

Advances in neuroimaging techniques: implications for the shared syntactic integration resource hypothesis.

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The shared syntactic integration resource hypothesis (SSIRH) generates specific predictions about neural overlap in the instantiation of processes required for syntactic integration in music and language. Syntactic integration occurs over time, through communication between areas maintaining domain-specific representations and areas responsible for domain-general processing. Analyzing neural overlap and temporal communication requires techniques that enable superior spatial resolution and localization, as well as dynamic connectionist frameworks, rather than interpretation of static activation maps. With recent advances in neuroimaging analysis techniques, we are coming closer to be able to address these questions. For example, multivoxel pattern analysis (MVPA) techniques can make more effective use of information in the fMRI signal, whereas examinations of connectivity between different neural areas can tell us more about the dynamic temporal interactions occurring in the brain. What follows is a review of a selection of the techniques in development for functional neuroimaging data, the use of which may be able to provide definitive evidence for or against the SSIRH.

fMRI and pattern analysis

The advantages in fMRI lie in ‘its noninvasive nature, ever-increasing availability, relatively high spatiotemporal resolution, and its capacity to demonstrate the entire network of brain areas engaged when subjects undertake particular tasks’ (Logothetis, 2008). However, the main disadvantage is that it measures a signal that inherently reflects neuronal mass activity. In addition, the spatial specificity of the signal (most commonly the blood-oxygen-level dependent response) is limited by its ‘point spread function’, which blurs the measured signal about 2-3 millimetres beyond the locus of neuronal activity. Thus, within the smallest spatial unit measured in fMRI, a single voxel (volumetric pixel), over a million neurons may be present. Conventional fMRI analysis uses mass univariate techniques to

identify voxels that show a significant response in certain experimental conditions.

Interdigitated networks below the resolution of the voxel cannot be distinguished. In fact, to increase sensitivity to a particular condition, signal is spatially averaged across voxels.

Although averaging reduces noise, it also reduces signal, leading to a downweighting of information from voxels with weaker responses to a particular condition. Weakly responsive voxels still might carry some information about what experimental condition is currently being experienced by the participant. In addition, spatial averaging blurs out the fine-grained spatial patterns that could be used to discriminate between experimental conditions.

New techniques such as MVPA take advantage of signal in weakly responsive voxels, by capitalizing on the fact that these voxels will have differing proportions of neurons that may be involved in the different processes of interest. The MVPA approach uses pattern-classification techniques to extract the signal that is present in the *pattern* of responses across multiple voxels, even if (considered individually) the voxels might not be significantly responsive to any of the conditions of interest. The multi-voxel pattern of response can be thought of as a combinatorial code with a very large capacity for representing distinctions between cognitive states. Instead of examining the localization of significantly active voxels in both conditions of interest, the pattern of activity across *all* voxels in one condition is correlated with the pattern observed in another condition: Areas with high correlations between conditions suggest similar neural operations, whereas those with low correlations suggest differing operations. Considering the SSIRH, the brain ‘states’ for syntactic integration of musical material versus linguistic material should differ in domain-specific areas of the brain: distinctive patterns should be observed, based on the material being syntactically integrated by the volunteer. By asking where in the brain these distinctive patterns occur, the power of MVPA to clarify the structure of neural representations can be

harnessed (Norman, Polyn, Detre, & Haxby, 2006). Areas in which distinctive patterns occur between musical and linguistic conditions are likely to encode domain-specific information.

Perhaps more importantly, MVPA can also be used to discriminate overlapping functional activations (Peelen & Downing, 2007; Peelen, Wiggett, & Downing, 2006). Observations of overlapping activity across stimuli or tasks are frequently used as evidence of overlapping function when comparing fMRI studies. For example, as mentioned in the target article, Broca's area has found to be commonly activated in both musical and linguistic syntactic tasks (Koelsch 2002, Tillmann, 2003, Maess 2001), which could be evidence for a shared, domain-general syntactic function. However, when a set of voxels is commonly activated by different experimental conditions, two interpretations exist. The first interpretation is that the area commonly activated between conditions contains neurons that are engaged in a common computational process. This process is thought to be shared by the two experimental conditions (for example, syntactic integration of both music and language), but not by the control conditions (for example, semantic processing). This interpretation is generally the favoured account when overlapping activations are observed.

However, there is an alternative interpretation of overlapping activation (also mentioned in the target article): two overlapping but functionally independent neural populations are present and active within the common region. In this interpretation, a commonly activated area does not indicate a common function. Conventional fMRI analyses cannot discriminate between these two interpretations, yet this is often ignored, and overlapping activations are taken as evidence for overlapping function. MVPA analyses, however, can be used to discriminate between the two interpretations. A voxel-by-voxel pattern of selectivity to musical or linguistic stimuli can be calculated. In a simple form, this can be accomplished by extracting a t value at each voxel in a neural area of interest for music stimuli (against baseline) and then for language stimuli (against baseline). The t value

provides a useful musical/linguistic selectivity index for each voxel, because it combines in a single measure the magnitude of the difference between two conditions relative to the within-condition variance. Then, the pattern of t-values in each voxel can be correlated for music stimuli and language stimuli. A positive voxelwise correlation between music selectivity and linguistic selectivity indicates that (1) the two conditions do indeed activate the same neurons and (2) the variation in this selectivity across voxels is stable. Thus, the results of MVPA experiments can support or reject claims about neural mechanisms that are shared across the music and linguistic syntactic domains.

