visual cortex. Direct comparisons between the present findings and studies using visual cues should therefore be made cautiously.

Future Directions

Future studies could investigate cross-modal attentional modulation using larger samples and a greater number of observations per participant, which would increase statistical power and provide more reliable estimates of individual differences. Individually defined retinotopic visual ROIs could also be used to examine whether attentional modulation is associated with specific stages of the visual hierarchy. In addition, future work

could directly compare auditory and visual cueing within the same experimental design to determine whether cross-modal and within-modal attention produce different patterns of modulation across visual cortex.

Societal and Ethical Considerations

The present study involved healthy adult participants and used non-invasive behavioural and fMRI procedures. Written informed consent was obtained from all participants, and the study was approved by the relevant ethical review authority.

The study has no immediate clinical application, but research on attention, perception, and awareness contributes to a broader understanding of how sensory information is selected and consciously experienced. Because the study involved individual behavioural and neuroimaging data, confidentiality and secure data handling were important ethical considerations.

The interpretation of null and exploratory findings also has an ethical dimension. Uncorrected clusters should not be presented as reliable neural effects, and conclusions should remain proportional to the strength and limitations of the evidence. In the present study, the behavioural findings are therefore discussed separately from the absence of robust corrected neural evidence.

Conclusion

The present study examined the behavioural and neural consequences of cross-modal auditory cueing during a visual contrast-discrimination task. Behaviourally, cueing was associated with a significant improvement in tilt-discrimination accuracy for easy conscious trials, whereas no reliable cueing effect was observed for hard conscious trials. The psychometric analysis revealed a negative mean difference between the fitted test and standard PSEs, although this difference should not be interpreted by itself as a direct measure of cue-induced changes in perceived contrast.

At the neural level, none of the four whole-brain contrasts survived the prespecified voxel-level FWE-corrected threshold of $p < .05$. Exploratory analyses using an uncorrected voxel-level threshold identified clusters that survived cluster-level FWE correction, but coordinate inspection suggested that the prominent clusters were located in primary motor regions associated with finger responses rather than in visual cortex. These effects were therefore interpreted as response-related activity and were not treated as evidence for reliable attentional modulation of visual cortex.

The predefined exploratory ROI analysis did not identify effects that survived correction for multiple comparisons. Similarly, the PSE-parametric whole-brain analyses did not reveal reliable associations between individual PSE differences and neural activity. Overall, the findings provide behavioural evidence for a cueing benefit under relatively easy task conditions, but they do not support a clear or reliable neural signature of progressive attentional enhancement across visual cortex.

The absence of robust neural findings should be interpreted in light of the limited number of trials available per participant, the use of anatomically defined rather than individually mapped visual ROIs, and the possibility that auditory cueing produces weaker or more variable modulation of visual cortex than visual cueing. Future studies using larger datasets and individual retinotopic localizers could provide a more sensitive test of cross-modal attentional modulation across the visual hierarchy.

Word Count: 6875

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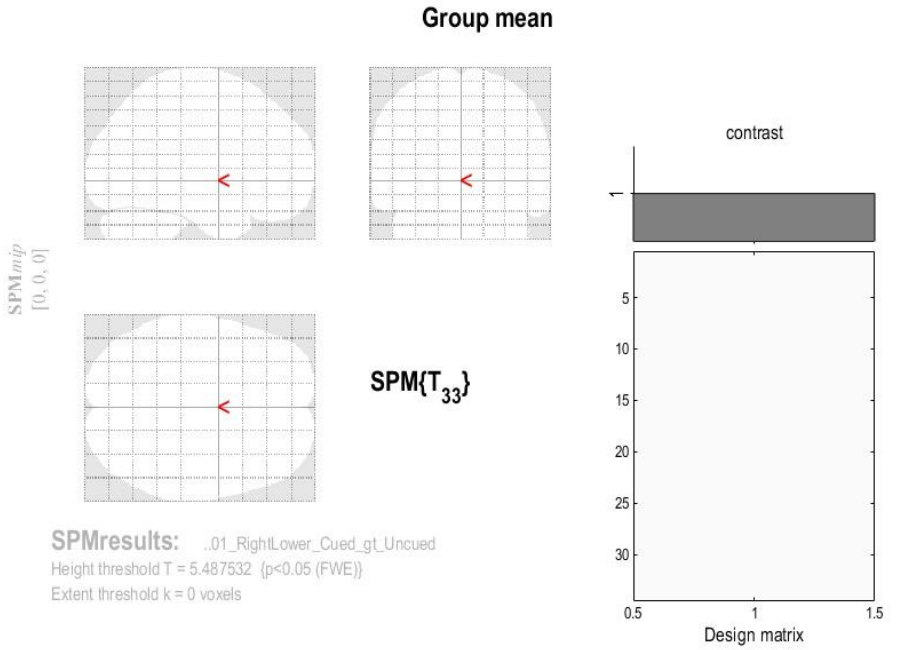
Appendix A. Whole-Brain SPM Results

This appendix presents supplementary whole-brain SPM outputs for the four group-level cueing contrasts examined in the study.



Statistics: *p-values adjusted for search volume*

set-level		cluster-level				peak-level					mm mm mm
p	c	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	T	(Z_E)	p_{uncorr}	

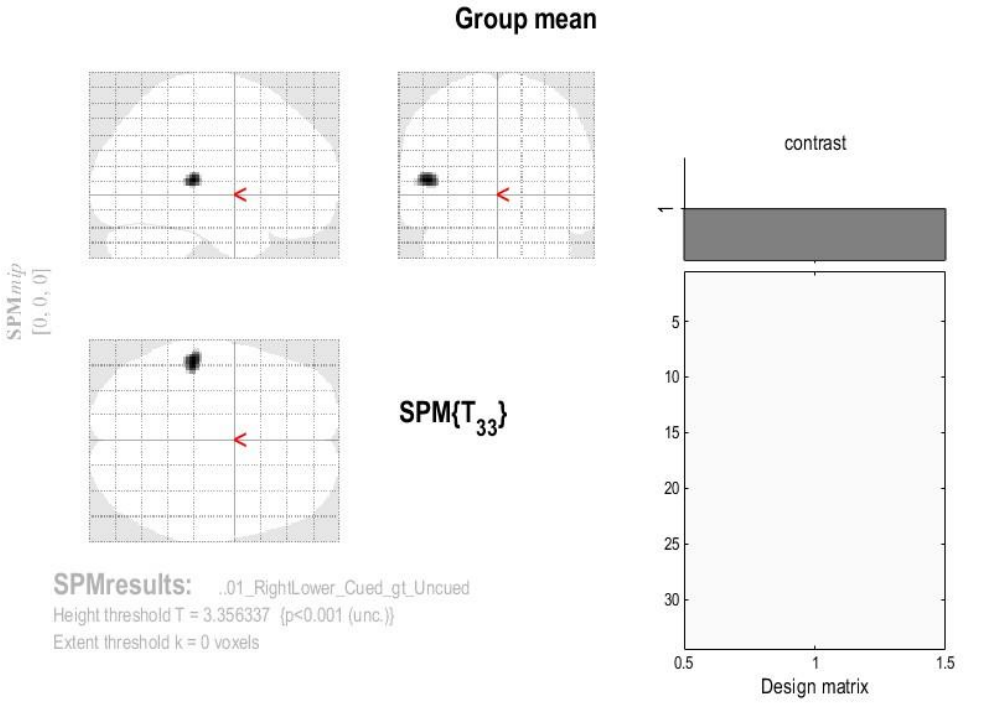
no suprathreshold clusters

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 5.49, p = 0.000 (0.050)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 8.037
Expected number of clusters, <c> = 0.05
FWEp: 5.488, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 33.0]
FWHM = 14.7 14.8 13.9 mm mm mm; 7.4 7.4 6.9 {voxels}
Volume: 1388320 = 173540 voxels = 423.8 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 378.26 voxels)

Figure A1. Whole-brain second-level SPM results for the RightLower Cued > Uncued contrast at the FWE-corrected threshold of $p < .05$. No suprathreshold clusters were identified.



