Supplementary Material

Distinct and distributed functional connectivity patterns across cortex reflect the domain-specific constraints of object, face, scene, body, and tool category-selective modules in the ventral visual pathway

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Supplementary Discussion

An unexpected observation in the present investigation was the extent to which the patterns of FC within OTC drastically differed from the patterns of FC that OTC shared with the rest of the brain. At the level of OTC, we found that FC patterns between different OTC areas could be largely described according to the dimensions of neuroanatomical location (i.e., seed hemisphere and location along the OTC posterior-anterior axis) and categorical specificity. However, once outside of OTC, we found enormous divergence in the FC patterns of the different category-selective ROIs. This was not only the case for object categories already thought to be represented and processed relatively independently in the brain, such as faces and scenes, but also for regions situated in close neuroanatomical proximity to one another in OTC. This can be easily observed, for example, in the whole-brain FC maps of the body- and tool-selective areas, left EBA (L-EBA) and L-pMTG, located in the lateral occipital/middle temporal gyrus region, as well as the face- and body-selective areas, R-FFA and R-FBA, located in the fusiform gyrus. Furthermore, and perhaps most notable, was that we observed highly distinct whole-brain FC patterns for areas thought to form core components of the same category-selective network (e.g., OFA and FFA). The Supplementary Discussion provided below strives to provide a more general context for these important findings.

What can the whole-brain FC patterns of OTC tell us about how its information is used by the rest of the brain to guide behavior and cognition?

Recognizing that OTC regions form only one component of a much more widely distributed functional neural architecture (see Figs. 7 and 10) makes it clear that its activity should not merely support the performance of visual-perceptual tasks requiring explicit cognitive knowledge, but also, and more importantly, action and survival (Goodale and Milner, 2004; Mahon and Caramazza, 2009, 2011). Indeed, from an ecological viewpoint, it would seem unlikely that OTC evolved for the purposes of pure visual-perceptual processing as such, but rather for a more primitive and essential role in extracting information from the environment for the guidance of behaviour (Cisek, 2007; Cisek and Kalaska, 2010). With the aim of more fully capturing the scale and diversity of the findings presented, we now turn to a broader and more general discussion of how the distributed whole-brain FC patterns of OTC may reveal components of an underlying functional neural architecture that enables behavior and communication, the understanding of others' intentions, visual imagery, and the recall of complex memories.

In the current study, we found that several OTC areas displayed FC with sensorimotor areas of parietal and premotor cortex. From the standpoint of guiding behaviour and communication, what sharing of information might OTC-frontoparietal FC enable? The most likely possibility is that this pattern of FC would enable cross-talk between ventral and dorsal stream processes; for example, recognizing a visual stimulus, such as a face, and then generating the appropriate set of motor commands, such as speech. At the anatomical level, such functional interactions are supported by the vast and reciprocal web of interconnections between ventral visual areas and dorsal visual areas involved in action and speech/auditory processing (Rushworth et al., 2006; Hickok and Poeppel, 2007; Borra et al., 2008; Blank et al., 2011; Kravitz et al., 2011; Yeterian et al., 2012). At the

neurophysiological level, with respect to guiding action, this connectivity is thought to help mediate the transformation of visual information regarding object properties (e.g., object material, compliance, fragility, surface friction, etc.), which often depends on object identification and knowledge concerning its physics, into motor commands concerning their use, such as reaching, grasping, and manipulation (e.g., applying the appropriate grip forces to an empty versus full glass of water). With respect to speech processing and voice recognition, this connectivity is thought to help mediate the integration of visual face/body information with the individual's voice (Blank et al., 2011), a basis for engaging in conversations with familiar individuals.

The widely distributed whole-brain FC patterns generated from category-selective OTC regions may also provide glimpses into the underlying network architecture that supports the understanding of other's actions. Nearly two decades have passed since the discovery by Rizzolatti and colleagues of so-called 'mirror-neurons' — neurons which discharge both when the monkey performs a motor act and when the monkey views the same act performed by another individual (Gallese et al., 1996; Rizzolatti et al., 1996). While the cognitive functions and capabilities ascribed to mirror-neurons have been vast, ranging from action recognition and intention understanding to imitation and learning (Rizzolatti et al., 2001; Rizzolatti and Craighero, 2004), little work has sought to investigate exactly how mirror neurons may ultimately derive their complex visual-motor properties. As emphasized by Meyer and Damasio (2008), mirror-neurons — like all neurons in the brain — express functional properties that are not intrinsic to those neurons themselves, but rather arise from a specific set of interactions within the distributed and integrated sensorimotor networks in which they are embedded. Focusing on the functional network architecture supporting the sensorimotor properties of mirror-neurons not only helps demystify their activity (Damasio and Meyer, 2008), but it corresponds well with the widely distributed complex of brain areas activated in humans by the observation of other's actions. Previous work has identified two separate networks: a 'frontoparietal mirror system', comprising the parietal and premotor cortex plus caudal IFG, thought to be involved in the recognition of voluntary behavior, and a 'limbic mirror system', comprising the insula and anterior mesial frontal cortex, thought to be involved in the recognition of affective behavior (Rizzolatti and Craighero, 2004; Cattaneo and Rizzolatti, 2009). In line with the idea that at least some of the observation-related visual response properties of mirror-neurons might be derived from their connectivity with ventral visual pathway neurons, here we show that many key areas of both the frontoparietal and limbic mirror systems show FC with various category-selective OTC regions. Furthermore, in addition to mirror-neurons deriving their motor response properties from sensorimotor areas in frontoparietal cortex to which they are functionally connected, it is possible that some of these response properties also stem from OTC. Indeed, fMRI activation in OTC can be observed when individuals perform actual movements of the body, even in the dark (Astafiev et al., 2004; Filimon et al., 2009; Orlov et al., 2010), and it has recently been shown that pre-movement activity patterns in OTC can even be used to decode upcoming actions of the hand (Gallivan et al., 2013).

