Naturalistic language comprehension:

a fMRI study on semantics in a narrative context

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Tiivistelmä – Referat – Abstract

Semantiikka tutkii kieleen sisältyviä merkityksiä, joita tarvitaan kielen ymmärryksessä. Kuinka aivomme käsittelevät semantiikkaa ja kuinka ymmärrämme erityisesti luonnollisessa muodossa olevaa kieltä, on vielä aivotutkijoille epäselvää. Tässä tutkimuksessa kysyttiin, miten laajemmassa kontekstissa, narratiivissa, olevan kielen ymmärrys ja semanttinen prosessointi heijastuu aivojen aktiivisuuteen. Koehenkilöt kuulivat narratiivin toiminnallisen magneettiresonanssikuvantamisen (fMRI) aikana. Narratiivin semanttinen sisältö mallinnettiin laskennallisesti word2vec algoritmin avulla, ja tätä mallia verrattiin veren happitasosta riippuvaiseen (BOLD) aivosignaaliin ridge regression avulla vokseli kerrallaan. Lähestymistavalla saatiin eristettyä yksityiskohtaisempaa tietoa jatkuvan stimuluksen aivodatasta perustuen kielen semanttiseen sisältöön. Subjektien välinen BOLD-signaalin korrelaatio (ISC) itsessään paljasti molempien aivopuoliskojen osallistuvan kielen ymmärrykseen laajasti. Alueellista päällekkäisyyttä löytyi muiden aivoverkostojen kanssa, jotka vastaavat mm. mentalisaatiosta, muistista ja keskittymiskyvystä, mikä viittaa kielen ymmärryksen vaativan myös muiden kognition osien toimintaa. Ridge regression tulokset viittaavat bilateraalisten pikkuaivojen, superiorisen, keskimmäisen sekä mediaalisen etuaivokuoren poimujen, inferiorisen ja mediaalisen parietaalikuoren sekä visuaalikuoren, sekä oikean temporaalikuoren osallistuvan narratiivin semanttiseen prosessointiin aivoissa. Aiempi semantiikan tutkimus on tuottanut samankaltaisia tuloksia, joten word2vec vaikuttaisi tämän tutkimuksen perusteella mallintavan semantiikkaa riittävän hyvin aivotutkimuksen tarpeisiin. Tutkimuksen perusteella molemmat aivopuoliskot osallistuvat kielen laajemman kontekstin käsittelyyn, ja semantiikka nähdään aktivaationa eri puolilla aivokuorta. Nämä aktiivisuudet ovat mahdollisesti riippuvaisia kielen sisällöstä, mutta miten paljon kielen sisältö vaikuttaa eri aivoalueiden osallistumiseen kielen semanttisessa prosessoinnissa, on vielä avoin tutkimuskysymys.

Semantics is a study of meaning in language and basis for language comprehension. How these phenomena are processed in the brain is still unclear especially in naturalistic context. In this study, naturalistic language comprehension, and how semantic processing in a narrative context is reflected in brain activity were investigated. Subjects were measured with functional magnetic resonance imaging (fMRI) while listening to a narrative. The semantic content of the narrative was modelled computationally with word2vec and compared to voxel-wise blood-oxygen-level dependent (BOLD) brain signal time courses using ridge regression. This approach provides a novel way to extract more detailed information from the brain data based on semantic content of the stimulus. Inter-subject correlation (ISC) of voxel-wise BOLD signals alone showed both hemispheres taking part in language comprehension. Areas involved in this task overlapped with networks of mentalisation, memory and attention suggesting comprehension requiring other modalities of cognition for its function. Ridge regression suggested cerebellum, superior, middle and medial frontal, inferior and medial parietal and visual cortices bilaterally and temporal cortex on right hemisphere having a role in semantic processing of the narrative. As similar results have been found in previous research on semantics, word2vec appears to model semantics sufficiently and is an applicable tool in brain research. This study suggests contextual language recruiting brain areas in both hemispheres and semantic processing showing as distributed activity on the cortex. This activity is likely dependent on the content of language, but further studies are required to distinguish how strongly brain activity is affected by different semantic contents.

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Abstract: Semantics is a study of meaning in language and basis for language comprehension. How these phenomena are processed in the brain is still unclear especially in naturalistic context. In this study, naturalistic language comprehension, and how semantic processing in a narrative context is reflected in brain activity were investigated. Subjects were measured with functional magnetic resonance imaging (fMRI) while listening to a narrative. The semantic content of the narrative was modelled computationally with word2vec and compared to voxel-wise blood-oxygen-level dependent (BOLD) brain signal time courses using ridge regression. This approach provides a novel way to extract more detailed information from the brain data based on semantic content of the stimulus. Inter-subject correlation (ISC) of voxel-wise BOLD signals alone showed both hemispheres taking part in language comprehension. Areas involved in this task overlapped with networks of mentalisation, memory and attention suggesting comprehension requiring other modalities of cognition for its function. Ridge regression suggested cerebellum, superior, middle and medial frontal, inferior and medial parietal and visual cortices bilaterally and temporal cortex on right hemisphere having a role in semantic processing of the narrative. As similar results have been found in previous research on semantics, word2vec appears to model semantics sufficiently and is an applicable tool in brain research. This study suggests contextual language recruiting brain areas in both hemispheres and semantic processing showing as distributed activity on the cortex. This activity is likely dependent on the content of language, but further studies are required to distinguish how strongly brain activity is affected by different semantic contents.

Keywords: naturalistic language, comprehension, semantic processing, narrative, lexicon, concept, cognition, context, computational linguistics, word2vec, functional magnetic resonance imaging, inter-subject correlation, ridge regression, cortex

Introduction

As language is the basis of how we humans interact but also partly what we construct our inner worlds with, there has been many attempts to explain the mechanisms behind it. Some theories in philosophy have tried but could not explain our ability to creatively combine information and to talk about entirely abstract ideas that do not physically exist in our world (Lakoff, 1988). One example of such a theory was Hilary Putnam's theory of semantic externalism (Putnam, 1973, 2013), also known as objectivistic semantics – meaning lies in the objects around the subject. Putnam's and other philosophers such as Noam Chomsky's work at the time was followed by a theory called experientialist cognition, supported by philosophers in the late 1980. As opposed to semantic externalism, experientialist cognition focused more on internal events when talking about semantics, suggesting meaning of language being more psychological in nature (Lakoff, 1988). This view has also been called constructivist semantics - the meaning is constructed in the subject's mind.

Moreover, some have suggested a need for entirely new philosophical view instead of objectivist or constructivist approaches (Jonassen, 1991). One could argue, that meaning of language must lie somewhere in between the external world and consciousness of an individual, shaped by social interaction between people. Later on, with the advances in brain imaging many of the linguistic phenomena discussed in philosophy have been studied from an experimental point of view (Mashal, Faust and Hendler, 2005; Ahrens *et al.*, 2007; Rapp *et al.*, 2011; Saban-Bezalel *et al.*, 2017). For this field of research, the use of naturalistic stimuli in functional brain imaging studies might provide new insights on how human brain processes meaningful information during more natural phenomena and not only during simple stimuli and tasks.

Semantic processing of language

Semantic processing refers to understanding the meaning of words and sentences, and larger texts these comprise (Cruse, 2011). Therefore, within this framework, semantics is thought to be part of the process of comprehending language. The meaning in words is based on the knowledge we acquire through experience (Bréal, 1897). Since there is meaning encoded into words, we humans are able to meaningfully communicate with each other via language.

The importance of semantic processing in language comprehension is reflected in acquired disorders, such as semantic variant of primary progressive aphasia (svPPA), and developmental disorders, such as semantic-pragmatic language disorder (SPD). SvPPA, also known as semantic dementia (SD), is a degenerative nervous system disorder that affects semantic memory of the patient and causes anomia, difficulty in retrieving words from memory (Mesulam *et al.*, 2003). Semantic-pragmatic language disorder (SPD) is a language impairment that has an effect on semantic and pragmatic, i.e. context related, processes of an individual. Its core symptom is delayed language development. Research on semantics could potentially benefit patients with deficiencies in language comprehension.

Research on genetics has shown the importance of conservation of and missense mutations on FOXP2 gene in the development of human language to its current form (Enard *et al.*, 2002; Atkinson *et al.*, 2018). It has been proposed that this gene has also a role in our symbolic thought and abstraction (Atkinson *et al.*, 2018). FOXP2 encodes a transcription factor forkhead box protein P2 that has a role in the development and plasticity of the brain among its other effects (Fisher and Scharff, 2009; Atkinson *et al.*, 2018). Mice that were transfected with human version of FOXP2 showed altered dopaminergic concentrations. Dopaminergic cells target striatal D1 receptor expressing medium spiny neurons that express also FOXP2 (Wijchers *et al.*, 2006; Enard *et al.*, 2009). Most of the dopaminergic cells react to stimuli with a prediction error response by bursting with an unexpected reward and silencing their firing with an expected but a failed one (Bayer and Glimcher, 2005; Schultz, 2016). Some of these dopaminergic cell bodies in substantia nigra and ventral tegmental area project to dorsal striatum. Contextual information from cortex is suggested to merge with the information from reward system in striatum (Enard *et al.*, 2009; Lieberman, 2009).

Mutations on FOXP2 gene correlate with deficits in linguistic skills (Fisher and Scharff, 2009) but some argue these to be related to motoric language production, such as in developmental verbal dyspraxia (Ocklenburg *et al.*, 2013). Other genetic influences on language functions have been suggested. For example, missense mutation on progranulin (GRN) coding gene has been found in a patient with svPPA (Cerami *et al.*, 2013). Then again, other sources suspect svPPA to be sporadic in its pathology (Landin-Romero *et al.*, 2016). Genetic screening of patients with language disorders combined with behavioral and genetic studies on animals might provide an additional layer in the field of language research from the evolutionary perspective.

Communication context evolutionally important

Communication has been the core drive for complex language development (Arbib, 2005), from us being able to refer to concrete items in the surroundings all the way to the ability to make abstractions, name them and share those with others. Evolution of language has evidently had an effect on the semantic capabilities of humans, by expanding these over the course of time. Semantic abilities of other species such as primates have also been studied. Primate calls contain different combinations of sounds that specify the nature of danger, thus having semantic variability in them (Arnold and Zuberbühler, 2006). Studies on animal behavior and genetics could further lead to understanding at least the basis of human language, although the ability to think abstractly is thought to be unique for humans.