Statistics: ***p-values adjusted for search volume***

cluster-level				peak-level					mm mm mm
$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	T	(Z_E)	p_{uncorr}	
0.409	0.089	101	0.089	0.496	0.117	4.39	3.87	0.000	-50 -30 8

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.36, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.801
Expected number of clusters, <c> = 5.87
FWEp: 5.488, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 33.0]
FWHM = 14.7 14.8 13.9 mm mm mm; 7.4 7.4 6.9 {voxels}
Volume: 1388320 = 173540 voxels = 423.8 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 378.26 voxels)

Figure A2. Whole-brain second-level SPM results for the RightLower Cued > Uncued contrast at an uncorrected voxel-level threshold of $p < .001$. The exploratory cluster did not survive cluster-level FWE correction.

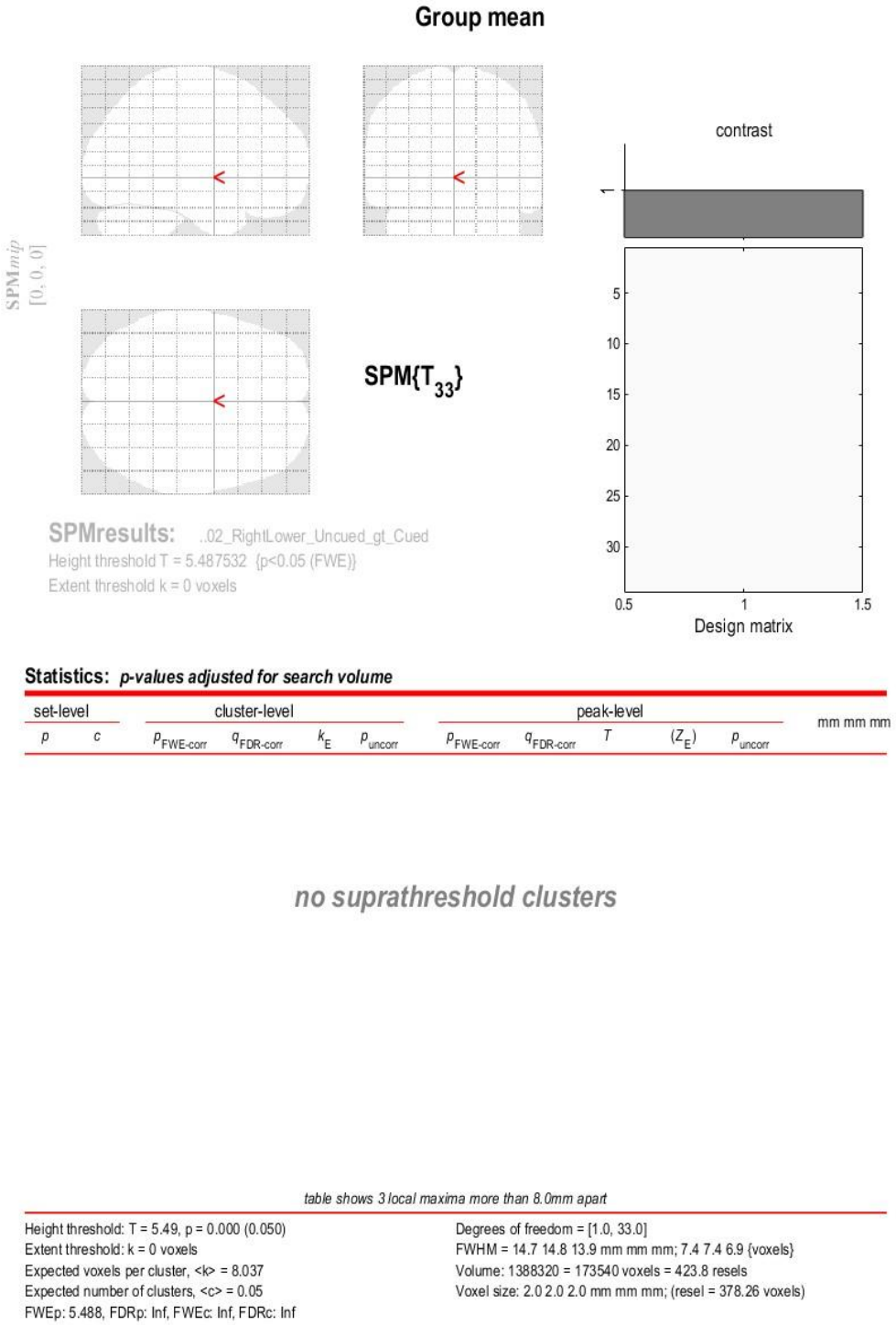
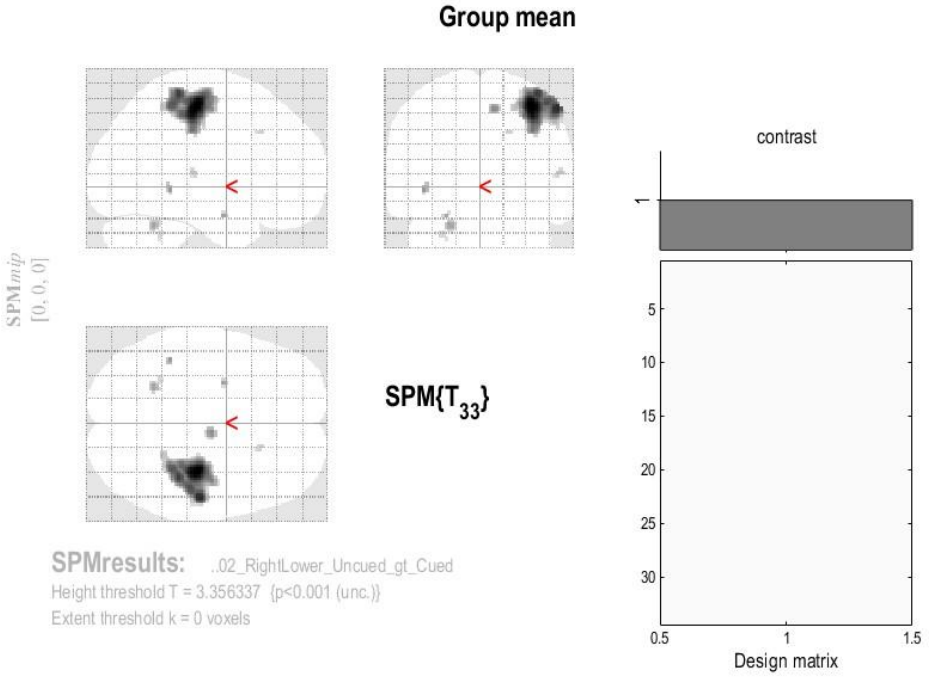


Figure A3. Whole-brain second-level SPM results for the RightLower Uncued > Cued contrast at the voxel-level FWE-corrected threshold of $p < .05$. No suprathreshold clusters were identified.



