DYNAMIC ANTICIPATORY PROCESSING OF HIERARCHICAL SEQUENTIAL EVENTS: A COMMON ROLE FOR BROCA'S AREA AND VENTRAL PREMOTOR CORTEX ACROSS DOMAINS?

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Abstract

This paper proposes a domain-general model for the functional contribution of ventral premotor cortex (PMv) and adjacent Broca's area to perceptual, cognitive, and motor processing. We propose to understand this frontal region as a highly flexible sequence processor, with the PMv mapping sequential events onto stored structural templates and Broca's Area involved in more complex, hierarchical or hypersequential processing. This proposal is supported by reference to previous functional neuroimaging studies investigating abstract sequence processing and syntactic processing.

Key words: sequence processing, syntactic processing, hierarchical processing, Broca's area, ventral premotor cortex

Introduction

This paper suggests a putative functional profile for the frontal lobe region comprising the agranular ventral premotor cortex (PMv) located in Brodmann area (BA) 6, and the adjacent posterior third of the inferior frontal gyrus, the dysgranular BA 44, called Broca's area in the left hemisphere. Both regions share a prominent anatomical characteristic, the lack of a full-blown granular layer IV (which receives input from the thalamus). For this reason, Broca's area is sometimes viewed as an anterior extension of PMv. On the other hand, Broca's area lacks the giant Betz cells (layer V) typical for the motor cortex indicating that it may serve as a transition area between the PMv and prefrontal cortex.

The PMv subserves the control of complex sequential movements of fingers and articulators including lips, tongue and larynx (Juergens, 2002; Wise et al., 1999). Premotor neurons also fire during attention and perception, suggesting that they code body part-related as well as environmental information (Rizzolatti and Luppino, 2001). Canonical neurons in premotor area F5ab in monkeys respond both during grasping and mere observation of manipulable objects (Murata et al., 1997). In area F5c, anterior and inferior to F5ab, mirror neurons fire during execution and observation of manual actions performed by others (Di Pellegrino et al., 1992). The function of these mirror neurons is not well understood, but their behavior suggests a fairly high level of integration, with the goal determining if a neuron fires (Umiltà et al., 2001). Neuroimaging studies in humans have provided evidence for parallel functionalities in humans, with PMv responding during exposure to tools (Martin and Chao, 2001) and the PMv/Broca transition area responding during action observation (Schubotz and von Cramon, 2004). These findings support the assumption that Broca's Area, more precisely BA 44, might be the human homologue of monkey region F5c (Rizzolatti and Arbib, 1998).

This assumption differs from the traditional view of Broca's area representing speech motor programs with a higher level of integration than those provided by PMv (Hillis et al., 2004). Nowadays, it is clear that Broca's Area and the adjacent PMv have a role in controlled phonological processing (Bookheimer, 2002) and in subvocal articulatory rehearsal during verbal working memory (Paulesu et al., 1993). More complex linguistic functions such as grammatical processing have also been ascribed to this brain region (Friederici, 2002).

This summary highlights aspects of behavior and cognition associated with the PMv and Broca's area – with language and action processing being the most prominent examples. It might be conceivable that distinct, functionally specialized neuronal subpopulations within this broad region support different behavioral and cognitive demands. However, we consider it more likely that this particular brain region carries out neural computations sufficiently general and abstract in order to contribute to a wide range of attentional, cognitive, and motor processes. Based on ontogenetic and phylogenetic accounts that stress the general role of Broca's area in hierarchically organized sequential behavior (Greenfield, 1991), we suggest that the common denominator of the

different behavioral and cognitive demands resulting in PMv/Broca activation is that all of the demands involve complex, temporally laid out (i.e., sequential) events with a hierarchical internal structure. The sequentiality of these events requires a mechanism to 'bind' the temporally segregated sub-entities of these events into a single unified entity. We propose that this mechanism might be provided by the PMv/Broca region. We will elaborate on this position after reviewing some of our previous work on sequential processing and syntax that led us to the formulation of this proposal.

ABSTRACT SEQUENCE PROCESSING AND THE PMv/BROCA REGION

The processing of sequential structure in trains of abstract stimuli has been investigated in a series of fMRI studies using the so-called serial prediction task (SPT) paradigm (Schubotz, 1999). In this task, participants are required to attend to the temporal order of a sequence of abstract stimuli presented several times, thus forming a hypersequence. At the beginning of each trial, a cue indicates which stimulus property provides temporal order information and has to be attended to: spatial, object-related, or rhythmic or pitch properties. At the end of each trial, participants indicate whether or not the hypersequence contained a sequential violation. Functional MRI of SPT shows robust activation along the entire premotor belt (Schubotz et al., 2000, 2003; Schubotz and von Cramon, 2001a, 2001b, 2002a, 2002b). Most interestingly, PM activations are distributed according to the to-be-attended stimulus properties. Processing temporal order of duration (i.e., rhythm) or pitch engages the inferiormost PMv, an area which contains lip, tongue, and larynx representations; attending to the temporal order of objects engages the (left) middle PMv (containing hand representations), and finally, spatial sequences engage the dorsalmost PMv (which contains a representation of the arm). Overall, this pattern of activation suggests that sequence processing follows a default body-referenced organization, or "habitual pragmatic" body map. These findings correspond to conclusions from neurophysiological studies that the PM participates in the representation of the pragmatic features – i.e., the potential motor significance – of attended perceptual events (Fadiga et al., 2000).