Lastly, the widespread FC of OTC regions may also reveal components of a vast network architecture enabling visual imagery and the recall of complex memories. Imagery and

recall, rather than relying on the 'bottom-up', caudal-to-rostral sweep of sensory information from primary to association cortical areas, is instead thought to require 'top-down' projections affecting information flow in the opposite direction (Lamme and Roelfsema, 2000; Bullier, 2001; Meyer and Damasio, 2009). According to the model of "multiregional retroactivation" (Damasio, 1989), just as behavior results from top-down signaling along the appropriate motor pathways, imagery and recall results from top-down signaling along sensory pathways, allowing any sensory stimulus to automatically trigger the re-experience of associated stimuli not only within that specific modality, but also that of other modalities (see also Meyer, 2011, 2012). For instance, viewing or imagining the face of a loved one (e.g., coded initially in FFA) automatically evokes a variety of multisensory responses typically associated with that face (e.g., auditory images of their voice, visual images of their body, etc.). Under this view, such associated images are thought to be stored in dispositional form in so-called 'convergence-divergence zones' (CDZs) in the association cortices, with the associated sensory images being reconstructed via top-down signals to the relevant sensory cortices (e.g., auditory cortex, and EBA). Notably, the convergence and divergence of sensory information predicted by this model corresponds well with the highly distributed patterns of FC observed here for each OTC region. For example, the face-selective areas, L-OFA and L-FFA, not only show connectivity with 'higher-order' association areas in parietal and frontal cortex, but also the 'lower-order' early visual and auditory cortices, respectively (see Figure 3). With regards to previous task-based fMRI work, this general FC network architecture may also help account for why purely visual stimuli implying touch or sound can produce content-specific patterns of activity in the somatosensory and auditory cortices, respectively (Meyer et al., 2010; Meyer et al., 2011), despite those particular modalities not actually being stimulated in the task. When considered together, the FC patterns of OTC regions seem particularly well suited to interface between bottom-up (visually-driven) and top-down (sensory cortex-targeted) signals.

Supplementary Figure Captions:

Supplementary Figure 1: Statistical comparisons of object-selective (LO and pFs) group averaged whole-brain functional connectivity maps. The four panels (A-D) correspond to those shown in Figure 2, representing the contrast (top left and right) and similarity (bottom) maps for left and right LO and pFs, separated according to putative subdivisions (A-B) and cortical hemisphere (C-D). Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 2: Statistical comparisons of face-selective (OFA and FFA) group averaged whole-brain functional connectivity maps. The four panels (A-D) correspond to those shown in Figure 3, representing the contrast (top left and right) and similarity (bottom) maps for left and right OFA and FFA, separated according to putative subdivisions (A-B) and cortical hemisphere (C-D). Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 3: Statistical comparisons of scene-selective (RSC and PPA) group averaged whole-brain functional connectivity maps. The four panels (A-D) correspond to those shown in Figure 4, representing the contrast (top left and right) and similarity (bottom) maps for left and right RSC and PPA, separated according to putative subdivisions (A-B) and cortical hemisphere (C-D). Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 4: Statistical comparisons of body-selective (EBA and FBA) and tool-selective (left pMTG) group averaged whole-brain functional connectivity maps. The top three panels (A-C) correspond to those shown in Figure 5, representing the contrast (top left and right) and similarity (bottom) maps for left and right EBA and right FBA, separated according to putative subdivisions (B,C) and cortical hemisphere (A). Panel D corresponds to Figure 6A, showing the contrast and similarity of the left EBA ROI and the left pMTG ROI. Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 5: Statistical comparisons of left lateral occipital category-selective regions (LO, OFA and EBA) group averaged whole-brain functional connectivity maps. The three panels (A-C) correspond to those shown in Figure 7A, representing the contrast (top left and right) and similarity (bottom) maps for left lateral occipital areas. Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 6: Statistical comparisons of right lateral occipital category-selective regions (LO, OFA and EBA) group averaged whole-brain functional connectivity maps. The three panels (A-C) correspond to those shown in Figure 7B, representing the contrast (top left and right) and similarity (bottom) maps for right lateral occipital areas. Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 7: Statistical comparisons of left ventro-medial category-selective regions (pFs, FFA and PPA) group averaged whole-brain functional connectivity maps. The three panels (A-C) correspond to those shown in Figure 7C, representing the contrast (top left and right) and similarity (bottom) maps for left ventro-medial areas. Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

Supplementary Figure 8: Statistical comparisons of right ventro-medial category-selective regions (pFs, FFA, PPA and FBA) group averaged whole-brain functional connectivity maps. The three panels (A-C) correspond to those shown in Figure 7D, representing the contrast (top left and right) and similarity (bottom) maps for right ventro-medial areas. Panel D corresponds to Figure 7E, comparing connectivity maps of right FFA and FBA. Mixed effects (ME; yellow) and fixed effects (FE; orange) results are overlaid on the flattened cortical surfaces ($z > 2.3$; cluster significance: $p < 0.05$, corrected). LH = left hemisphere, RH = right hemisphere.