Statistics: *p-values adjusted for search volume*

set-level		cluster-level				peak-level					mm mm mm		
p	c	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	T	(Z_E)	p_{uncorr}			
0.239	8	0.000	0.000	1396	0.000	0.090	0.130	5.24	4.44	0.000	36	-24	54
						0.222	0.227	4.83	4.17	0.000	54	-20	52
						0.309	0.252	4.66	4.05	0.000	40	-36	62
		0.878	0.755	28	0.358	0.782	0.462	4.03	3.60	0.000	8	-12	52
		0.973	0.755	9	0.618	0.847	0.511	3.93	3.53	0.000	-42	-42	-4
		0.865	0.755	30	0.341	0.901	0.530	3.83	3.46	0.000	-24	-54	-28
		0.988	0.755	4	0.755	0.903	0.530	3.82	3.45	0.000	-26	-4	-22
		0.970	0.755	10	0.597	0.976	0.723	3.59	3.28	0.001	56	-26	8
		0.988	0.755	4	0.755	0.988	0.807	3.50	3.21	0.001	18	24	36
		0.986	0.755	5	0.722	0.993	0.857	3.44	3.16	0.001	-28	-50	-36

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.36, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.801
Expected number of clusters, <c> = 5.87
FWEp: 5.488, FDRp: Inf, FWEc: 1396, FDRc: 1396

Degrees of freedom = [1.0, 33.0]
FWHM = 14.7 14.8 13.9 mm mm mm; 7.4 7.4 6.9 {voxels}
Volume: 1388320 = 173540 voxels = 423.8 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 378.26 voxels)

Figure A4. Whole-brain second-level SPM results for the RightLower Uncued > Cued contrast at an uncorrected voxel-level threshold of $p < .001$. A cluster of 1,396 voxels survived cluster-level FWE correction ($pFWE < .001$), with a peak T-value of 5.24 at MNI coordinates [36, −24, 54].

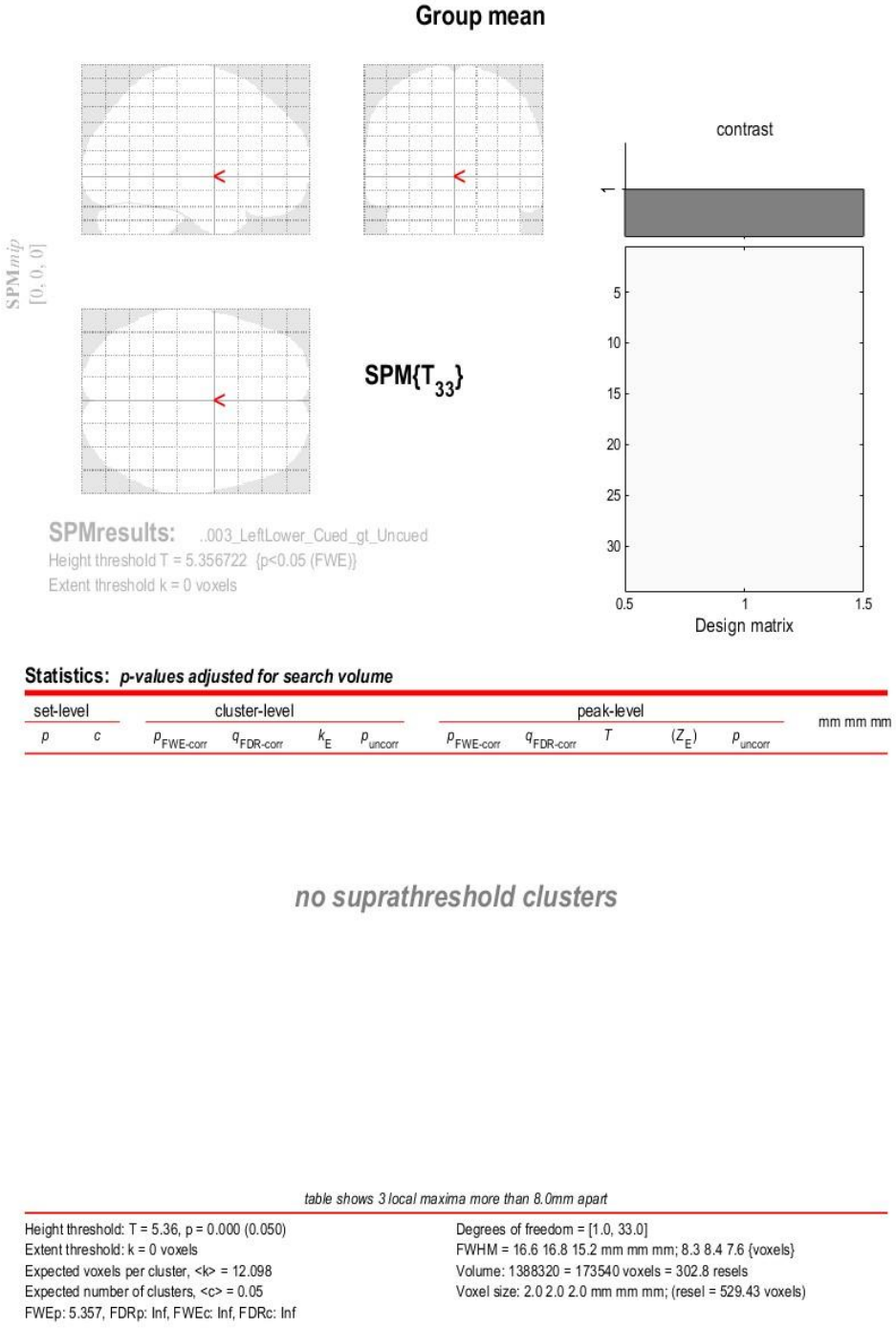
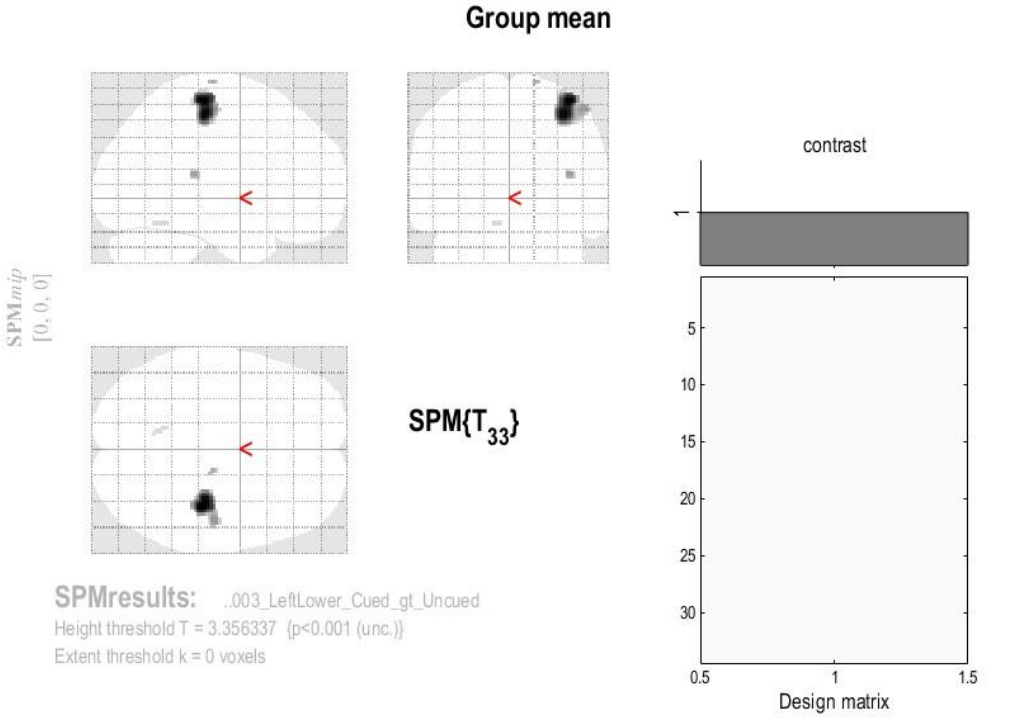