In a recent paper, we compared action observation, action imagery, and an SPT condition, testing the hypothesis that these three tasks produce overlapping activation in PMv (Schubotz and von Cramon, 2004). Beyond confirming this hypothesis, we also found the dorsal part of BA 44 (and BA 45) to be exclusively activated by the action

conditions. PMv activation during rhythm sequences or pitch sequences in the SPT paradigm typically encroaches into BA 44. However, this activation remains localized in the lowest portion of the inferior precentral sulcus dividing BA 6 from BA 44 suggesting that dorsal BA 44 may be specific for action conditions, potentially reflecting the response of mirror neurons. Ventral BA 44, in contrast, may be related to the representation of sequentially structured information, particularly those that are defined by parameters of the voice and that can be transformed into articulatory patterns.

BROCA'S AREA AND PMv IN SYNTAX PROCESSING

Sentences are complex, hierarchically organized sequences of words. Sentence processing involves building up a mental representation of these hierarchical relations among the sentence constituents on-line. For example, although the nouns and verb in 'The boy was hit by the girl' are in the same order as 'The boy hit the girl', differences in the structural relations among constituents result in opposite meanings. During processing, anticipations concerning the most likely structure of a sentence (syntactic predictions; Gibson, 1998) based on grammatical rules and simplicity principles are constantly being generated. Given the complexity inherent to human language, simplicity-based structural predictions frequently have to be revised in order to adapt to structurally complex sentences.

Processing complex sentences (e.g., sentences that deviate from the preferred subject-first structure and have a clause-initial object noun phrase) activates Broca's area – among other regions – more strongly than simpler sentences (e.g., Just et al., 1996; Stromswold et al., 1996; Fiebach et al., 2004a). This is attributed to the presence of additional syntactic transformation operations in complex sentences, resulting in dependencies between sentence constituents and sentential positions that have to be resolved (Ben-Shachar et al., 2003). We demonstrated that Broca's area is especially involved when syntactic operations result in increased working memory demands (Fiebach et al., 2004b, 2005). When a sentence's structure is not compatible with the rules of grammar a slightly more posterior PMv region deep in the operculum is activated (Friederici et al., 2003; Fiebach et al., 2004a).

These results suggest PMv/Broca involvement whenever the structure of a sentence deviates from a preferred structural template (defined according to grammatical rules and simplicity considerations). Within this region, distinct subregions appear to respond more specifically to different kinds of deviations – indicating they may be involved in different aspects of on-line syntactic processing.

We suggest that (a) PMv/Broca region is involved in analyzing sentences according to grammatical rules, and that (b) the complexity of rule-based processes carried out in the PMv/Broca region varies along a posterior-to-anterior gradient. More posterior subregions perform an initial check concerning the compatibility of the input with grammatical rules, which might be best described as mapping the input onto structural templates of simple and frequent sentence structures. More anterior regions (BA 44 and 44/45) utilize these rules to adjust syntactic predictions when processing complex sentences and to relate grammatically more complex sentence structures back to the simplicity-based structural templates (see Friederici, this issue, for a similar proposal).

DYNAMIC ANTICIPATORY PROCESSING OF HIERARCHICAL SEQUENCES

From a more general perspective, the SPT paradigm mimics crucial similarities between action and language: the compositionality of sequential signals or events and the resulting prospective, anticipatory, rule- or experience-based attention paid to such signals. We propose that the function of PMv and Broca's area is the detection, extraction, and/or representation of regular, rule-based patterns in such temporally extended events. This is a necessary core function of sensorimotor processing considering almost all behavioral challenges involving sensorimotor mapping – including observed locomotion, executed motor actions, music, or sentences – extend over time.

This model proposes that whenever we attend to such sequential events, we attempt to extract the inherent hierarchical sequential structure and, by combining these extracted structures with pre-existing knowledge, form structural expectations regarding the ongoing sequential event. The behavioral benefit of such anticipatory processing is an increase in speed, accuracy, and efficiency of perceptual processing. In the following, we will speculate how PMv and Broca's area may contribute to this function.