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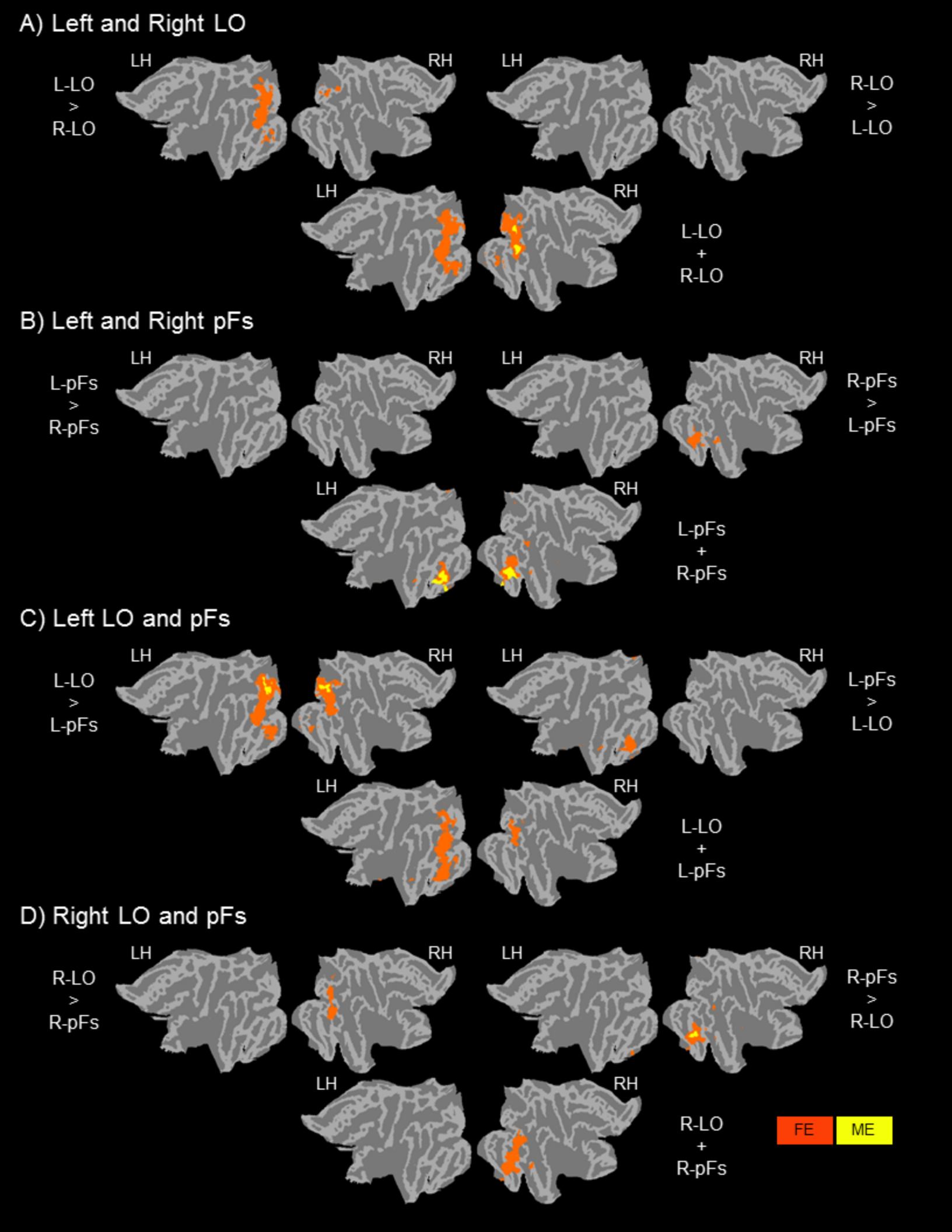
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