Figure A5. Whole-brain second-level SPM results for the LeftLower Cued > Uncued contrast at the voxel-level FWE-corrected threshold of $p < .05$. No suprathreshold clusters were identified.



Statistics: ***p-values adjusted for search volume***

set-level		cluster-level				peak-level					mm mm mm
p	c	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	T	(Z_E)	p_{uncorr}	
0.627	4	0.034	0.032	399	0.008	0.240	0.261	4.65	4.05	0.000	40 -28 62
						0.275	0.261	4.58	4.00	0.000	36 -26 54
						0.862	0.808	3.75	3.40	0.000	50 -18 56
		0.914	0.831	16	0.568	0.887	0.808	3.71	3.36	0.000	38 -32 14
		0.972	0.831	3	0.831	0.917	0.808	3.64	3.31	0.000	16 -20 74
		0.964	0.831	5	0.771	0.978	0.933	3.42	3.14	0.001	-12 -54 -18

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.36, p = 0.001 (0.987)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 50.108
Expected number of clusters, <c> = 4.32
FWEp: 5.357, FDRp: Inf, FWEc: 399, FDRc: 399

Degrees of freedom = [1.0, 33.0]
FWHM = 16.6 16.8 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388320 = 173540 voxels = 302.8 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 529.43 voxels)

Figure A6. Whole-brain second-level SPM results for the LeftLower Cued > Uncued contrast at an uncorrected voxel-level threshold of $p < .001$. A cluster of 399 voxels survived cluster-level FWE correction (pFWE-corr = .034), with a peak T-value of 4.65 at MNI coordinates [40, −28, 62].

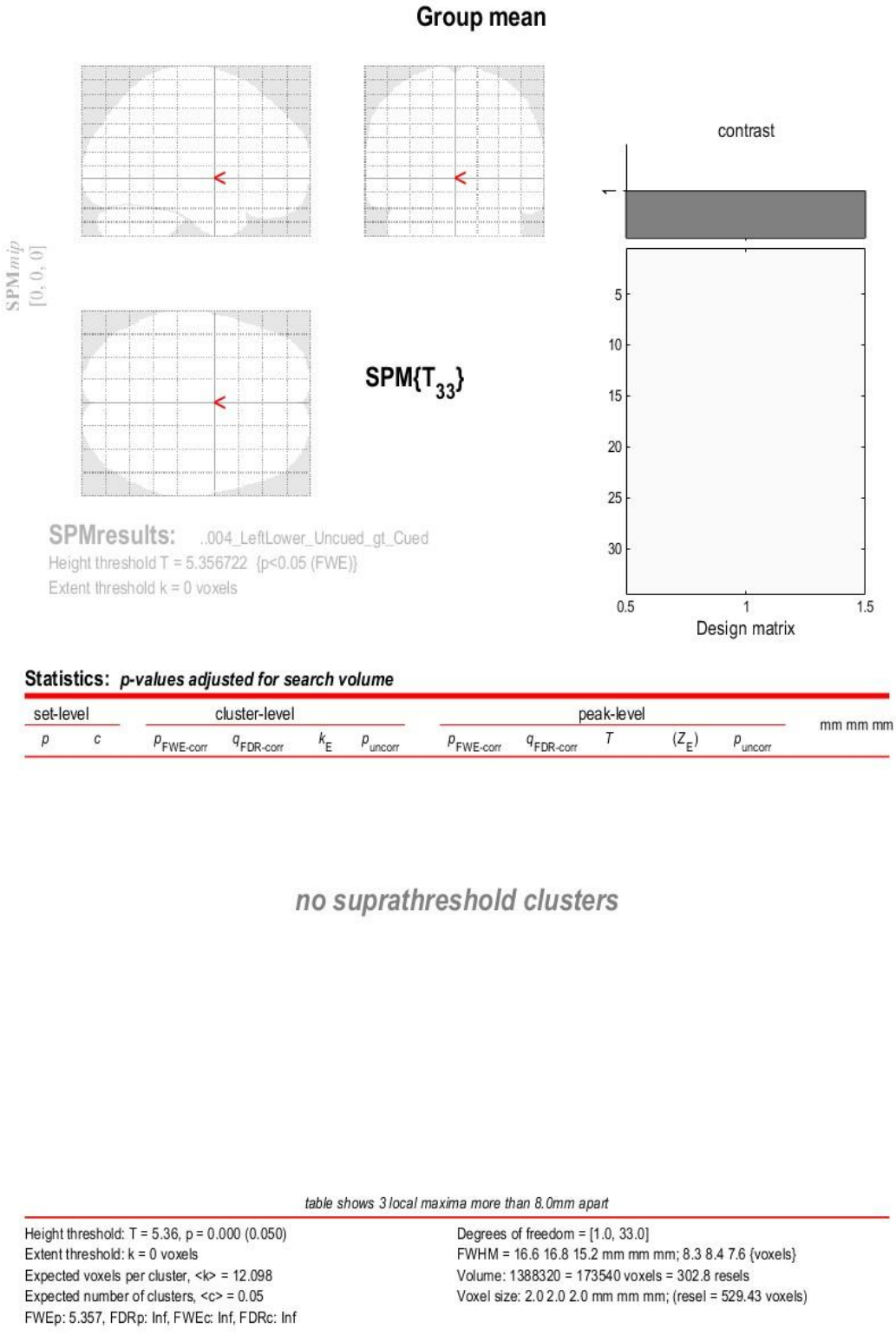
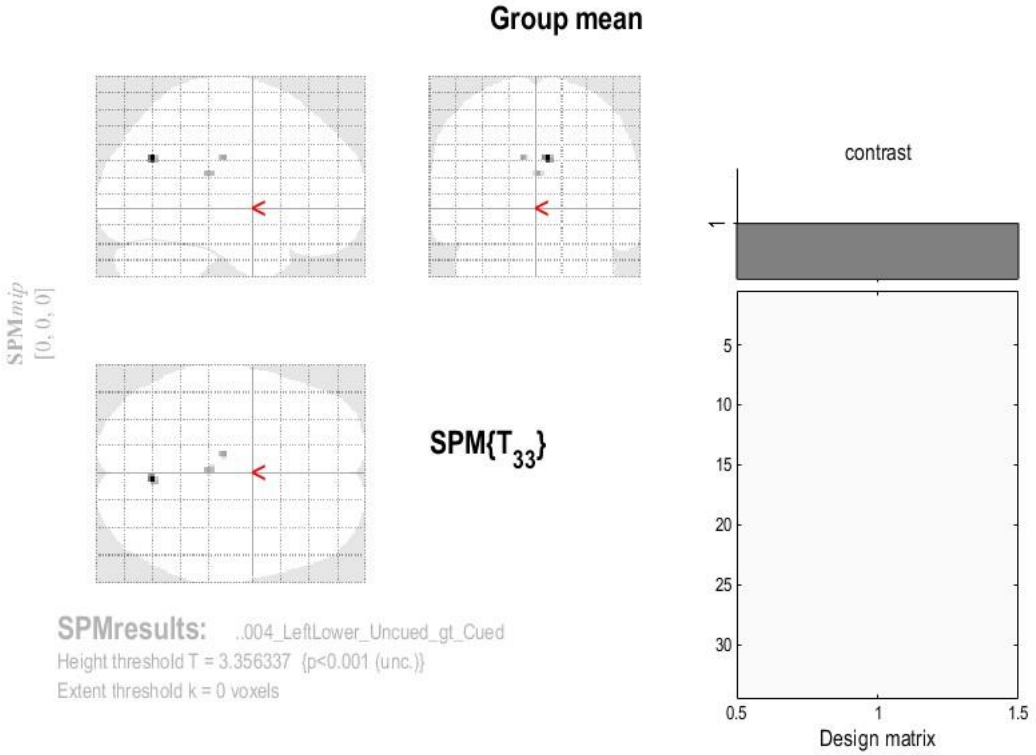