Context is important in language comprehension and is the most important cue for predicting what is about to come next in language. Meaning of a single word can vary even drastically depending on the referent context (Pulvermüller, 2019). A sentence taken out of its context can be understood very differently from what was meant by it in the first place. This path is dual: the brain makes attempts to bring together the context from the language already used, and from this context it makes predictions for the future. In the field of semantics context of language is especially important and research using linguistic stimuli without wider context might not represent semantics fully.

During recent years, language research has shifted from using parts of language taken out of their context towards more naturalistic settings (Verga and Kotz, 2019). While block or event-related study designs with simple stimuli have been traditionally used in BOLD fMRI studies (Pan *et al.*, 2011), naturalistic stimuli are continuous and offer an alternative approach to study language with fMRI. As communication is the most natural form of language, it should be taken into account as the context when studying meaning. Use of communicationally informative stimuli should thus be considered in brain research – studying brain with narratives or conversations might reveal more about semantics than single words.

Language as a part of cognition

Understanding naturalistic language is a complex cognitive event often recruiting other modalities of cognition for its function (Zwaan *et al.*, 2004; Jung-beeman, 2005; Bastiaansen and Hagoort, 2006). Networks overlapping with language processing are for example networks of attention, working memory, mentalization and consciousness (Chafe, 1974; Baddeley, 1992; Garagnani, Wennekers and Pulvermüller, 2008; Vanlangendonck, Willems and Hagoort, 2018). In addition, emotional aspects of our mind are playing a role in understanding language fully (Ferstl, Rinck and Cramon, 2005). Complete separation of these networks might not always be the most functional approach for studying language and cognition, since they seem to be interconnected to each other (Mill, Ito and Cole, 2018). In addition, brain areas have multiple functions (Kanwisher, 2010), thus having a role in multiple networks.

Attention in language comprehension

Literature suggests varying theories over how these networks are related to language processing. For example, the more attentive the individual is the better comprehension of language the person has (Kristensen *et al.*, 2013). Attentive processes direct our focus on incoming sensory information or alternatively to internal processes of the mind (Lepsien and Nobre, 2006). This might not be directly part of the linguistic network in its core but have a role in what information in language we are putting our focus on. Some attention deficits might also disturb language comprehension even if there are not direct problems in the traditional linguistic areas or their connectivity (Mcinnes *et al.*, 2003).

Attention network has been thought to divide into ventral and dorsal streams in the fronto-parietal networks (Scolari, Seidl-Rathkopf and Kastner, 2015). Areas such as ventral precuneus (vPCUN) (Zhang and Li, 2012), middle frontal gyrus (MFG) and temporal-parietal junction (TPJ) are associated with attentive processes (Ptak and Schnider, 2011). Fronto-parietal network functions have also been found to contribute to enhanced speech comprehension in narrative context (Smirnov *et al.*, 2014). These brain areas are involved both in spatial attention tasks and sentence comprehension, suggesting attention having a role in language comprehension. Clear language pitch used in the stimuli recruit attention areas more robustly than non-articulated sentences suggesting direction of attention favoring sounds typical to spoken language (Kristensen *et al.*, 2013).

Language comprehension recruit memory

Networks of memory are closely related to language (MacKay, Stewart and Burke, 1998; Bastiaansen and Hagoort, 2006). Both short- and long-term memory are important for language comprehension (Hagoort, 2005). Enough working memory capacity is required to maintain the context in mind (Baddeley, 1992; Cain, Oakhill and Lemmon, 2004). Explicit (declarative) memory is required for the storage, and later retrieval of words and their meanings from this long-term memory. Memories are thought to be stored as engram cells that are controlled over hippocampal activity (Semon, 1921; Blank *et al.*, 2016). Some research puts more emphasis on the connectivity of the brain, and the strength of these connections between nodes in the networks (MacKay, Stewart and Burke, 1998). In spite of the framework or theory discussed, memory functions are important in language processing.

Maintaining context in mind is needed for comprehending language, and working memory capacity has been suggested to have an effect on word comprehension (Daneman and Merikle, 1996). Working memory has been suggested to take place in dorsolateral prefrontal cortex (DLPFC; Barbey, Koenigs and Grafman, 2013). Activity in inferior frontal gyri (IFG) and some inferior parietal lobular (IPL) areas have been found to correlate with working memory tasks (Newman, Just and Carpenter, 2002; Barbey, Koenigs and Grafman, 2013). DLPFC has been found to be involved in sentence comprehension (Klaus and Schutter, 2018). IFG and IPL contribution in language comprehension have been found in studies with words and naturalistic stimuli (Binder *et al.*, 2009; AbdulSabur *et al.*, 2014). Overlapping in these areas suggest that working memory is recruited in language processing and its capacity has an effect on language comprehension.

Semantic memory – storage for meaning

Semantic memory is the part of declarative memory that consists the linguistic knowledge of a person (Tulving, 1972). This collection of knowledge in words, that changes over time, is referred as lexicon (Bréal, 1897). Semantic memory is recruited in language comprehension (Kutas and Federmeier, 2000). Even though it does not represent our memory as a whole, it contains associations we make in this world, such as names for people and objects, but also for more abstract phenomena and concepts (Binder and Desai, 2011). Some have argued that as well as lexicon is related to semantic memory, it associates to episodic memories especially in children whose semantic memory is not as structured as that of adults (Petrey, 1977). Important is that we are able to make associations between words and experiences, and eventually retrieve these associations again in future situations.

Literature suggests that knowledge within the lexicon contributes more to meaning than for example syntax, the structure of language (Fedorenko, Nieto-castañon and Kanwisher, 2012). This statement contains a presumption that language structure and semantic meaning are separate phenomena. Other sources claim that lexical knowledge contains both semantic and syntactic properties of language (Bastiaansen and Hagoort, 2006; Müller and Hagoort, 2006). The distinction between these two is not clear and they are often intertwined in neuroscientific research (Fedorenko, Nieto-castañon and Kanwisher, 2012). Another debate is whether lexical semantic processing differs from semantic processing of non-linguistic visual cues (Bright, Moss and Tyler, 2004).

Conceptual categories, such as tools and animals, are our way to generalize, store and organize information (Pustejovsky, 1991; Pulvermüller, 2019). As we use categorization to simplify our world, our brain uses similar approach to reduce its computational load. Conceptual knowledge divided into these categories can be attained with visual or verbal cues (Bright, Moss and Tyler, 2004). Thus, we can think lexicon to be divided into semantic conceptual categories (Müller and Hagoort, 2006), and each word in the lexicon seems to fall into these categories based on the features they have. The core semantic network is activated in a similar manner when processing conceptual similarity between items such as an apple and a pear and the associative links between dissimilar items such as apple and a tree, that often occur in a similar context but are not under the same semantic category (Jackson *et al.*, 2015).

Feature semantics refer to our ability to associate certain features to words and concepts. Such features can for example be perceptual properties related to our sensory systems, such as visual shapes, somatosensory cues, sounds and smells (Jackson *et al.*, 2015; Pulvermüller, 2019). Some literature in cognitive science refers the group of features related to concepts as conceptual spaces. Each space is formed by quality dimensions, that are mathematically measurable. For example, color of an object can have dimensions of hue, saturation and brightness (Gärdenfors, 1996). We can also associate emotions (Binder and Desai, 2011), other objects and environments (Jackson *et al.*, 2015), movement (Hauk, Johnsrude and Pulvermüller, 2004) and episodic memories (Takashima *et al.*, 2014) to a concept or an item. These all might not be considered as features but can be thought as associative relationships between different words, items and phenomena (Jackson *et al.*, 2015). Various associations are thought to be represented in the brain as connections (Pulvermüller, 2019).

One example of a theory on memory and language is called MUC (Memory, Unification, Control) that discusses the storage and retrieval of memories, unification processes on syntactic, semantic and phonological levels and top-down prefrontal control of linguistic processes (Hagoort, 2005). Phonology is related to sounds in language and is thought to be lower level language process when semantics occur later in time in higher brain areas (Vigneau *et al.*, 2006). Some research discuss the dynamic nature of cognitive functions in general (Mesulam, 1990). As natural language is often complicated, progresses in time and is context dependent, brain recruits different modalities of cognition dynamically for proper comprehension (Medaglia, Lynall and Bassett, 2015).

In computational linguistics, the research in cognitive sciences and linguistics are used in the development of computational models for language processing, analysis and research (Pustejovsky, 1991). The research on memory and language has inspired computational models such as Dynamic Memory Networks (DMN) for analysis and processing of natural language (Kumar *et al.*, 2016). Computational cognitive science has generated models such as word2vec and latent semantic analysis (LSA) that are used to model semantic content of language in numeric form (Landauer, 1997; Mikolov *et al.*, 2013). These tools base their computation on linguistic content using for example parts of internet as a corpus to analyze word context, i.e. their relation to each other. Some of these tools are being adapted in experimental studies in cognitive brain research.

Language perception affected by previous experiences

We do not necessarily take incoming information as it is, but our perception is subjectively affected by previous experiences that again reshape the associations we make. If we create a prior of the concept, and predict the world based on this information, our way of understanding the world is already biased towards our previous knowledge (Hari, 2018). This knowledge is, to our fortune, prone to change through error. As prediction error in the dopaminergic reward system directs behavior of mice and monkeys (Bayer and Glimcher, 2005; Schultz, 2013), predictive coding is thought to apply to sensory systems in a hierarchical generative manner (Iglesias *et al.*, 2013), and even further, to language perception (Hickok, 2013; Pickering and Garrod, 2013; Lupyan and Clark, 2015).

Subjective perception of an object, a word or a concept is the combination of action potentials within the inter-connected cells (Pulvermüller, 2019), and the formation of these connections is following the Hebbian rule – cells that fire together, wire together (Hebb, 1949). Thus, semantic meaning lies in the patterns of activation over these cells, in the neural networks they comprise. Since these connections keep being molded by each experience, reshaping the associations we make, also the way we understand and make meanings in this world is being shaped throughout a lifetime.