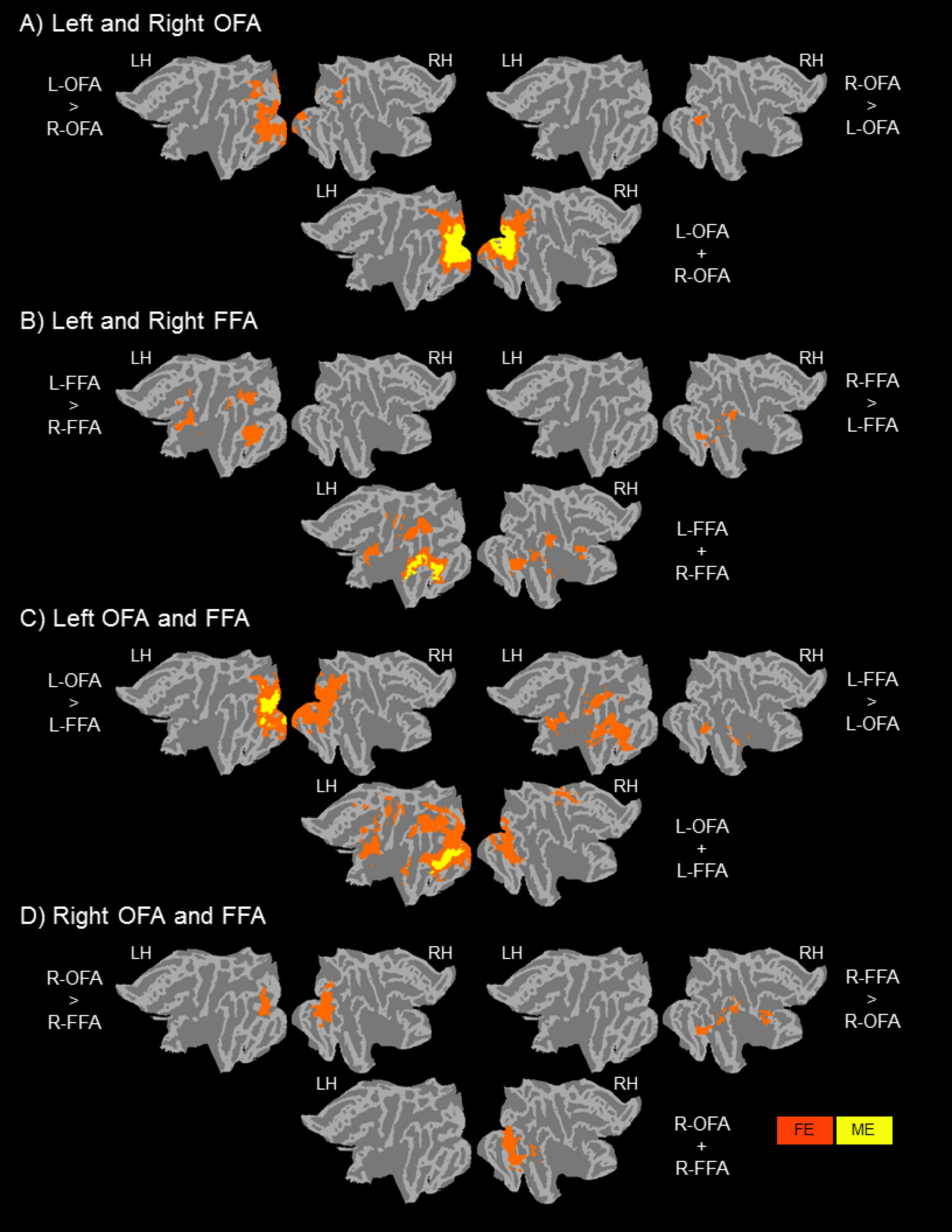
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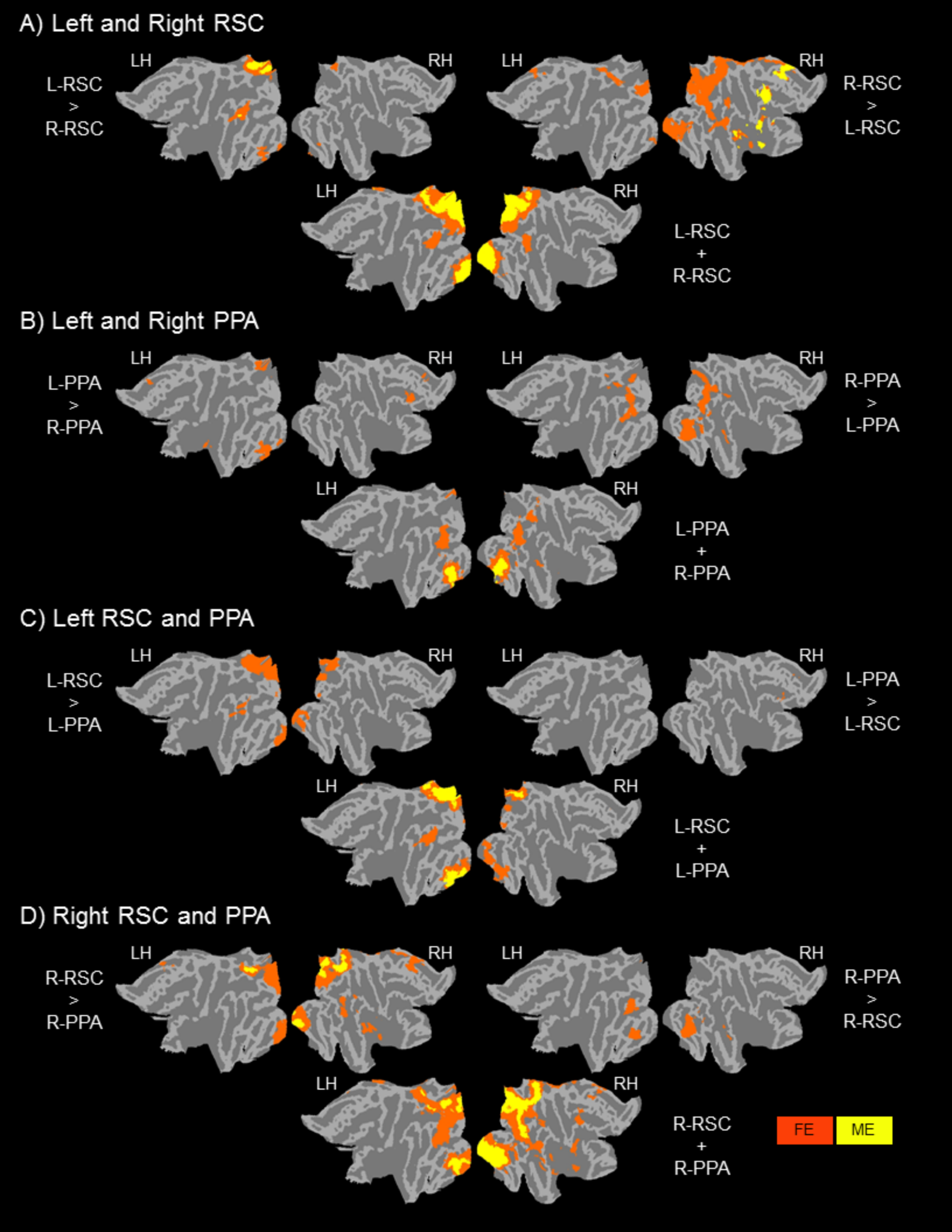