Figure A7. Whole-brain second-level SPM results for the LeftLower Uncued > Cued contrast at the voxel-level FWE-corrected threshold of $p < .05$. No suprathreshold clusters were identified.



Statistics: ***p-values adjusted for search volume***

set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}	
0.805	3	0.943	0.831	10	0.662	0.872	0.844	3.74	3.39	0.000	6 -66 30
		0.972	0.831	3	0.831	0.972	0.844	3.46	3.17	0.001	-10 -20 30
		0.964	0.831	5	0.771	0.974	0.844	3.45	3.16	0.001	0 -30 20

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.36, p = 0.001 (0.987)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 50.108
Expected number of clusters, <c> = 4.32
FWEp: 5.357, FDRp: Inf, FWEc: Inf, FDRc: Inf

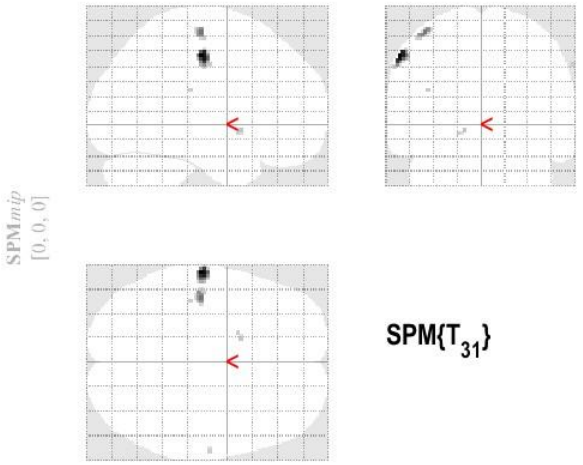
Degrees of freedom = [1.0, 33.0]
FWHM = 16.6 16.8 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388320 = 173540 voxels = 302.8 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 529.43 voxels)

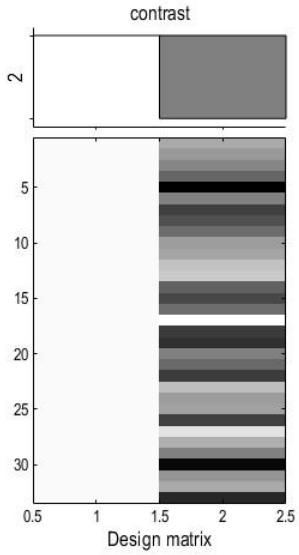
Figure A8. Whole-brain second-level SPM results for the LeftLower Uncued > Cued contrast at an uncorrected voxel-level threshold of $p < .001$. The exploratory cluster did not survive cluster-level FWE correction.

Appendix B. PSE-Parametric Whole-Brain SPM Results

This appendix summarises the positive and negative PSE-parametric whole-brain analyses conducted for the four cueing contrasts. None of the tested associations survived whole-brain voxel-level FWE correction or exploratory cluster-level FWE correction.

PSE negative association





Statistics: *p-values adjusted for search volume*

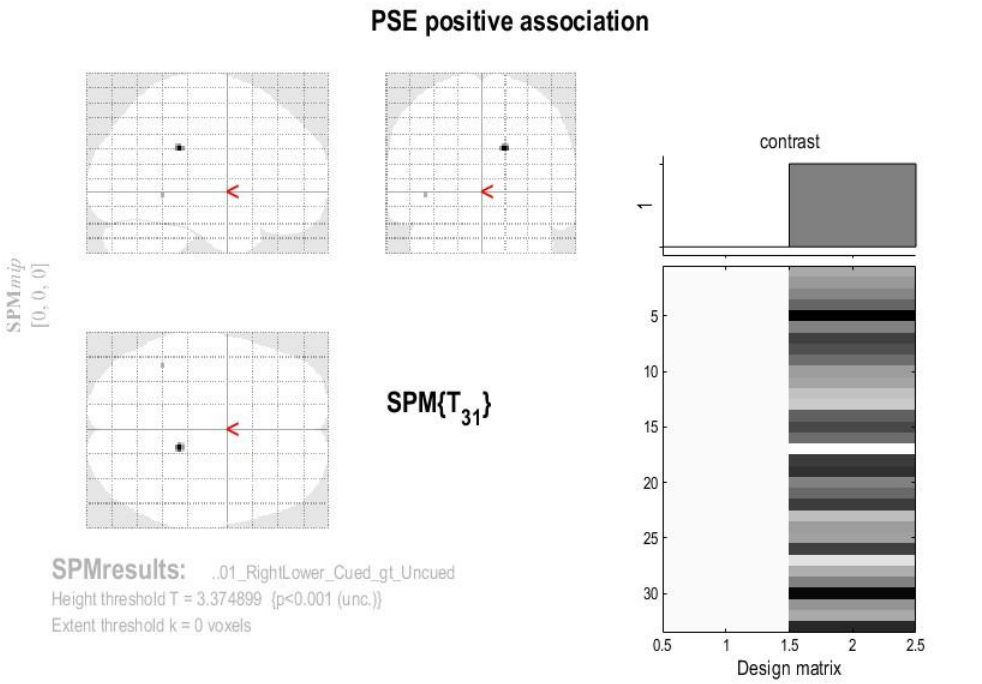
set-level		cluster-level				peak-level					mm mm mm		
p	c	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	T	(Z_E)	p_{uncorr}			
0.702	5	0.784	0.894	42	0.259	0.431	0.669	4.52	3.93	0.000	−60	−20	46
		0.945	0.894	16	0.492	0.877	0.860	3.91	3.50	0.000	−42	−20	62
		0.991	0.894	3	0.793	0.990	0.860	3.51	3.20	0.001	−14	8	−6
		0.995	0.894	1	0.894	0.992	0.860	3.48	3.17	0.001	−40	−28	22
		0.993	0.894	2	0.838	0.994	0.860	3.46	3.15	0.001	64	−14	40