Networks of consciousness might define what sort of sensory information, or more specifically, what sort of information in language we are actually conscious of (Chafe, 1974; Bimmel, van den Bergh and Oostdam, 2001). We are naturally biased due to our previous experiences (Gilovich, Griffin and Kahneman, 2002) and these biases may be largely unconscious (Perry, Murphy and Dovidio, 2015). This can mold our language comprehension to be very different from the way another person with different experiences and biases understands language.

Depending on the content of the language, different networks might be recruited in its processing in a dynamic manner (Sporns, 2014). With social content mentalization networks are more involved than with non-social content (Vanlangendonck, Willems and Hagoort, 2018). With contexts and tasks that might not appear so interesting to us, larger contribution of attention is required (Langer and Eickhoff, 2013). Also, the level of how complex the used language is, has an effect on how heavily memory functions are recruited in the task (Bastiaansen and Hagoort, 2006).

Brain research of semantics

Brain uses multiple areas to process language. Traditionally Broca's and Wernicke's areas are addressed. Wernicke's area has been thought to play a key role in processing semantic content of the language. Anyhow, much wider areas are recruited in this task than previously has been thought (Ardila, Bernal and Rosselli, 2016). Focusing on merely anatomical areas when considering complex cognitive functions, such as language production or perception, is debatable. Opposing ideas suggest that more distributed neural processing is taking place in cognition, and the focus should be more on the functional specificity rather than regional emphasizing the engagement of a certain region into certain task (Kanwisher, 2010).

As semantic literature suggests wide brain areas to be involved, some have introduced hub-based models, where hubs are the important crossroads for connectivity of the brain. It has been suggested that words related to different functions, such as actions, are connected to certain areas, such as pre-central gyrus, and these different semantic centers or hubs are activated based on the semantic categories within the language (Garagnani and Pulvermüller, 2016). A theory called hub-and-spoke considers the concept formation being based on verbal and non-verbal input, and that these concepts are represented by the engagement and activation of modality-specific hubs distributed across the cortex (Mesulam, 1990; Ralph *et al.*, 2017). This theory pinpoints bilateral contribution of anterior temporal lobe (ATL) in this process, and suggest ATL to be a mediator of the semantic network (Ralph *et al.*, 2017). It does seem that ATL has a role in semantic functions, as for example neurodegeneration of these areas disturb both verbal and non-verbal semantic comprehension (Gorno-Tempini *et al.*, 2011), but the nature of this role remains unclear. Hub based models have an emphasis on brain connectivity which is in line with theories on lexical categories and features.

Literature suggests language as a distinct network from these other modalities of cognition. Research with words and sentences implies that most of the linguistic areas in inferior frontal and posterior temporal gyri are shared between lexico-semantic and syntactic processes. The more meaningful content there is in the stimulus, the wider brain areas seem to take part in semantic processing (Fedorenko, Nieto-castañon and Kanwisher, 2012). Once brain makes more associations with comprehensible content in contrast with incomprehensible, wider areas are recruited (Fedorenko *et al.*, 2010; Saalasti *et al.*, 2017). Further on, research has found evidence for more detailed recruitment of brain areas: in a meta study on language processing, areas anteriorly from precentral gyrus along IFG and areas in posterior temporal lobe were found to correlate with phonological processing. Syntactic processes recruited similar areas extending posteriorly to parietal areas including angular gyrus (AG) and to areas anteriorly further in IFG (Vigneau *et al.*, 2006).

In the same meta-analysis, semantic studies were investigated. Semantics recruited similar but wider areas in temporal lobe extending to anterior parts and posteriorly in parietal AG when compared to phonological and syntactic areas. Also, frontal areas were recruited similarly but more widely, especially in IFG, but less towards precentral gyrus that is responsible of motor functions (Vigneau *et al.*, 2006). These results suggest semantic processing recruiting brain widely. In addition to frontal areas, parietal activity is often found in brain research of semantics. In a study on semantic aphasia, disturbed connectivity or lesions in TPJ were found in patients (Dragoy, Akinina and Dronkers, 2017) suggesting it to have a role in semantics. In EEG studies, negative N400 response in centro-parietal electrodes and has been liked to language comprehension tasks (Bambini *et al.*, 2016). Also, positive parietal P600 responses have been found to correlate with language comprehension, even though it has been previously associated with syntactic tasks.

Study on svPPA patients found atrophies in temporal pole and orbitofrontal areas bilaterally, left ventral temporal areas, fusiform gyrus and amygdala (Mummery *et al.*, 2000). More specifically, left posterior middle and anterior superior temporal gyri (MTG, STG), superior temporal sulcus (STS) posteriorly, AG, MFG and parts of IFG were found to relate language comprehension in other lesion studies (Dronkers *et al.*, 2004). In addition, connectivity between these areas has been studied. They are interconnected by multiple white matter tracts: fascicles of inferior occipito-frontal, arcuate and middle and inferior longitudinal play a role in this connectiveness. Disturbances also in these tracts might result in impaired comprehension (Turken and Dronkers, 2011).

While structural processing of language takes generally place on the left hemisphere, it seems that more complex semantic processing of language takes also place widely on the right hemisphere (Jung-beeman, 2005). Right lateralization of semantic processes could be the case at least in parts where other language related functions are taking place on the left hemisphere. Some functional brain imaging studies using metaphorical linguistic stimuli have found tendency towards right hemispheric activation with novel combinations of figurative language (Mashal, Faust and Hendler, 2005; Ahrens *et al.*, 2007).

Research suggests that wide areas in temporal and frontal cortex, as well as parietal AG and supramarginal gyrus (SMG; Binder and Desai, 2011) are playing a role in word and sentence comprehension. These areas might be related to various aspects of language processing and might not be linked merely to semantics but contribute to the overall task of comprehension. In addition to cerebrum, cerebellar areas are suggested to play a role in cognition in general, but also in language processing (Leiner, Leiner and Dow, 1993; Schmahmann, 2004). The role of cerebellum has only recently been acknowledged in linguistic studies, even though lesions in cerebellar areas crus I and crus II has been associated with language disturbances (Richter *et al.*, 2007; Stoodley *et* *al.*, 2016). Cerebellum is highly connected to cerebrum. Some research suggests lobule IV and vermis to be taking part in this connectivity (Stoodley and Schmahmann, 2011). Closed-loop connectivity between frontal cortical areas and cerebellum have been suggested (Watson *et al.*, 2014), and this could play a role also in semantic processing.

Combined PET and fMRI study with auditory stories and nursery rhymes found involvement of PCUN, inferior parietal and dorsomedial prefrontal cortices and premotor areas in language comprehension. They also found that language production in a narrative form showed mostly left hemisphere correlation when comprehension tasks recruited also right hemisphere (AbdulSabur *et al.*, 2014). In a fMRI study on narrative comprehension in a developing brain, bilateral activation of superior temporal areas was found to correlate positively with age (Szaflarski *et al.*, 2012) suggesting its role in semantic memory. A fMRI study with over two hours long narrative stimulus showed similar results: relatively symmetrical bilateral correlation was observed in lateral and ventral temporal cortices (LTC, VTC), lateral and medial parietal cortices (LPC, MPC) and medial, superior and inferior PFC. Patterns of how these areas were recruited were category specific – social content elicited different patterns of brain activity than for example numerical or locational contents (Huth *et al.*, 2016).

Furthermore, semantic processing of words and pictures differ only partly in PET studies (positron emission tomography; Vandenberghe *et al.*, 1996; Bright, Moss and Tyler, 2004). Most of the semantic system seems to be shared between these modalities of input, and both seeing a picture of an apple and reading the word apple elicit somewhat similar responses in higher brain areas. Differences seem to be in the areas processing sensory and structural linguistic information, but the so called semantic network is hypothesized to be activated similarly in both cases (Vandenberghe *et al.*, 1996). Supporting results have been found in fMRI studies comparing words to objects (Devereux *et al.*, 2013). This distributed activation of the cortex is thought to vary depending on the properties and functionality of the word or the object: non-living tools are categorized differently than living animals, and this is also reflected in the patterns of brain activity (Mahon *et al.*, 2007; Devereux *et al.*, 2013).

As discussed in the beginning, semantics most often refer to the meaning of language. Studies on natural language processing across subjects might reveal more about the underlying brain processes of language comprehension. On the other hand, results from research using naturalistic stimulus are more difficult to interpret than simpler stimuli such as words or sentences. As stimulus gets more complicated, there are also more variables to be taken into account during the analysis. Therefore, it is important to model the used stimulus as accurately as possible. In the current study, semantic comprehension of language was studied by measuring fMRI-BOLD responses while participants listened to an auditory narrative. Semantic content of the narrative was modelled computationally with word2vec and compared to voxel-wise BOLD time courses using ridge regression. The aim was to identify brain areas underlying narrative comprehension and further discover more specifically how semantic processing during naturalistic narrative is represented in the brain.

Methods

Subjects and MRI acquisition

31 healthy right-handed Finnish-speaking females volunteered as a subject. None of the subjects had psychiatric or neurological disorders, and all reported normal hearing. Two of these subjects were excluded from the study due to artefacts in the data and lack of attention, resulting in total 29 subjects.

Subjects were scanned with a 3T MRI scanner (Magnetom Skyra, Siemens Healthcare, Erlangen, Germany) with a 20-channel coil at Advanced Magnetic Imaging (AMI) Centre at Aalto University School of Science. Anatomical T1-weighted images were obtained using MPRAGE pulse sequence (repetition time, TR=2,530 ms; echo time, TE=3.3 ms; flip angle 7°, 256 x 256 matrix, 1x1x1 mm^3 resolution, 176 sagittal slices). Echo planar imaging (EPI) pulse sequence was used to attain functional T2-weighed images (TR=1700 ms, TE=24 ms, flip angle 70°, 202 x 202 matrix, in plane resolution 3x3 mm^2, each volume comprising 33 slices of 4 mm thickness, 295 volumes).

Stimuli and experimental design

An auditory narrative was presented to the subjects during fMRI with MRI-compatible headphones (Sensimetrics S14 insert earphones) on top of which earmuffs were placed for safety and canceling the noise in the MRI scanner. The narrative was told from a female first-person perspective and it described everyday life situations such as social interaction at home and work. Some parts focused more on the narrator's mental processes, while others were more descriptive in nature. The auditory stimulus was a 7 minutes and 54 seconds long. Following is a short sample of the narrative translated from Finnish to English (Saalasti *et al.*, 2017).