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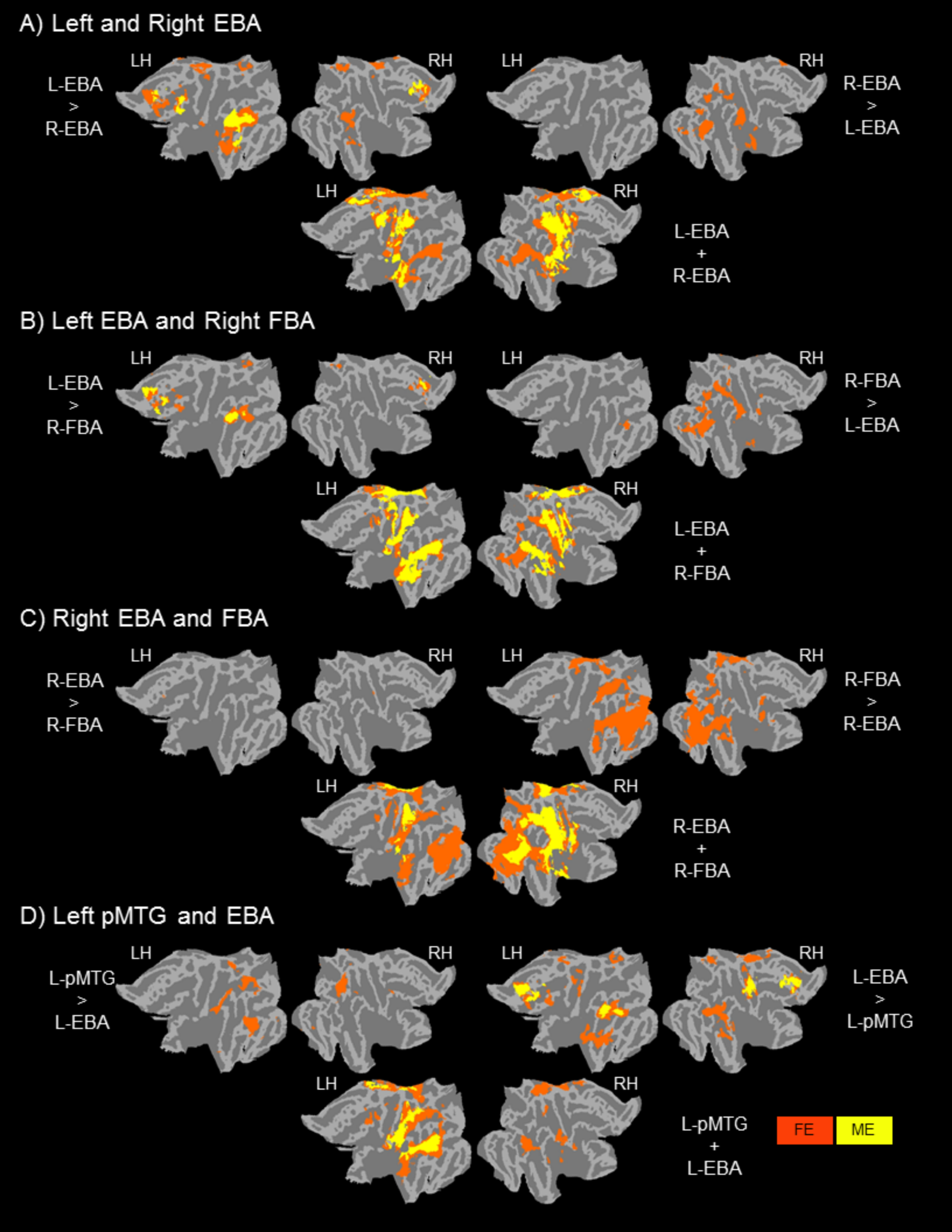