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.617
Expected number of clusters, <c> = 5.90
FWEp: 5.565, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 14.8 14.8 13.9 mm mm mm; 7.4 7.4 7.0 {voxels}
Volume: 1388416 = 173552 voxels = 419.7 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 382.02 voxels)

Figure B1. Whole-brain PSE-parametric analysis showing the negative association between PSE difference and neural activity for the RightLower Cued > Uncued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: ***p-values adjusted for search volume***

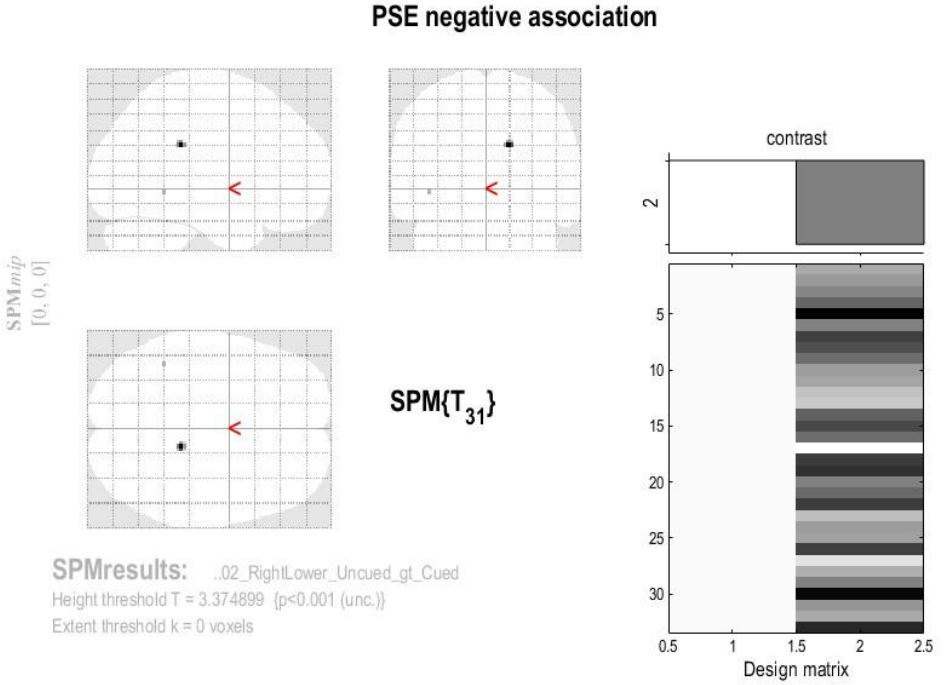
set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	*T*	(Z_E)	p_{uncorr}	
0.981	2	0.967	0.894	11	0.576	0.848	0.639	3.96	3.53	0.000	14 -36 28
		0.995	0.894	1	0.894	0.990	0.772	3.51	3.20	0.001	-42 -48 -4

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.617
Expected number of clusters, <c> = 5.90
FWEp: 5.565, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 14.8 14.8 13.9 mm mm mm; 7.4 7.4 7.0 {voxels}
Volume: 1388416 = 173552 voxels = 419.7 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 382.02 voxels)

Figure B2. Whole-brain analysis of the positive association between PSE and neural activity for the RightLower Cued > Uncued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: *p-values adjusted for search volume*

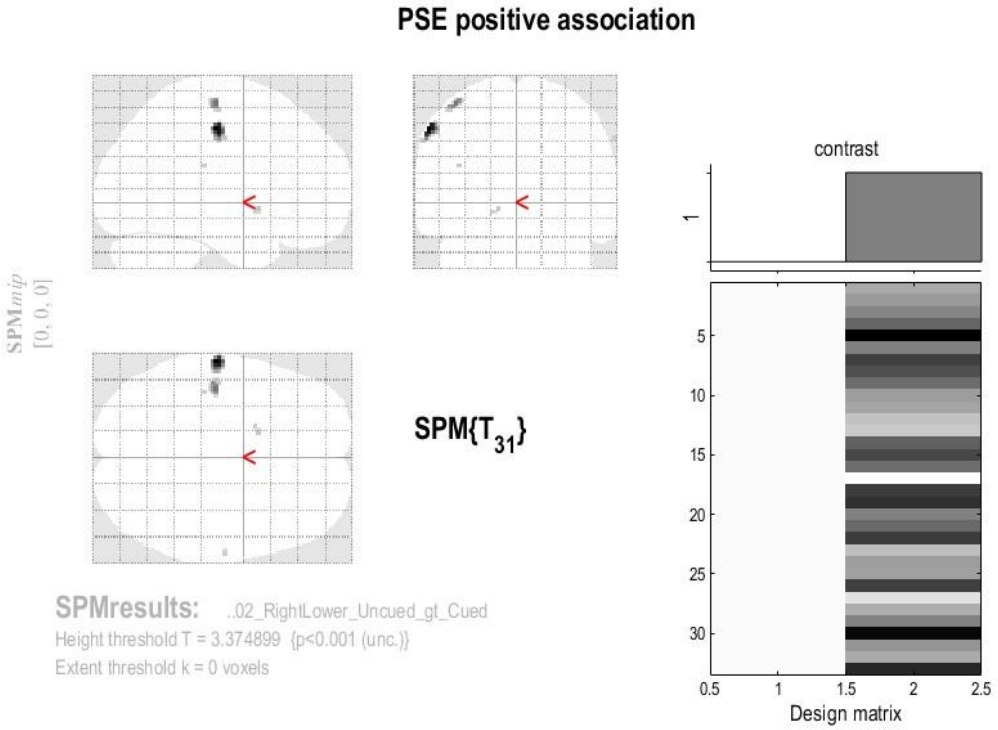
set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE-corr}$	$q_{FDR-corr}$	k_E	p_{uncorr}	$p_{FWE-corr}$	$q_{FDR-corr}$	*T*	(Z_E)	p_{uncorr}	
0.981	2	0.967	0.894	11	0.576	0.848	0.639	3.96	3.53	0.000	14 -36 28
		0.995	0.894	1	0.894	0.990	0.772	3.51	3.20	0.001	-42 -48 -4

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.617
Expected number of clusters, <c> = 5.90
FWEp: 5.565, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 14.8 14.8 13.9 mm mm mm; 7.4 7.4 7.0 {voxels}
Volume: 1388416 = 173552 voxels = 419.7 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 382.02 voxels)

Figure B3. Whole-brain analysis of the negative association between PSE and neural activity for the RightLower Uncued > Cued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: *p-values adjusted for search volume*