"-- On ridges grew pines and in valleys dense spruce. In other places the road crossed over small rapids. Nature already started to turn green, much to the influence of the spring sun.

I reflected on the behavior of Jarkko this morning: his sudden disconnection of the phone call and blushing as if guilty. I wonder whether Jarkko had something inappropriate going on with someone--."

Preprocessing of the data

Data were preprocessed with an in-house MATLAB toolbox (BraMiLa; available at https://version.aalto.fi/gilab/BML/bramila). Preprocessing included slice-timing and movement correction, and co-registration of functional and structural images. Also, blood-oxygen-level dependent (BOLD) signal time series detrending, nuisance signals and noise regression, temporal high-pass filtering (cut-off at 0.01 Hz) and spatial smoothing with a Gaussian kernel (8 mm) were applied.

Inter-subject correlation (ISC)

Similarities of BOLD signal time courses between the subjects were calculated using inter-subject correlation (ISC; Hasson *et al.*, 2004) implemented in ISCtoolbox (Kauppi *et al.*, 2010). ISC analysis compares the time courses of each voxel between the subjects by predicting the activations in the following subject based on the previous without having to specify certain regions of interests in advance (Hasson *et al.*, 2004). In the analysis, 406 pairwise Pearson's correlation coefficients were acquired with ISC for each voxel's time course.

Computational linguistic model

Semantic content of the narrative was modelled with a computational linguistic model Word2vec (Mikolov *et al.*, 2013). Word2vec creates a vector space based on co-occurrences of words in a large corpus (here the Finnish language internet). Following literature, we created a 300-dimensional vector space (dos Santos and Gatti, 2014; Pereira *et al.*, 2018; Van Uden *et al.*, 2018; Kivisaari *et al.*, 2019). The less dimensionality in the model, the easier it is to analyze and interpret as it also reduces the computational demands (Ordentlich *et al.*, 2016). Although, reducing dimensionality comes with the expense of how descriptive the model is (Mikolov *et al.*, 2013).

These vectors are used to describe semantics of language numerically by placing the words that share similar context near to each other. For example, in *Figure 1*, word pine is spatially closer to spruce than to phone because they share their context in the corpus. For clarification, *Figure 1* is merely an illustration of the principle idea of the word2vec model. In the actual model, a 300-dimensional numerical vector describing a single word is more similar between words sharing the same context than between words that rarely occur in similar contexts. Thus, in the word2vec model, semantics of the language is encoded in the similarity of these 300-dimensional vectors.

In practice, the language model was a 282x300 matrix of numerical values. The 282 rows equated the repetition times in fMRI, thus representing the functional images collected every 1.7 second. Each of these rows were the 300-dimensional vectors describing the content of the narrative during each repetition time. The vectors for each lemmatized word were acquired with word2vec (Mikolov *et al.*, 2013). The content of the narrative was divided to 1.7 second items from the audio file using Transcribe! software (1998-2019 *Seventh String Software*), and the vectors of words occurring in each repetition time were summed accordingly. As follows, the columns of the matrix were the 300 numerical values describing the sum of the semantic content of the narrative during each 1.7-second-long timeslots.

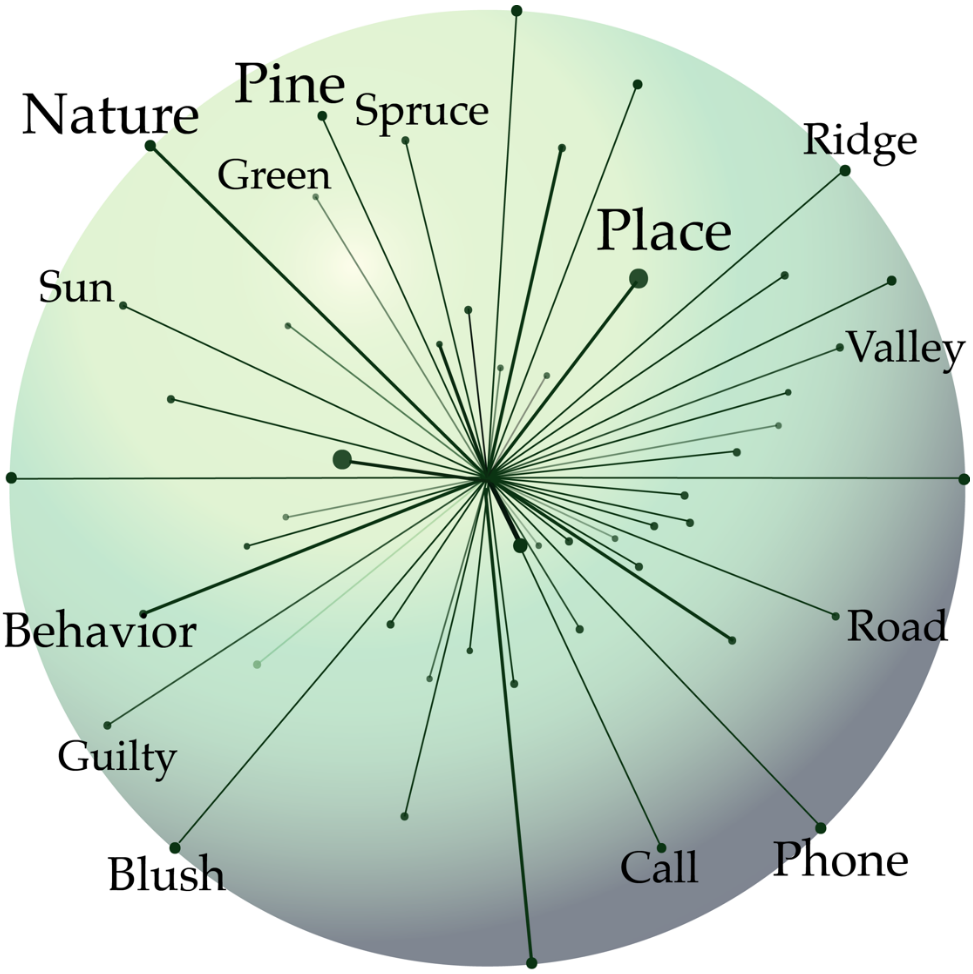

Figure 1, Illustration of the principal idea of word2vec, where contextually similar words, such as pine and spruce, are located near to each other while words that occur in a different context within the used corpus, such as road or phone, are located further away. The relation of these words is represented with 300-dimensional vectors – each word is described with one, and the more similar these vectors are the nearer these words are to each other's contextually.

Canonical correlation

Regularized kernel canonical correlation analysis (rKCCA) was used to compare the semantic content of the stimulus with the voxel-wise blood-oxygen-level dependent (BOLD) brain signal time course. rKCCA was chosen as an analysis method for its ability to estimate correlation between different-sized multidimensional matrices and because it allows data regularization (Bilenko and Gallant, 2016). L2 regularization was used to minimize the size of the fitted parameters (Ng, 2004). L2 is a derivative of Tikhonov regularization with the addition of using identity matrices (Wager, Wang and Liang, 2013).

rKCCA creates a feature space where the maximum correlation, ρj, between word2vec model and fMRI data was evaluated across subjects. The datasets X and Y were combined linearly with canonical weight vectors (support vectors) aj and bj. Dot product of the dataset and these coefficients resulted as canonical components uj and vj in the feature space, from which the canonical correlation was calculated as in *eq.1*.

$$uj = < aj, X > , \quad vj = < bj, Y > \qquad \rho j = \max \frac{< uj, vj >}{\|uj\| \|vj\|} \tag{1}$$

Equation 1, maximum correlation ρj between canonical components uj and vj, that are inner products of the weights aj and bj, and datasets X and Y, in this study word2vec model and BOLD time course.

Regularization parameter was validated with Monte Carlo cross-validation. Because validating the parameter was computationally expensive, linear kernelization was used to reduce the dimensionality of the data. This simplified the computing process by making an inner product of the pairs of data in feature space (Akaho, 2006). In the analysis, 70 % of the data was used in training and 30 % for testing. One canonical component was used. An open-source toolbox for Python was applied in the analysis (Bilenko and Gallant, 2016).

Ridge regression

We then analyzed the correlation between word2vec model and brain data with another commonly used multivariate analysis method, ridge regression. The used ridge parameter *k* was 10^6.

Coefficients ($\hat{\beta}$) of a ridge regression between the word2vec model and BOLD time course were calculated as in *eq.2*. (Hoerl and Kennard, 1970). This was done with ridge regression, *ridge*(y,W,k), in which the definable arguments were observed response *y*, predictor data *X* and ridge parameter *k*. In this case, *y* was the voxel time course from fMRI, *W* the word2vec model and *k* was predefined based on previous knowledge. Usually, *k* is cross-validated from the data used, but in this study, we did not have enough data for cross-validation as observed also in the canonical correlation analysis. Voxel wise time course was obtained with taking a z-score as in *eq.3.* from each voxel of the fMRI data from which every dimension with length 1 were removed.

$$\hat{\beta} = (X^T X + kI)^{-1} X^T y \tag{2}$$

Equation 2, Ridge regression coefficients, $\hat{\beta}$, are products between the observed response *y*, transpose of the design matrix *X*, and $(X^T X + kI)$ to the power of -1. In the latter, product of design matrix *X* and X^T is summed with the product of ridge parameter *k* and identity matrix I. In ridge regression, the data matrix will be transformed to invertible with coefficients for it to be computable.

$$z = \frac{(x-\mu)}{\sigma} \tag{3}$$

Equation 3, z-score *z,* in which mean of the data μ is subtracted from the data point x, in this case voxel, which is then divided with the standard deviation σ of the dataset, resulting as the voxel time course *S*.