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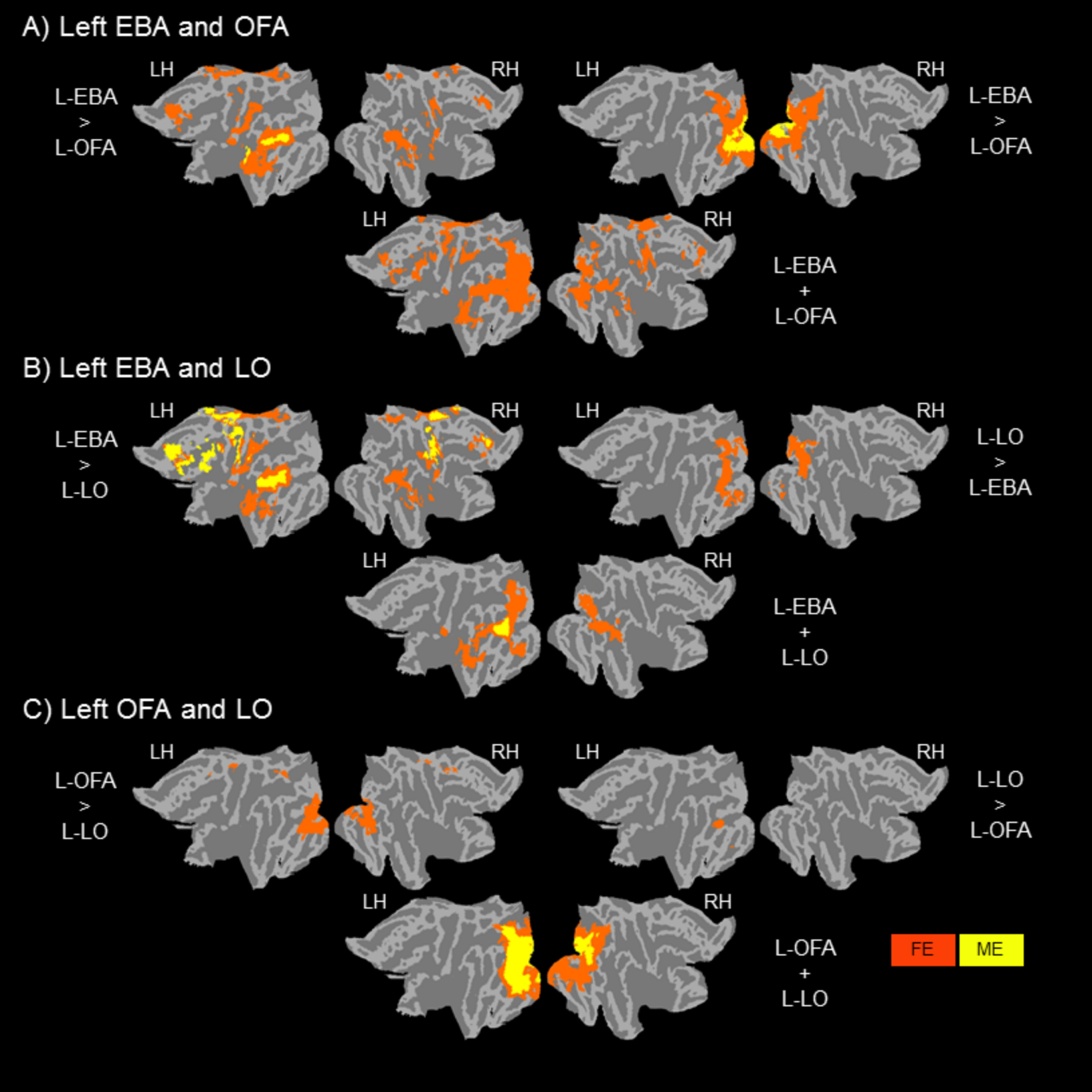
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