Underlying the representation of highly overlearned, frequently used, and flexibly re-combinable articulatory and manual sequences, the PMv may provide a representation of frequently needed templates. Such templates could be conceived of as sequences of the most invariant perceptual states (sub-goals) that recur in every *effective* action. Templates are the *predictable* constituents of an action that an actor plans to cause and that both the actor and a potential observer expect to perceive (c.f., Byrne and Russon, 1998). The PMv could be the store of such templates (e.g., Fadiga et al., 2000). Alternatively, the PMv may transiently select and enhance such templates from stores in its parietal and temporal projection fields. Or the PMv may transiently integrate single elements stored in posterior brain areas into sequential structures. Whatever the exact nature of the sequential templates represented in PMv, our model suggests that PMv matches simple sequential structures of a perceived event with an appropriate default template of that type of event. The above-cited fMRI results suggest that these templates can be rapidly established during ongoing processing, as in the SPT paradigm, or can be highly overlearned rules such as the grammatical rules of language or everyday routine behaviors.

In order to successfully deal with complex, behaviorally relevant sequences, this function needs to be supplemented – at least in the case of goal-directed action and linguistic functions – by hyper-sequential or hierarchical representations, a function that could be provided by Broca's area[1]. Endowed with prefrontal characteristics, the function of Broca's area might be the integration of sequential templates (series of sub-goals) into higher-order structured events (c.f., Wood and Grafman, 2003). Just as there are many ways to execute a simple action, one and the same meaning can be expressed in multiple ways by structurally different sentences. In both cases, the sensorimotor system has to be able to relate the perceived sequence to a simpler default template. It remains to be understood how neurons may be able to integrate over unlimited instantiations, a process requiring 'abstract' representations.

To summarize, we suggest that Broca's area contributes to the generation of higher-level organization in actions and language, operating upon lower-level, serially organized representations provided by the adjacent PMv. The PMv/Broca region, according to this view, constitutes a processor for sequential events crucial for large numbers of different cognitive and sensorimotor domains. This sequence processing mechanism may operate on different levels of resolution. For example, while we describe how the brain might integrate sequentially perceived words into larger hierarchical units (phrases and sentences), analogous processes might apply for the integration of sequences of phonemes into words.

In conclusion, we propose that the posterior inferior third of the frontal lobe is a highly flexible sequence processor, with a complexity gradient from PMv towards Broca's area. Further neuroimaging and neurophysiological research is needed to empirically test several aspects of this proposal, in particular, the nature of the sequential templates represented in PMv and Broca's Area,

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[1] Hypersequences could be additionally accomplished by the pre-supplementary motor area (pre-SMA) which is known to represent abstract (not limb-dependent) sequences in the monkey (Shima and Tanji, 2000). In support of this, pre-SMA has been observed for complexity effects in sentences (Fiebach et al., 2004a) as well as in abstract non-linguistic sequences (Schubotz and von Cramon, 2002b).

the proposed complexity gradient within these two areas, and the applicability of this model to alternative cognitive and sensory domains.

REFERENCES

BEN-SCHACHAR M, HENDLER T, KAHN I, BEN-BASHAT D and GRODZINSKY Y. The neural reality of syntactic transformations: Evidence from functional magnetic resonance imaging. *Psychological Science, 14:* 433-440, 2003.

BOOKHEIMER S. Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Reviews in Neuroscience, 25:* 151-188, 2002.

BYRNE RW and RUSSON AE. Learning by imitation: A hierarchical approach. *Behavioral and Brain Sciences, 21:* 667-684, discussion 684-721, 1998.

DI PELLEGRINO G, FADIGA L, FOGASSI L, GALLESE V and RIZZOLATTI G. Understanding motor events: A neurophysiological study. *Experimental Brain Research, 91:* 176-180, 1992.

FADIGA L, FOGASSI L, GALLESE V and RIZZOLATTI G. Visuomotor neurons: ambiguity of the discharge or motor perception? *International Journal of Psychophysiology, 35:* 165-177, 2000.

FIEBACH CJ, BORNKESSEL ID, SCHLESEWSKY M and FRIEDERICI AD. Distinct neural correlates of legal and illegal word order variations in German: How can fMRI inform cognitive models of sentence processing. In Carreiras M. and Clifton C (Eds), *The On-Line Study of Sentence Comprehension*. New York: Psychology Press, 2004a.

FIEBACH CJ, SCHLESEWSKY M, LOHMANN G, VON CRAMON DY and FRIEDERICI AD. Revisiting the role of Broca's area in sentence processing: Syntactic integration versus syntactic working memory. *Human Brain Mapping, 24:* 79-91, 2005.

FIEBACH CJ, VOS SH and FRIEDERICI AD. Neural correlates of syntactic ambiguity resolution in sentence comprehension for low and high span readers. *Journal of Cognitive Neuroscience, 16:* 1562-1575, 2004b.