A dot product between the coefficients ($\hat{\beta}$) and the word2vec model was computed to obtain voxel-wise word2vec model time course as in *eq.4*. Time courses of BOLD signal and word2vec model were finally correlated with each other to obtain a brain map of Pearson coefficients as in *eq.5*. Custom MATLAB script was implemented for the analysis.

$$T = < \hat{\beta}, W > \tag{4}$$

Equation 4, word2vec model time course *T,* in which dot product of Ridge regression coefficients and word2vec model was computed.

$$rho(a,b) = \frac{\sum_{i=1}^{n}(T_{a,i}-\overline{T}_a)(S_{b,i}-\bar{S}_b)}{\left\{\sum_{i=1}^{n}(T_{a,i}-\overline{T}_a)^2\sum_{j=1}^{n}(S_{b,j}-\bar{S}_b)^2\right\}^{1/2}} \tag{5}$$

Equation 5, where linear correlation between word2vec model time course *T* and voxel time course *S* from fMRI, was calculated with Pearson's Correlation Coefficient *rho(a,b),* in which *a* and *b* are columns in related matrices. $(T_{a,i}-\overline{T}_a)(S_{b,i}-\bar{S}_b)$ is summed from time point 1 to *n*, in which *n* is the number of timepoints in this experiment, 281, T*a* is a column in matrix *T,* S*b* is a column in matrix *S,* $\overline{T}_a$ is the mean $\sum_{i=1}^{n}(T_{a,i})/n$ and $\bar{S}_b$ is the mean $\sum_{j=1}^{n}(S_{b,j})/n$. This is then divided with $\left\{\sum_{i=1}^{n}(T_{a,i}-\overline{T}_a)^2\sum_{j=1}^{n}(S_{b,j}-\bar{S}_b)^2\right\}^{1/2}$, where the sums of squares of means of the matrix columns *a* and *b* subtraction from each datasets columns *Ta* and *Sb* are multiplied with each other's, and the result the sums of is raised to the power of ½.

Parametric cluster correction with a threshold t-value of 1.7 and minimal cluster size of 5x5x5 voxels was done with FSL. Thus, remaining clusters after the correction were at least 125 voxels large with a t-value of 1.7, equaling to p- value of 0.05. Results were finally visualized with CARET software (Van Essen, 2005).

Results

Inter-subject correlation

Inter-subject correlation (ISC) suggests that neural activation while listening to a narrative is similar across subjects in extensive cortical areas (*Figure 1,* $p< 0.05$, cluster corrected). Temporal cortical areas in superior temporal gyrus (STG) and middle temporal gyrus (MTG) correlated strongly between subjects. Bilateral similarity of activity was observed with a slight left hemispheric dominance.

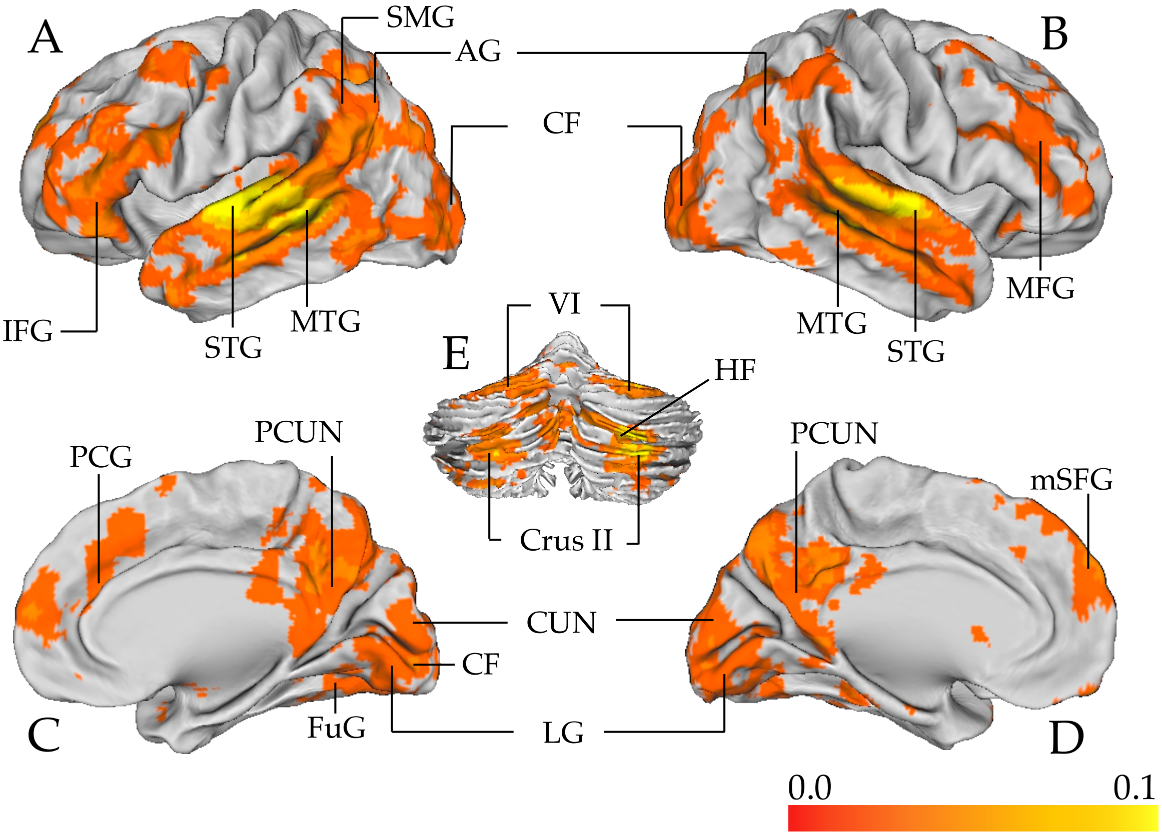

Figure 2 Inter-subject correlation (ISC) of cortical activities related to auditory narrative ($p \leq 0.05$, cluster corrected) from lateral views of A) left hemisphere, B) right hemisphere, from medial views C) right hemisphere, D) left hemisphere and E) dorsal view of cerebellum. Bilaterally correlating brain areas found were calcarine fissure (CF), superior and middle temporal gyri (STG, MTG), middle frontal gyrus (MFG), precuneus and cuneus (PCUN, CUN), lingual gyrus (LG) and cerebellar lobules VI and crus II. Inferior frontal gyrus (IFG), supramarginal gyrus (SMG) and paracingulate gyrus (PCG) correlated mostly on left and fusiform gyrus (FuG) on right hemisphere. Threshold-free cluster enhancement (as implemented in FSL randomise) was used as cluster correction (Woolrich et al., 2009). Results are visualized with CARET software (Van Essen, 2005).

Some variation was observed in which brain areas showed correlation across subjects between the two hemispheres. For example, activation on inferior frontal gyrus (IFG), medial superior frontal gyrus and supramarginal gyrus (SMG) correlated in the left hemisphere but not as widely in the right. On the contrary, correlation in middle frontal gyrus (MFG), paracingulate gyrus (PCG) and fusiform gyrus (FuG) was more similar between the subjects in right than in left hemisphere.

In addition to areas of temporal and frontal lobes, angular gyrus (AG) in inferior parietal lobule and areas around calcarine fissure (CF) in occipital lobe showed bilateral correlation of activation. Correlation of brain activation across subjects was also similar between the hemispheres in some parts of middle frontal gyrus (MFG) and lingual gyrus (LG). Same was observed in cuneal (CUN) and precuneal (PCUN) areas in medial occipital lobe.

ISC was bilaterally significant also in the cerebellum. Correlation was found between the subjects in cerebellar cortical areas in lobules VI and crus II. Also, horizonal fissure (HF), the largest one in cerebellum, showed correlation bilaterally. The inter-subject correlation was dominated in the right cerebellar hemisphere in crus II and horizontal fissure, but not in VI.

Combining fMRI time courses with word2vec model

Next, word2vec model of semantic content of the narrative was compared to the group level similarities in brain activation patterns. Regularized canonical correlation analysis showed even stronger correlation in more widespread areas than seen in the ISC (*Figure 1*). It seemed irrational to gain higher correlation as a result after including the semantic content of the stimulus in the analysis. This suggested that the results were incorrect and thus not reliable, and that this particular analysis method was not suitable for these data.

Ridge regression analysis suggested some correlation across subjects between BOLD signal and word2vec model of the semantic content of the stimulus (Table 1 and Figure 3). The clusters of correlating activity were spread widely on the cortical surface. Activity in cerebellum, especially in cerebellar crus II, was correlated more on the right hemisphere while correlation in cerebrum was spread bilaterally. Although, some spatial variation in the correlation between the hemispheres was observed. Supramarginal gyrus and middle frontal gyrus on right hemisphere were the largest clusters. Also, maximal t-values were highest in these areas.

Frontal cortical areas seen in *Figure 3* had most correlation in the orbital middle frontal gyrus (oMFG), triangular inferior frontal gyrus (triangIFG) and precentral gyrus (PreCG) on left hemisphere and medial orbitofrontal cortex (mOFC) bilaterally. On the contrary, medial part of superior frontal gyrus (SFG), middle frontal gyrus (MFG) and orbital inferior frontal gyrus (oIFG) showed correlation on right hemisphere. Also, insular cortex (INS) on right and olfactory cortex (OLF) on left hemisphere showed significant correlation between the subjects and the linguistic model.

Table 1, peak voxels from ridge regression analysis

Cluster anatomical region	Hemisphere	Size of cluster	MNI coordinates (x,y,z)	max t-value
Supramarginal gyrus	R	4814	(66, -32, 28)	5,4638
Middle frontal gyrus	R	2551	(36, 62, 6)	5,4965
Cerebellar crus II	R	1652	(38, -74, -48)	4,4214
Angular gyrus	L	657	(-44, -62, 46)	5,1008
Orbital middle frontal gyrus	L	356	(-34, 66, -2)	3,9859
Cerebellar crus II	L	318	(-28, -68, -42)	4,3767
Orbital inferior frontal gyrus	R	300	(56, 32, -6)	3,3183
Rolandic operculum	L	232	(-64, -4, 16)	4,0188
Postcentral gyrus	R	220	(64, -6, 26)	3,6835
Supramarginal gyrus	L	212	(-56, -28, 40)	3,8418
Olfactory cortex	L	194	(-4, 12, 0)	4,3376
Middle temporal gyrus	R	185	(66, -34, -6)	4,2516
Precentral gyrus	R	167	(50, -10, 56)	3,8454
Insula	R	137	(38, 24, 2)	3,8456
Medial superior frontal gyrus	L	133	(-12, -28, 28)	3,2527
Triangular inferior frontal gyrus	L	129	(-48, 38, 4)	2,9379
Inferior temporal gyrus	R	127	(56, -60, -18)	3,3035

Correlation was also observed in middle temporal gyrus (MTG) in right hemispheric temporal cortical areas. In right temporal lobe, some correlation was observed near temporo-parieto-occipital junction (TPOJ), extending below from the supramarginal gyrus (SMG). Clearly largest cluster in temporal cortical areas was anyhow MTG (*Table 1*). Similar correlation was not found on the left hemispheric temporal cortex.