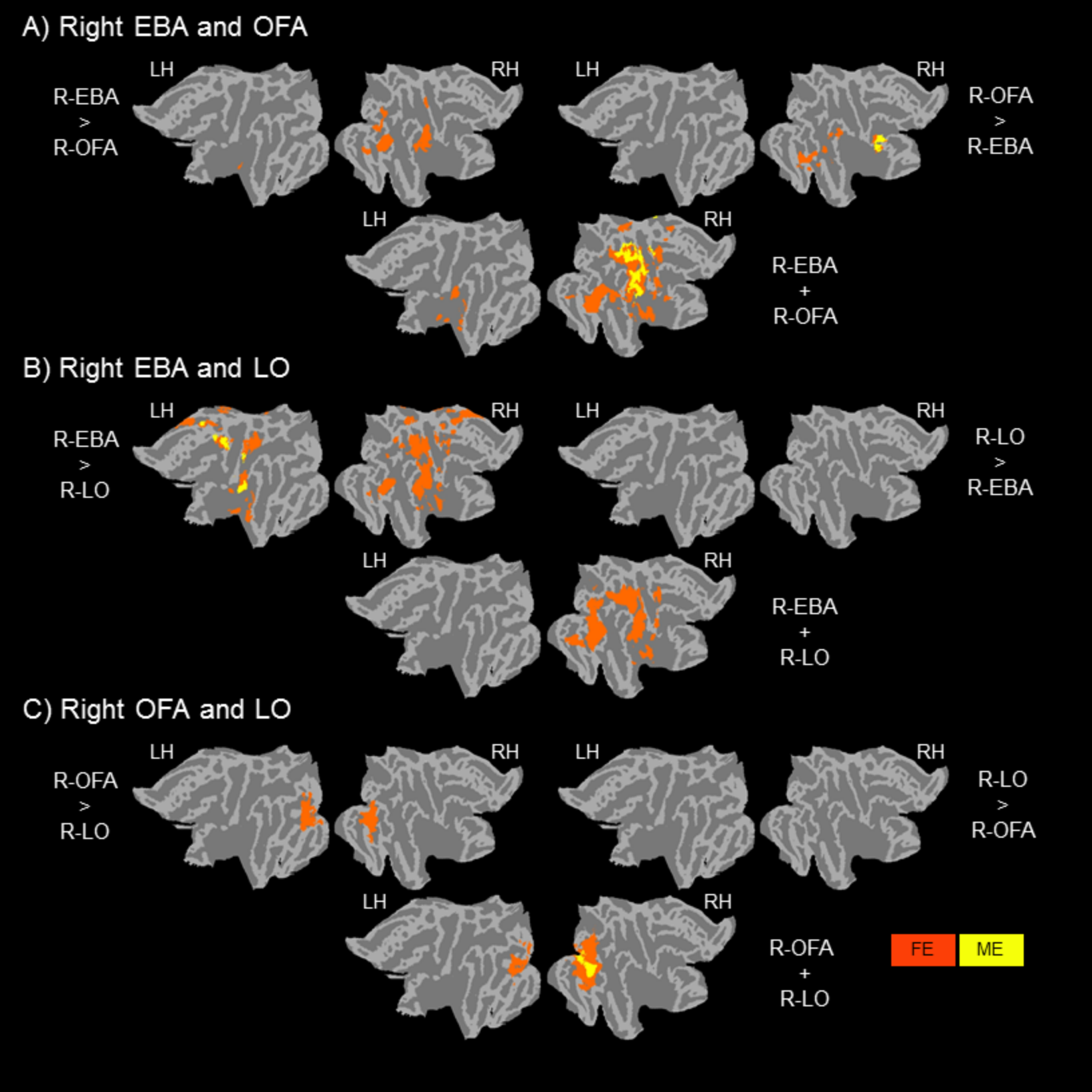
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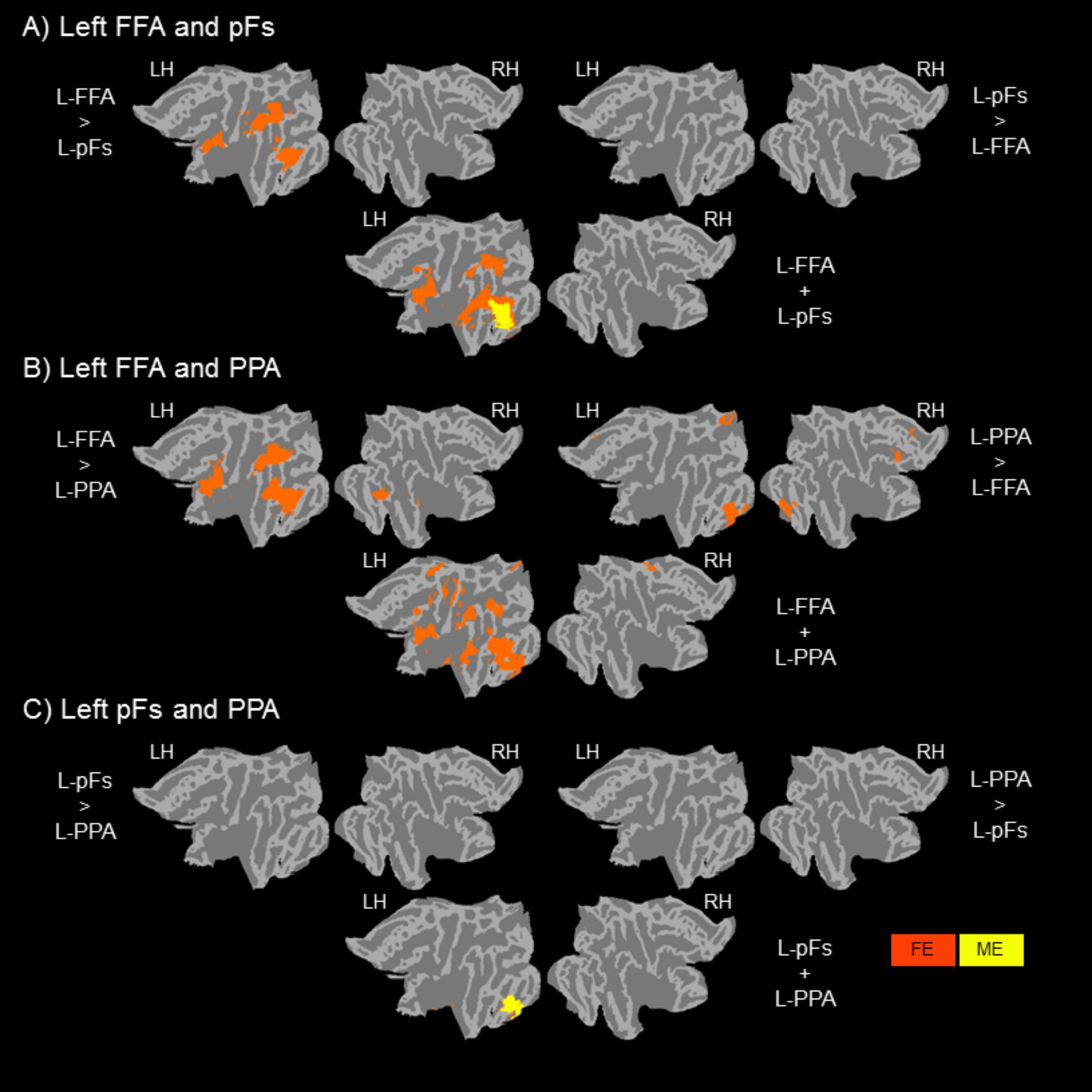