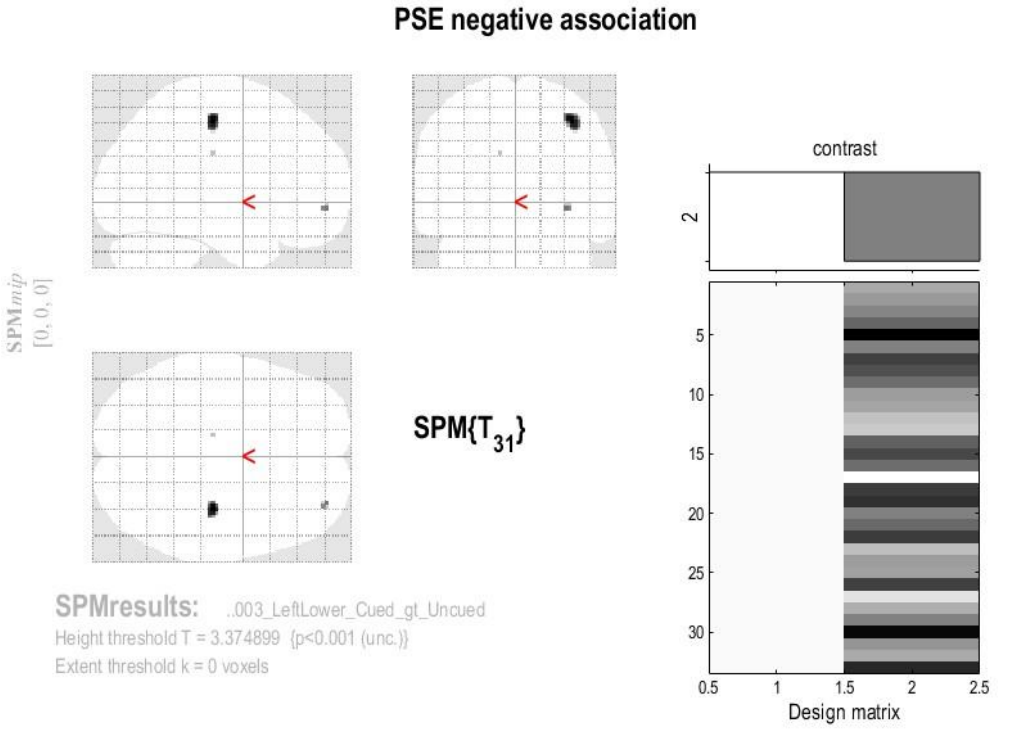
set-level		cluster-level				peak-level					mm mm mm		
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}			
0.702	5	0.784	0.894	42	0.259	0.431	0.669	4.52	3.93	0.000	-60	-20	46
		0.945	0.894	16	0.492	0.877	0.860	3.91	3.50	0.000	-42	-20	62
		0.991	0.894	3	0.793	0.990	0.860	3.51	3.20	0.001	-14	8	-6
		0.995	0.894	1	0.894	0.992	0.860	3.48	3.17	0.001	-40	-28	22
		0.993	0.894	2	0.838	0.994	0.860	3.46	3.15	0.001	64	-14	40

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.997)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 35.617
Expected number of clusters, <c> = 5.90
FWEp: 5.565, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 14.8 14.8 13.9 mm mm mm; 7.4 7.4 7.0 {voxels}
Volume: 1388416 = 173552 voxels = 419.7 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 382.02 voxels)

Figure B4. Whole-brain analysis of the positive association between PSE and neural activity for the RightLower Uncued > Cued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: ***p-values adjusted for search volume***

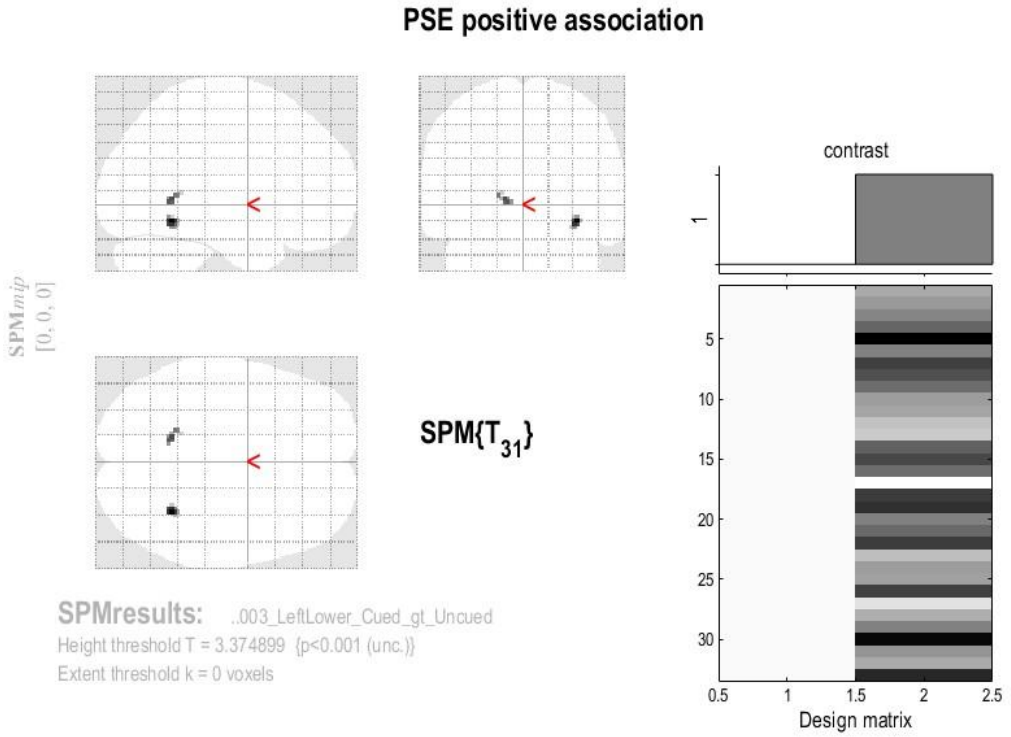
set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}	
0.816	3	0.709	0.840	53	0.280	0.872	0.900	3.77	3.39	0.000	36 -22 50
		0.966	0.914	5	0.768	0.956	0.900	3.56	3.23	0.001	32 54 -6
		0.982	0.914	1	0.914	0.981	0.900	3.43	3.14	0.001	-12 -22 30

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.988)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 49.023
Expected number of clusters, <c> = 4.41
FWEp: 5.437, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 16.5 16.7 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388416 = 173552 voxels = 304.9 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 525.81 voxels)

Figure B5. Whole-brain analysis of the negative association between PSE and neural activity for the LeftLower Cued > Uncued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: *p-values adjusted for search volume*