In left parietal cortex, correlation spread anteriorly from angular gyrus (AG) towards central sulcus, covering some areas of SMG and postcentral gyrus (PostCG). Similarly, supramarginal gyrus (SMG) on the right parietal cortex showed correlation with the linguistic model while this was not seen in right PostCG or AG. More correlation was seen on right precuneus (PCUN) than on left. SMG cluster in right parietal cortex was the largest one found in the analysis (*Table 1*). In parietal cortex, following largest clusters in size were left AG, right PreCG and finally left SMG. Clusters in PCUN were quite scattered, so they did not reach other clusters in size to fit the peak table. Also, Rolandic operculum in left opercular cortical areas around sulcus lateralis showed significant correlation.

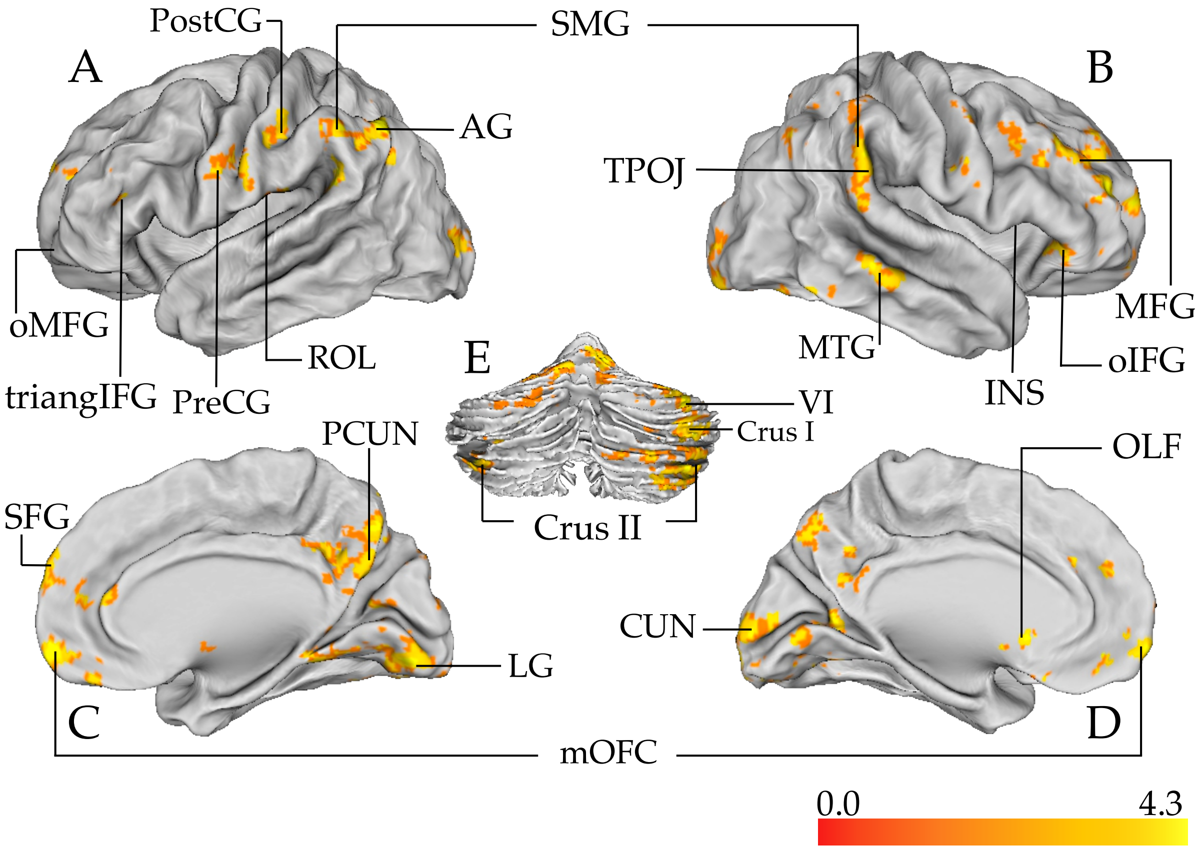

Figure 3, Correlation with ridge regression between BOLD signal and the semantic model visualized on cortical surfaces (cluster corrected, $p \leq 0.05$) from lateral views of A) left hemisphere, B) right hemisphere, from medial views C) right hemisphere, D) left hemisphere and E) dorsal view of cerebellum. Figure shows correlations that reached significancy ($p \leq 0.05$) on yellow and orange color scale. These areas of similarity include clusters in left medial superior frontal gyrus (SFG), left orbital middle frontal gyrus (oMFG) and triangular inferior frontal gyrus (triangIFG), left pre- and postcentral gyri (PreCG, PostCG), left rolandic operculum (ROL), left angular gyrus (AG), supramarginal gyrus (SMG) bilaterally, right medial temporal gyrus (MTG), right insula (INS), right medial frontal gyrus (MFG), right orbital inferior frontal gyrus (oIFG), right lingual gyrus (LG), right precuneus (PCUN), right temporo-parieto-occipital junction (TPOJ), left cuneus (CUN), medial orbitofrontal cortex (mOFC) bilaterally, left olfactory cortex (OLF), right cerebellar VI and crus I and cerebellar crus II bilaterally.

Other significantly correlated areas were found in occipital lobe where lingual gyrus on right and cuneus on left hemisphere seemed to correlate the most between subjects and the linguistic model. On cerebellar cortex, significance was found in lobules VI, crus I and crus II. Although correlation was lateralized clearly more on the right hemisphere, also left crus II activity correlated significantly with the model.

Discussion

The current study addressed questions of how brain contributes to language comprehension during narrative listening and what are the neural correlates of semantic processing in the brain. Brain research has implemented computational methods to study concepts and semantic representations in the functional brain (Binder *et al.*, 2009; Fedorenko *et al.*, 2010; Pereira *et al.*, 2018). The approach was to implement methods of cognitive neuroscience and computational linguistics to investigate further this complex question using a continuous naturalistic stimulus taking the context of language into account.

Semantics in narrative elicit correlation on distributed cortical areas

Inter-subject correlation analysis of auditory intelligible narrative suggested wide correlation in the BOLD signals between the subjects as seen in *figure 2*. Not all of the correlation can be related with semantic understanding. In fact, these results describe the whole process occurring in the brain while listening to the narrative, showing also lower level activation in for example sensory auditory areas. Because the task was to listen to the stimulus, especially auditory areas in temporal cortices correlated between the subjects. As the stimulus is naturalistic and it activates brain on wider areas than for example a simpler and more controlled one, it is difficult to make conclusions from the ISC analysis to separate these events. The task does not only produce semantic understanding of the narrative but also the processes prior to this. Thus, it is not possible to separate which of the responses are actually related to semantic, phonologic or auditory processes based on ISC alone.

In ISC, the correlation in temporal cortical areas extended from auditory areas in lateral fissure and superior temporal gyrus to anterior parts of temporal lobe on left hemisphere and this result supports the previous findings (Fedorenko *et al.*, 2010; Binder and Desai, 2011). This does not necessarily relate only to auditory and phonological processing. Some semantic processing has also been thought to occur in these brain areas (Démonet *et al.*, 1992; Mummery *et al.*, 2000; Friederici *et al.*, 2003; Visser and Lambon Ralph, 2011).

Correlation of brain data with the semantic model in ridge regression (*Figure 3*) was in line with previous research using narrative stimuli. Inferior parts of parietal lobe and on medial plane in PCUN are involved in semantic processing of narrative and similar results were found in previous studies (AbdulSabur *et al.*, 2014; Huth *et al.*, 2016). In addition, involvement of medial, superior and inferior PFC in narrative comprehension was found in ridge regression supported by research. In previous studies, temporal areas were found to take more part in semantic processing compared to these results. Only right MTG in temporal areas was involved with semantic processing in ridge regression. MTG is usually left lateralized in language tasks with simple stimuli, and with narrative context, bilateral activity of MTG has been found (Huth *et al.*, 2016). It could be that once word2vec maps the semantic content of words based on their context, these results describe the content that is clearly associated to some distinct feature. Maybe left temporal areas more traditionally associated to semantics are processing some more basic, procedural aspects of semantics that these algorithms cannot mimic. Thus, the semantic model used in this study could have such limitations or properties that these areas are not shown so strongly in the analysis. Another possibility is that semantics are not processed as much in temporal lobes with wider context. It is possible, that when the contextual information increases, detailed linguistic processing is in less importance in relative to larger semantic meaning elicited by larger context.

In ridge regression, some motor areas seemed to be involved in semantic processing of language. Left rolandic operculum, ventral part of the premotor cortex correlated with word2vec, suggesting them having a role in semantics. Some research has associated rolandic operculum with linguistic functions, but mostly with articulatory and other speech related aspects. Rolandic operculum is connected to SMG with a white matter tract (Maldonado, Moritz-Gasser and Duffau, 2011), and also SMG is involved in semantics in ridge regression. In addition, correlation was shown on left preCG. Similar result was found in another fMRI study using narratives (AbdulSabur *et al.*, 2014). Across the central sulcus, somatosensory areas in postCG showed correlation as well. Motor areas might have a role in understanding the movement described in the narrative and somatosensory the somatic sensations. Olfactory cortex was involved indicating olfaction taking part in comprehending the narrative content, as visual areas around calcarine fissure might have a role in imagining the scenery while listening to the narrative. Involvement of these sensory and motor areas could be related to features, such as smell or texture, of the concepts used in the text. Following, combination of these features would construct the meaning of a concept, semantics showing as a distributed correlation in the brain many brain areas being involved in its processing.