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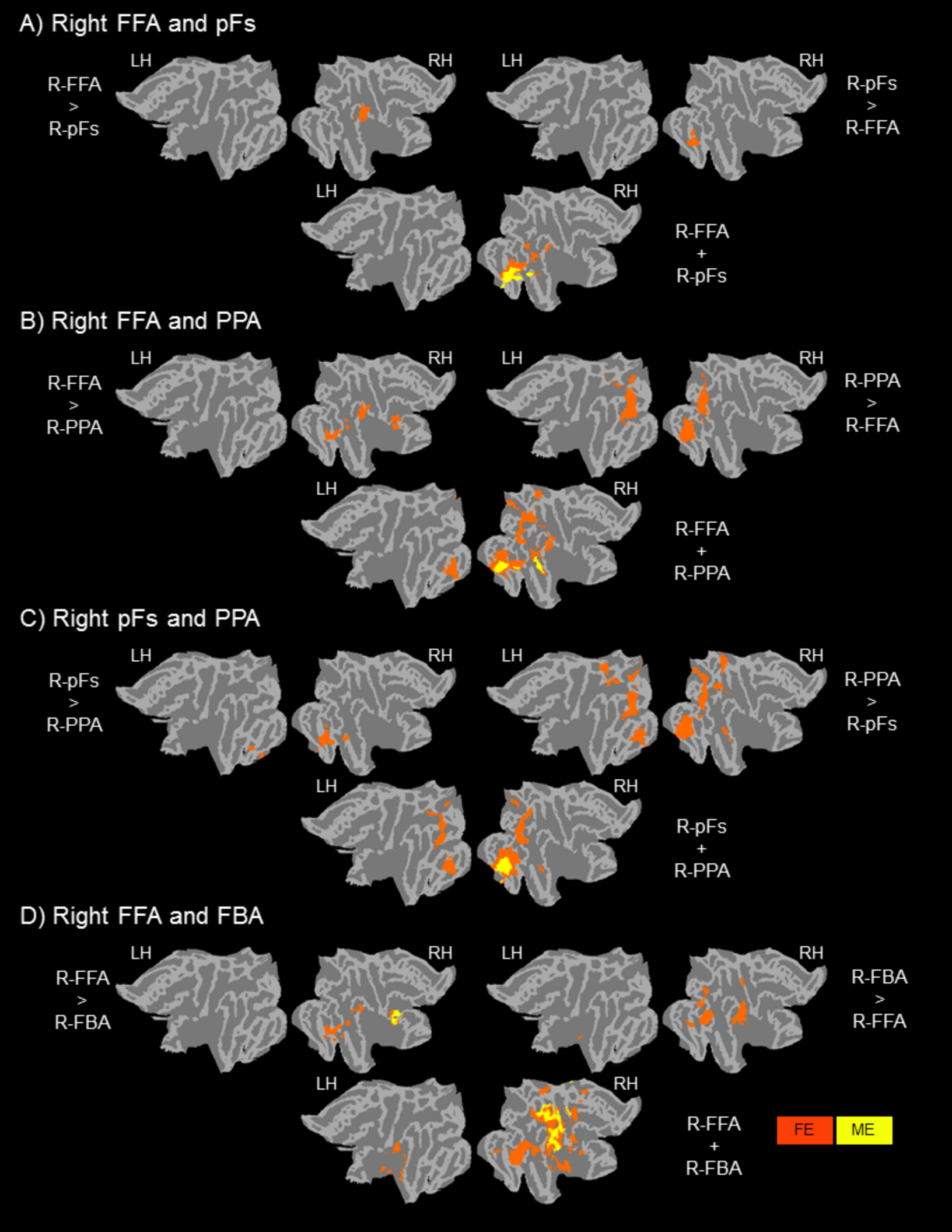
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