So, how might these approaches be used in the study of the SSIRH? Firstly, fMRI studies of musical and linguistic syntax, conducted within the same subjects, would be useful in determining areas of functional overlap as well as functional separation across the brain (the inferior frontal gyrus seems a likely candidate for overlap from previous work, or perhaps other perisylvian areas (Sammler, 2008)). Koelsch (this volume) has highlighted several brain areas which may be expected to be involved in the processes required for musical and linguistic syntactical integration. The areas of potential overlap identified using conventional analysis techniques can be further interrogated using MVPA analyses to determine if the common activation can be genuinely interpreted as true functional overlap.

Connectivity

Despite the low temporal resolution of fMRI (on the order of seconds, compared to neural firing which occurs on the order of milliseconds), measurements of neural interaction between brain regions can still be made. In general, we define networks of brain areas that are likely to be involved in a particular task based on static activation maps. For example, Broca's area, or more generally the inferior frontal gyrus, is a potential site for domain-general syntactic integration. If we want to understand the role that this area is playing within

a given network, we need to know if and how it interacts with the domain-specific language or music areas when syntactic integration is required.

To answer questions about the interaction between areas we require analyses of connectivity. Many people are familiar with the concept of *anatomical connectivity*: that of a direct neuronal connection between two brain areas; a connection comprised of neuronal axons. In the past, the majority of our knowledge of these anatomical connections came from histological studies of animals, with relatively little direct information in humans. Now, the advent of a new MRI technology, diffusion tensor imaging (DTI), provides visualizations of white matter tracts in vivo (Basser, 1994). DTI takes advantage of the fact that the membrane and myelin sheath surrounding axons provides a barrier to the diffusion of water across the membrane. Thus, water diffuses along the direction of axons more than across the membrane and myelin sheath. This “diffusion anisotropy” can provide estimation of the dominant orientation of axons within a particular section of white matter. DTI studies have already provided information about how musical experience may change anatomical connectivity between brain areas (Bengtsson et al., 2005; Schmithorst & Wilke, 2002), or how differences in anatomical connectivity correlate with language processing ability (Gold, Powell, Xuan, Jiang, & Hardy, 2007; Niogi & McCandliss, 2006).

However, in its current form, DTI methodology is limited, both in spatial resolution, and lack of information about the directionality (retrograde versus anterograde) of the white matter tracts. Directionality is a key consideration in neurobiologically plausible models of cognitive function: whether an area is providing information to or receiving information from another area is certainly non-trivial. Poor spatial resolution, however, is perhaps the biggest problem: multiple fibre directions within a single voxel cannot always be resolved. The presence of branching, crossing, or ‘kissing’ fibres requires probabilistic solutions or larger-scale trend solutions that may obscure more fine-grained patterns of connectivity. The

methods are in rapid development, though, so improvements are likely to occur in both data acquisition and the analysis techniques that can be applied to the acquired data. A more general limitation applies to the conclusions that can be drawn from anatomical connectivity studies: much of the brain is interconnected anatomically (either directly or indirectly), so studies of anatomical connectivity, although informative, cannot indicate which connections are actually being used at any given time to accomplish a particular task, or whether a connection is relevant for the process under investigation. Answering these questions requires analyses of functional or effective connectivity (Aertsen and Preissl, 1991).

Functional connectivity measures the correlations between the concurrent activities of different brain regions. This is a correlative, not causal approach, and can be used in metabolic techniques that measure blood flow as an indirect indicator of neural activity, like fMRI, or in techniques that measure electrical or magnetic signals resulting directly from neural activity, like electroencephalography (EEG) and magnetoencephalography (MEG). Generally, this approach computes covariances or correlations among brain activation time series in different brain regions. An alternative approach is to measure *effective connectivity*, or the influence one neuronal system causally exerts over another, either at a synaptic or cortical level. It is important to remember that functional connectivity may not be due to effective connectivity (e.g., common neuromodulatory input or afferents may mediate the correlation in activity) and, if it is, that effective connectivity may be indirect, through a path comprising several neurons in possibly different regions.