Involvement of insular cortex in ridge regression during narrative listening indicates some emotional processes of the brain taking part. In the narrative, there was for example surprisal of co-workers handing a gift, some confusing events such as phone in the refrigerator and backpack on the car roof, a car accident, mentalization eliciting paragraphs, fear of the narrator being cheated by partner and then revealing of the narrators own cheating to the listener. These are all events that should elicit some sort of emotions in the listener, and depending on the individual experiences, they might elicit very different kind of emotions with varying intensities. Insular cortex has been traditionally associated with disgust and its involvement in this data could indicates narrative eliciting disgust in subjects. It is known, that memories and concepts that are related to some emotions stay better in our memory (Kensinger and Corkin, 2003), and that words in our lexicon also associate to emotions (Binder and Desai, 2011). Emotional content of narrative has been found to elicit different patterns of activity than for example numeric suggesting these semantic categories being represented in the brain differently (Huth *et al.*, 2016). When a certain concept is associated to an emotion, correlation is seen in the areas processing the emotion. Same correlation is not seen with a neutral concept, which is why they are also felt differently in the light of this specific aspect.

ISC included all processes related to naturalistic narrative listening, but ridge regression took into account the semantic content of the narrative. These two analyses showed areas overlapping in their correlation. Many of these areas were bilateral in ISC but unilateral after applying word2vec. Correlation shown in ISC was naturally much stronger and covered wider areas. In ISC, frontal cortical areas correlated more on the left hemisphere than right. This is in line with previous studies (Vigneau *et al.*, 2006; Binder and Desai, 2011). In ridge regression, semantic processing of narrative recruited frontal cortical areas on right hemisphere. Bilateral parietal cortices and cerebellum were found to be involved in both ISC and ridge regression. Also, parts of visual and temporal cortices were involved in semantic processing in both analyses. Correlation was shown in distributed manner also on medial plane of cerebrum. Activation of frontal and parietal areas is found in previous studies with words and sentences (Vigneau *et al.*, 2006; Binder *et al.*, 2009), but these results lacked correlation in left temporal areas that is often shown in research. Semantics of language are encoded in distributed brain areas rather than one fixed area.

Left inferior frontal gyrus (LIFG) activation has been associated with sentence comprehension (Friederici *et al.*, 2003; Vigneau *et al.*, 2006). LIFG has been propose to play a role in unification, combining bits of linguistic information to larger entities (Hagoort, 2005). Correlation in left triangIFG was shown in both of the analyses. This suggests LIFG having a role also in narrative level comprehension, but the cluster was rather small in ridge regression. It might have a smaller role in relative to the rest of the brain when contextual information recruit other areas more strongly.

Research on genetics has shown the importance of FOXP2 in language but its role in language comprehension and semantics is not that clear. This gene encodes a protein that has an effect on brain plasticity. Research has suggested dopaminergic system and basal ganglia involvement in learning to be basis on how FOXP2 has had an effect on language development over the course of evolution. These areas are not shown in functional brain imaging studies of semantics, but they might anyhow have their role in learning process and formation of the semantic system via plasticity. This task does not necessarily trigger learning but merely comprehension that is based on already existing knowledge. Different kind of study design might be needed to study if basal ganglia have a role in language to further reveal the missing link between FOXP2 and language. Instead of nuclei in the basal ganglia, cerebellum was involved in both results. Cerebellum is one of the memory formation sites in the brain in addition to basal ganglia, hippocampus and amygdala (Gao, Van Beugen and De Zeeuw, 2012). Cerebellum role in semantics is still unclear.

Narrative context recruits both hemispheres for semantic processing

Quantitatively the difference in correlation was not large between left and right hemisphere in ISC. Previously, it was thought that language processing takes place on the left hemisphere (Krashen, 1973; Mori, Yamadori and Furumoto, 1989), and later studies claimed language being left lateralized in right-handed people (Binder *et al.*, 2009). As a naturalistic stimulus resembling more natural language was used, the task recruited wider networks than a simpler stimulus. Right hemisphere might thus contribute to language processing more than it has been previously thought to. Research using narrative stimulus show evidence that wider context recruits right hemisphere more to linguistic processing (Huth *et al.*, 2016). It is possible that different aspects of language are processed on different hemispheres in lateralized manner, and semantic processing of language takes place also on the right hemisphere (Martin and Chao, 2001; Mashal, Faust and Hendler, 2005; Ahrens *et al.*, 2007).

Ridge regression showed correlation on both hemispheres, but these areas involved in semantic processing were not bilateral in most parts. For example, SMG correlated on left the hemisphere in ISC but on both hemispheres in ridge regression, although SMG had almost 23 times larger cluster in the right hemisphere. AG then again was bilateral in ISC but showed correlation on left hemisphere in ridge regression. Areas on parietal cortex are found to correlate with linguistic tasks in general but spreading more posterior with semantic tasks compared to for example phonology (Vigneau *et al.*, 2006). SMG and AG in parietal areas are part of traditional Wernicke's area, and are related to semantic processing and integration (Smirnov *et al.*, 2014). LG and CUN were bilaterally involved in ISC but LG was right and CUN left lateralized in ridge regression. LG and CUN are located around calcarine fissure and are suggested to have a role in mental visual imagery (Winlove *et al.*, 2018), that the narrative listening could potentially elicit. Involvement of bilateral SMG, right LG and left AG and CUN support both hemispheres taking part in semantics.

Many brain areas were bilaterally involved in narrative listening ISC, and semantics recruited areas on both hemispheres in ridge regression. These results suggest that the brain does use both hemispheres for a complicated cognitive task such as understanding language, and this is in line with precious studies with narrative stimuli (Huth *et al.*, 2016). Bilateral activation was not only seen in cerebrum but also in cerebellar lobules VI and crus II. When combining semantic model with the data in ridge regression, both hemispheres still showed correlation but less areas were involved bilaterally. This result still suggests both hemispheres contributing to semantic processing, but brain areas are lateralized differently – hemispheres might contribute to different aspects of semantic processing.

Narrative stimulus includes wider context for the language used. Linguistic tasks with sentences and narratives have been found to elicit bilateral activity of the brain. Narrative context is suggested to recruit areas in addition to superior temporal, extending bilaterally to areas of default mode network including AG, medial PFC and PCUN, and inferior frontal and premotor areas (Wilson, Molnar-Szakacs and Iacoboni, 2008). Both results from ISC and ridge regression support these findings, but ridge regression lacked bilateral activation of many of these areas. Nevertheless, both hemispheres were recruited in the task and contextual language engages areas beyond superior temporal lobe.

Role of cognition in naturalistic language comprehension

Both analyses suggested other modalities of cognition taking part in language comprehension. Involvement of superior and middle frontal gyri in ISC and ridge regression might indicate working memory functions occurring during the task (Olesen, Westerberg and Klingberg, 2004; Boisgueheneuc *et al.*, 2006). PCUN activation was bilaterally involved in narrative comprehension in ISC and on right hemisphere in ridge regression. Ventral PCUN contribution might be due to attentive processes taking part (Zhang and Li, 2012). Observed involvement of MFG and TPJ in the task in both analyses support attention network role in comprehension tasks (Ptak and Schnider, 2011). Involvement of other cognitive processes in contextual language have been addressed in previous research with narrative stimuli (Wilson, Molnar-Szakacs and Iacoboni, 2008).

In hub-based models, semantics have been proposed to lie in the connectivity of the brain (Garagnani and Pulvermüller, 2016). For example, functional connectivity has been found between dorsal PCUN and CUN (Zhang and Li, 2012). Dorsal PCUN has is suggested to have a role in mental visuo-spatial tasks in a transcranial magnetic stimulation (TMS) study (Oshio *et al.*, 2010) which implies its role in imagining the scenery within a narrative. Cuneal activation is most evident in basic visual processing but it has been associated also with attention, especially when attending negative stimuli containing anger or disgust (Sander *et al.*, 2005; Carretié *et al.*, 2011). CUN activation has also been suggested to play a role in attention to speed and its changes (Sunaert *et al.*, 2000). CUN was bilaterally involved in narrative comprehension in ISC, but semantic processing recruits left CUN according to ridge regression. PCUN was then again mostly active on right hemisphere in ridge regression. CUN and PCUN could have both attentive and imagery related functions in language comprehension, and they might serve as semantic hubs. PCUN and CUN involvement in opposite hemispheres, and the connectivity between them, suggests that task requires information flow across the hemispheres. Some previous findings suggest that corpus callosum has its role in semantic processing (Hutchinson *et al.*, 2003).

Both ridge regression and ISC showed involvement of cerebellum in narrative comprehension, right hemisphere being more strongly engaged. In ridge regression, observed correlation of the word2vec language model with BOLD signals in cerebellum was more medial than correlation observed between subjects in ISC. Cerebellar functions have been associated with cognition (Schmahmann, 2004; Schmahmann and Caplan, 2006), also more specifically with language functions (Leiner, Leiner and Dow, 1993). Lesions in posterior cerebellar lobules VI and crus II have been linked with cognitive impairments, whereas anterior part has been associated more with motor functions (Stoodley and Schmahmann, 2011). These previous findings suggest cerebellum role also in various cognitive tasks in addition to more traditionally emphasized motor functions, and the results of this study support this view. How cerebellum takes part in language and more specifically in semantics of language is still unclear.

Mental imagery has been proposed as one of the cognitive control tasks of cerebellum (Doya, 2000). As one of the tasks of cerebellum is to control movement, also mental imagery of movement has been found to recruit cerebellum in several studies (Parsons *et al.*, 1995; Lotze *et al.*, 1999). Cerebellum activation by auditory mental imagery has been reported (Shergill *et al.*, 2001; Meister *et al.*, 2004). Visual mental imagery has been found to activate vermis and dentate nuclei within the white matter of cerebellum in a PET study (Mellet *et al.*, 2000), which supports connectivity of the brain being important in semantic processing. Narrative comprehension might require mental imagery in which cerebellum has a role.

Cerebellum is highly connected to the rest of the brain, but for the cognition, its connectiveness to frontal cortical areas raises most interest (Krienen and Buckner, 2009). Cerebellar crus II has been found to connect to MFG in prefrontal cortex (Diedrichsen *et al.*, 2009). Frontal cortex controls the rest of the brain in a top-down manner and connections from cerebellum might have an effect on this control. Some have suggested cerebellum to modulate cognitive loops in the rest of the brain (Stoodley and Schmahmann, 2011; Watson *et al.*, 2014).