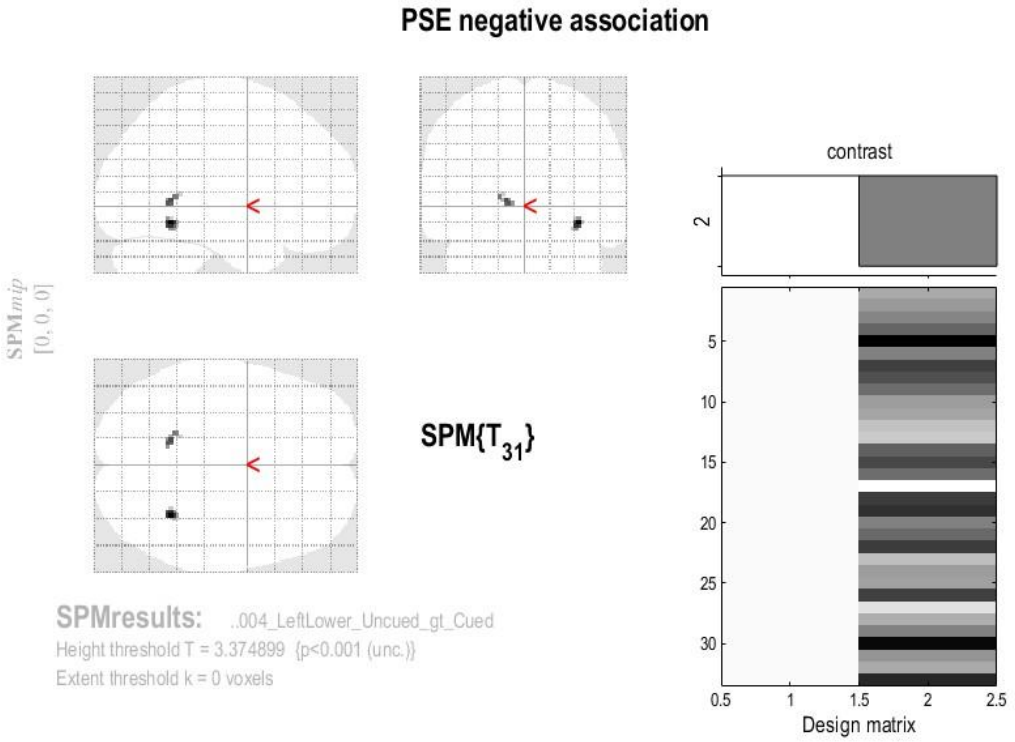
set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}	
0.642	4	0.886	0.914	22	0.492	0.855	0.867	3.80	3.42	0.000	34 -52 -12
		0.945	0.914	10	0.658	0.927	0.867	3.65	3.30	0.000	-14 -52 2
		0.978	0.914	2	0.867	0.953	0.867	3.57	3.24	0.001	-18 -50 4
		0.982	0.914	1	0.914	0.984	0.941	3.41	3.12	0.001	-16 -46 6

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.988)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 49.023
Expected number of clusters, <c> = 4.41
FWEp: 5.437, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 16.5 16.7 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388416 = 173552 voxels = 304.9 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 525.81 voxels)

Figure B6. Whole-brain analysis of the positive association between PSE and neural activity for the LeftLower Cued > Uncued contrast at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: *p-values adjusted for search volume*

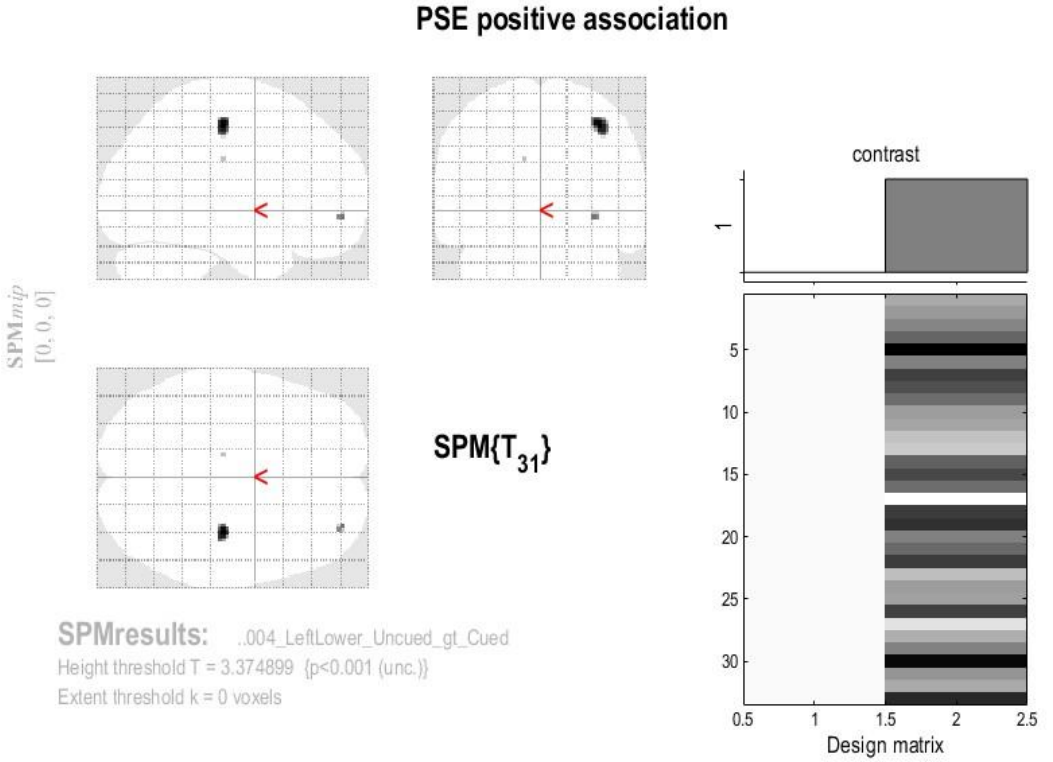
set-level		cluster-level				peak-level					mm mm mm
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}	
0.642	4	0.886	0.914	22	0.492	0.855	0.867	3.80	3.42	0.000	34 -52 -12
		0.945	0.914	10	0.658	0.927	0.867	3.65	3.30	0.000	-14 -52 2
		0.978	0.914	2	0.867	0.953	0.867	3.57	3.24	0.001	-18 -50 4
		0.982	0.914	1	0.914	0.984	0.941	3.41	3.12	0.001	-16 -46 6

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.988)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 49.023
Expected number of clusters, <c> = 4.41
FWEp: 5.437, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 16.5 16.7 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388416 = 173552 voxels = 304.9 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 525.81 voxels)

Figure B7. Whole-brain PSE-parametric analysis showing the negative association between PSE difference and neural activity for the LeftLower Uncued > Cued contrast, displayed at $p < .001$ (uncorrected). No clusters survived cluster-level FWE correction.



Statistics: ***p-values adjusted for search volume***

set-level		cluster-level				peak-level					mm mm mm		
p	*c*	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	k_E	p_{uncorr}	$p_{FWE\text{-}corr}$	$q_{FDR\text{-}corr}$	*T*	(Z_E)	p_{uncorr}			
0.816	3	0.709	0.840	53	0.280	0.872	0.900	3.77	3.39	0.000	36	-22	50
		0.966	0.914	5	0.768	0.956	0.900	3.56	3.23	0.001	32	54	-6
		0.982	0.914	1	0.914	0.981	0.900	3.43	3.14	0.001	-12	-22	30

table shows 3 local maxima more than 8.0mm apart

Height threshold: T = 3.37, p = 0.001 (0.988)
Extent threshold: k = 0 voxels
Expected voxels per cluster, <k> = 49.023
Expected number of clusters, <c> = 4.41
FWEp: 5.437, FDRp: Inf, FWEc: Inf, FDRc: Inf

Degrees of freedom = [1.0, 31.0]
FWHM = 16.5 16.7 15.2 mm mm mm; 8.3 8.4 7.6 {voxels}
Volume: 1388416 = 173552 voxels = 304.9 resels
Voxel size: 2.0 2.0 2.0 mm mm mm; (resel = 525.81 voxels)

Figure B8. Whole-brain PSE-parametric analysis showing the positive association between PSE difference and neural activity for the LeftLower Uncued > Cued contrast, displayed at p < .001 (uncorrected). No clusters survived cluster-level FWE correction.