FRIEDERICI AD. Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences, 6:* 78-84, 2002.

FRIEDERICI AD, RUESCHEMEYER S-A, HAHNE A and FIEBACH CJ. The role of left inferior frontal and superior temporal cortex in sentence comprehension: Localizing syntactic and semantic processes. *Cerebral Cortex, 13:* 170-177, 2003.

GIBSON E. Linguistic complexity: Locality of syntactic dependencies. *Cognition, 68:* 1-76, 1998.

GREENFIELD PM. Language, tools, and brain: The ontogeny and phylogeny of hierarchically organized sequential behavior. *Behavioral and Brain Sciences, 14:* 531-551, 1991.

HILLIS AE, WORK M, BARKER PB, JACOBS MA, BREESE EL and MAURER K. Re-examining the brain regions crucial for orchestrating speech articulation. *Brain, 127:* 1479-1487, 2004.

JUERGENS U. Neural pathways underlying vocal control. *Neuroscience and Biobehavioral Reviews, 26:* 235-258, 2002.

JUST MA, CARPENTER PA, KELLER TA, EDDY WF and THULBORN KR. Brain activation modulated by sentence comprehension. *Science, 274:* 114-116, 1996.

MARTIN A and CHAO LL. Semantic memory and the brain: structure and processes. *Current Opinion in Neurobiology, 11:* 194-201, 2001.

MURATA A, FADIGA L, FOGASSI L, GALLESE V, RAOS V and RIZZOLATTI G. Object representation in the ventral premotor cortex (area F5) of the monkey. *Journal of Neurophysiology, 78:* 2226-2230, 1997.

PAULESU E, FRITH CD and FRACKOWIAK RS. The neural correlates of the verbal component of working memory. *Nature, 362:* 342-345, 1993.

RIZZOLATTI G and ARBIB M. Language within our grasp. *Trends in Cognitive Science, 21:* 188-194, 1998.

RIZZOLATTI G and LUPPINO G. The cortical motor system. *Neuron, 31:* 889-901, 2001.

SCHUBOTZ, RI. Instruction differentiates the processing of temporal and spatial sequential patterns: evidence from slow wave activity in humans. *Neuroscience Letters, 265:* 1-4, 1999.

SCHUBOTZ RI, FRIEDERICI AD and VON CRAMON DY. Time perception and motor timing: A common cortical and subcortical basis revealed by event-related fMRI. *NeuroImage, 11:* 1-12, 2000.

SCHUBOTZ RI and VON CRAMON DY. Functional organization of the lateral premotor cortex: fMRI reveals different regions activated by anticipation of object properties, location and speed. *Cognitive Brain Research, 11:* 97-112, 2001a.

SCHUBOTZ RI and VON CRAMON DY. Interval and ordinal properties of sequences are associated with distinct premotor areas. *Cerebral Cortex, 11:* 210-222, 2001b.

SCHUBOTZ RI and VON CRAMON DY. Predicting perceptual events activates corresponding motor schemes in lateral premotor cortex: An fMRI study. *NeuroImage, 15:* 787-796, 2002a.

SCHUBOTZ RI and VON CRAMON DY. A blueprint for target motion: fMRI reveals perceptual complexity to modulate a premotor-parietal network. *NeuroImage, 16:* 920-935, 2002b.

SCHUBOTZ RI, VON CRAMON DY and LOHMANN G. Auditory what, where, and when: A sensory somatotopy in lateral premotor cortex. *NeuroImage, 20:* 173-185 2003.

SCHUBOTZ RI and VON CRAMON DY. Sequences of abstract non-biological stimuli share ventral premotor cortex with action observation and imagery. *The Journal of NeuroScience, 24:* 5467-5474, 2004.

SHIMA K and TANJI J. Neuronal activity in the supplementary and presupplementary motor areas for temporal organization of multiple movements. *Journal of Neurophysiology, 84:* 2148-2160, 2000.

STROMSWOLD K, CAPLAN D, ALPERT N and RAUCH S. Localization of syntactic comprehension by positron emission tomography. *Brain and Language, 52:* 452-473, 1996.

UMILTA MA, KOHLER E, GALLESE V, FOGASSI L, FADIGA L, KEYSERS C and RIZZOLATTI G. I know what you are doing. A neurophysiological study. *Neuron, 31:* 155-165, 2001.

WISE RJ, GREENE J, BUCHEL C and SCOTT SK. Brain regions involved in articulation. *Lancet, 353:* 1057-1061, 1999.

WOOD JN and GRAFMAN J. Human prefrontal cortex: processing and representational perspectives. *Nature Reviews Neuroscience, 4:* 139-47, 2003.

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