Again, turning to the SSIRH, if areas of genuine neural overlap are found using MVPA analyses, one type of functional connectivity analysis is easily applied, called psychophysiological interaction analysis (PPI) (Friston et al., 1997; Grahn & Rowe, 2009; Kim & Horwitz, 2008). This analysis can determine if the correlations in activity between domain-general and domain-specific areas change depending on whether the context is

musical or linguistic. That is, if the activity of one region is regressed on the activity of a second region (in a musical context, for example), the slope of this regression would reflect the influence the second area could be exerting over the first. If one then repeated this regression, using data acquired in a different context (a linguistic context), then the slope might change. This context-dependent change in slope is a psychophysiological interaction. In the syntactic domain, a logical starting place would be extracting activity in Broca's area during musical and linguistic syntactic tasks. Correlations between Broca's area and other brain areas can be examined, to determine which regions show high correlations with activity in Broca's area during musical but not linguistic tasks, and conversely, which areas which show high correlations during linguistic but not musical tasks. This would provide strong evidence for the hypothesized interaction between domain-general and domain-specific systems during syntactic integration. Studies of functional connectivity in syntax have already begun, although not specifically addressing parallels between music and language. One intriguing finding is that connectivity increases between Broca's area and other language production areas for more proficient (compared to less proficient) second language speakers (Dodel et al., 2005). It remains to be investigated whether parallel findings might exist for extensively trained musicians in the musical domain, or to what degree expertise can influence domain-general processes, rather than domain-specific.

Functional connectivity analyses such as these are not limited to fMRI, as similar analyses can be conducted in the electrophysiological domain: coherence (or synchrony) in neural firing between brain areas can be observed in EEG or MEG (Basar, Basar-Eroglu, Karakas, & Schurmann, 1999; Llinas, 1988). Coherence is simply a squared correlation coefficient that provides a measure of the linearity of the relationship between two EEG electrodes at a particular frequency (explained clearly in Shaw, 1981). The frequencies examined generally include delta (< 4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (13 to 30

Hz), and gamma (> 30 Hz) bands. High coherence in a particular band indicates the contribution of synchronized neuronal oscillations to each electrode, suggesting functional integration between neural populations, whereas low coherence suggests functional segregation. An advantage of EEG or MEG over fMRI is that the high temporal resolution allows the build-up of coherence over time to be observed. This is valuable for the study of syntactic processing, where integration of music or language structures also occurs over time. An important frequency band for linguistic syntactical processing appears to be the lower beta band: increased coherence is observed during syntactically demanding sentences (Bastiaansen & Hagoort, 2006). Coherence is only beginning to be investigated in the music syntactic domain, but the results thus far appear somewhat different from those for language. Synchronization during syntactically irregular musical sequences shows an early decrease in the synchrony within the alpha band and a later decrease in gamma band (Ruiz, Koelsch, & Bhattacharya, 2009). Thus violations of musical expectancy appear to be decreasing the integration between brain areas, rather than increasing it, as occurs for language.

For the SSIRH, one may well predict high coherence between domain-general syntactic areas and domain-specific music or language areas during the relevant context. This coherence may be expected to increase under difficult syntactic conditions (consistent with previous linguistic research) or may decrease when violations of syntax in either domain occur (consistent with previous musical research). Coherence changes between domain-general and domain-specific areas could provide converging evidence of functional connectivity. There are some methodological issues that will need to be addressed before these studies can be run. For example, how one can equate difficulty in musical and linguistic syntax remains an open question. What makes a syntactically difficult musical progression? And is this truly analogous to a syntactically difficult sentence? The answers to these questions may help clarify exactly which processes are shared across the two domains.

If one wishes to take connectivity analyses one step further, with relatively defined networks of interest, one can determine if the activity in a particular area is *causally* influencing the activity in another area, by performing analyses of effective connectivity. Methods of effective connectivity analysis include structural equation modelling and dynamic causal modelling (Friston & Harrison, 2003). These analyses take conclusions from functional analyses one step further, by testing whether neural activity in one area causally modulates activity in another area or other areas. In the current situation, these data could indicate whether Broca's area is indeed playing a top-down role in syntactic integration. Broca's area may bias auditory areas to pick up information relevant to the current musical or linguistic context, or perhaps allow an increase in processing efficiency when incoming stimuli match syntactic predictions. As before, effective connectivity measures also can be conducted in EEG and MEG. The calculation of phase relations in the coherence between brain regions can be taken as an indication of the direction of communication. Evidence from the neuroelectric domain may prove to be crucial, as the greater temporal resolution allows top-down versus bottom-up relationships to be characterized more accurately.

In conclusion, the SSIRH makes several predictions about domain-general processes that would be bolstered by studies finding neural areas that respond similarly during musical and linguist syntactical processes. The presence of significantly activated voxels in the same neural area for both domains may not result from similar activity of the underlying neural populations, therefore conventional analyses of functional neuroimaging data can only serve as a starting point. MVPA can test for similar patterns of activity in a neural area, providing stronger evidence for the activity resulting from similar rather than distinct neural populations. In addition, greater functional and effective connectivity between proposed domain-general areas and relevant domain-specific areas would provide converging evidence

for neural interactions that reflect the cognitive operations involved in musical and linguistic syntax computation.

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