Maybe cerebellum has a role not only in fine tuning motor functions but also other functions of cerebrum. Cerebellum has been thought to contain the detailed information of how motoric movements should occur in time. In a similar manner, as our brain modifies the motor functions and creates motor routines, cerebellum might take a part in molding our linguistic functions, patterns of thought and by this eventually our ways of thinking. By this, cognitive routines might be created similarly as motor routines in cerebellum. As cerebellum is a complex structure that is even more densely layered than cerebrum it should have a great importance in our brain functions also in cognition.

Ridge regression showed correlation of the word2vec language model with BOLD signals in prefrontal cortical areas on right hemisphere which could also indicate top-down frontal cortical control taking place. This control has been shown to be partly inhibitory (Medalla and Barbas, 2009). Also, right DLPFC has been shown activation during for example rumination but also mentalization (Carrington and Bailey, 2009; Vanderhasselt *et al.*, 2017). Some studies suggest that medial plane of prefrontal cortex takes part in mentalization (Frith and Frith, 2003; Gallagher and Frith, 2003), thus correlation found in right oIFG but also SFG might be part of this network (Vanlangendonck, Willems and Hagoort, 2018). Especially the medial plane of frontal cortical areas could take part when processing social context of the narrative. In addition, TPOJ has been found to correlate with mentalization tasks (Vanlangendonck, Willems and Hagoort, 2018) but has also been associated with spatial attention (Ptak and Schnider, 2011). TPOJ showed correlation between BOLD signals and word2vec on right hemisphere in ridge regression.

The results of these analyses suggest language processing, comprehension and semantics of language to recruit different cognitive modalities and networks for its optimal function. Some of these modalities might be related to attentional processes as discussed for example in the case of PCUN. In addition to attention, PCUN has been associated to self-reflecting conscious processes (Zhang and Li, 2012). Consciousness does not only affect what we are able to perceive in language, but literature suggests that consciousness is partly based on language (Arbib, 2001). By this, the interaction of consciousness and language might work in a dual manner – language we use has an effect on our consciousness and consciousness affects how we understand language.

By being conscious of, being able to direct attention to, being able to store and retrieve memories about, and to associate different sensory features to different words, we are able to perceive and process language and comprehend it in our own subjective ways. It could be, that listening to a narrative that describes our world, elicits eventually activity in different sensory areas in the form of mental imagery. As an experience, this is clearly different to actual perception as it is much weaker in its intensity. Cerebellum is suggested to play a role in separating how we experience for example imagining speech from perceiving actual speech (Shergill *et al.*, 2001).

Cognitive events could be more of a dynamic sum, a constantly varying weighed combination of different networks rather than one fixed state. Functional cognitive networks might thus work in a weighed manner. Language processes would for example recruit attention network relatively more with heavy sensory load in challenging environments. Then again, more weight would be given on working memory with challenging content rather than environment. This would also apply in stronger recruitment of mentalization network in social contexts. With less internal language that describes the world outside rather than inside human mind, more sensory areas might be activated. It could be that different networks contribute to comprehension of language, and how much they are recruited in the task depends on the content.

Limitations of the study

Functional magnetic resonance is one of the imaging tools that we have today to record brain events temporally, but the temporal properties are not as good as in for example encephalographic methods electro- and magnetoencephalography. Also, contrast in fMRI comes from deoxygenation of blood. The more oxygen is consumed in a certain brain area; the more energy is consumed at this specific location. It is true, that the cell metabolism must be due to action potentials occurring in the brain, but this activity does not yet separate if a certain brain area is actually inhibited or excited. GABAergic interneurons consume as well energy and thus oxygen in their metabolism as do excitatory glutamatergic pyramidal cells (Duarte and Gruetter, 2013) resulting in activation in fMRI. We can tell from fMRI studies that the cells in these specific brain areas consume more oxygen, but we cannot distinct to which function the resulting energy is used unless it is somehow taken into account in the study design.

After ISC, choice of further analysis method was challenging due to the limitations of the data set. In the analysis fMRI data was combined with a linguistic model. The first approach was to use regularized kernel canonical correlation analysis (rKCCA) as a multivariate analysis method to combine two different sized datasets, as described in Bilenko *and* Gallant (2016). The model was overfitting noise due to the small size of this dataset. 300 timepoints was not enough to both initialize the CCA object with Monte Carlo cross-validation and train the learning model. Cross-validation used 20 % of the training data (Bilenko and Gallant, 2016). Another approach was to use a single regularization parameter from the literature. This resulted as less correlation between the subjects but raised questions of the validity of the results. When using learning algorithms the sample size has to be taken into account (Cui and Gong, 2018).

Kernelization generalizes the system to nonlinear (Huang, Lee and Hsiao, 2006), whereas regular CCA and ridge regression are linear learning algorithms (Hoerl and Kennard, 1970; Hardoon, Szedmak and Shawe-Taylor, 2004). Maybe nonlinearity was the reason for overfitting the data in rKCCA. Ridge regression is beneficial when analyzing multimodal datasets (Cui and Gong, 2018) and the data had multiple variables in addition to limited amount of timepoints. Thus, ridge regression was more suitable for the data, even though the effect of sample size on prediction accuracies of both ridge regression and linear support vector machine seems to be rather similar. It was clear after the CCA, that with this specific dataset there was not enough data to cross-validate the hyperparameter in the following analysis ridge regression either. Thus, in ridge regression, the ridge parameter was chosen based on literature (Raz *et al.*, 2017). This was not the most optimal approach, because the choice of proper ridge parameter is essential when balancing between the variance and bias (Cui and Gong, 2018). Better approach would have been to use grid search to cross-validate the ridge parameter.

It seems that for these kinds of multivariate analyses the choice of specific hyperparameters is important for gaining accurate results, and the best option is to validate the hyperparameters either with the same dataset or with a pilot study. For example, the choice of regularization parameter could be done in advance for simplification of the computation in kernelized canonical correlation analysis as done in Hardoon *et al.* 2004. The regularization parameter chosen according to their approach should work with varying tasks and it overcomes some problems that occur in kernel space (Hardoon, Szedmak and Shawe-Taylor, 2004). Also, in rKCCA most of the dataset was used for training (70%). It is known that when using too large training sets with learning algorithms computational problems do occur (Hardoon, Szedmak and Shawe-Taylor, 2004). As these algorithms compute as they are coded to compute, and use the mathematics written in the code, it is important to know the properties of the data and choose a proper analysis method carefully in advance based on these features to get as accurate results as possible.

Algorithms such as word2vec and latent semantic analysis (LSA) are tools to encode semantic meaning into vector space (Landauer, 1997; Mikolov *et al.*, 2013). It is debatable if the word2vec algorithm describes semantics in the brain as is expected. Creating the vector space is based on a large corpus. In this study, Finnish internet was used. Technically, it is us people who have produced the text to internet, and it could be that this corpus represents the language structure and context as it is represented also in our minds. The debatable part is whether this is analogous to physical human brain and how the neurons consisting the memories are actually located in the brain structures (Poeppel and Embick, 2005). That is to say, is the semantic content represented in this word to vector model similarly located also physiologically in middle temporal gyrus etc. Anyhow, this is possibly the best way available to translate semantics in written text into computable form, although as all methods have their limitations, so do these algorithms.

There were some other limitations in the dataset in addition to its small size - the subjects had differing backgrounds and were of different ages. Different life experiences have an effect on how literature is comprehended, and how individuals engage with the narrative content (McNamara and Kintsch, 1996; Green, 2004). It is possible that different background and varying life experiences have also an effect on how brain is activated during narrative listening. Individuals who share similar mental associations also have more common in their brain activity when engaging into a narrative (Saalasti *et al.*, 2019), and similar associations might be due to similar experiences in life. Different experiences might result in varying associations of language in for example areas processing emotions and thus showing as differing neural patterns in fMRI. Literature suggests that linguistic behavior of an individual is affected by previous experience (Beckner *et al.*, 2009; Saalasti *et al.*, 2019).

Nevertheless, the results over subjects suggest which areas might be functionally important for semantic processing during naturalistic language comprehension. Within an individual, semantic processing most likely activates larger areas than is seen at group level. On the other hand, varying life experiences could also be a benefit with this kind of research question, where the focus is on the neural networks of comprehension. The more variation the subjects have in their experiences, the more different their dynamic patterns are during the narrative listening, and the more these differences cancel each other out. What is then left should be what is common across these subjects: comprehension.

Future directions

The next step in the analysis of this data will be a more detailed fragmentation of the narrative and the analysis of each of these paragraphs separately. The paragraphs had varying content from describing social phenomena and environment to more internal events, and they were planned to recruit different cognitive networks such as theory of mind, mentalization and default mode network. More detailed investigation on the paragraphs might reveal how brain processes varying semantic information and uses these networks in different contexts. Subjects also read and lipread the same narrative, so naturally the next step would be to analyze these data. Further on, the dataset could be divided into two larger compartments to compare these two data in the context of perspective taking. In the first part of the narrative, the husband seems to be cheating on her wife, but as the narrative evolves it is revealed to the reader that the wife is actually the one cheating on him. By analyzing these two data separately, the change of the perspective over time could then be compared.

Inter-subject correlation analysis of condition using intelligible narrative suggests that processing of semantic information activates brain in multiple areas. Some areas for future analysis are the anterior parts of medial temporal gyri and anterior temporal lobes, also referred as temporal poles. These areas have been associated with semantic processing. For example, temporal pole has been thought to take part in processing the emotional contents of information (Olson, Plotzker and Ezzyat, 2007), but has also suggested to play a modulatory role in semantics (Ralph *et al.*, 2017). The dynamics of semantic processing during naturalistic language with a focus in emotional processing would be an interesting approach in the future. Also, there was interesting correlation in the visual cortical areas suggesting some mental imagery taking place during the listening of the narrative. Further studies on this might require a set up excluding the visual stimulus from the study set-up.

Studying the language and the brain could potentially lead to more quantitative methods for clinicians in the diagnosis processes. By creating for example an easily repeatable semantic task for valuating connectivity in fMRI could potentially be one possible measure when diagnosing a patient with language disturbances leading to better targeting of intervention. These tasks could also be useful in following the development of these disorders, especially if they are progressive in their pathology. Research in semantics could also lead to potential therapeutic discoveries – many other phenomena than language, such as music, have semantic content in them, and they share some underlying mechanisms. Studies on priming effects have found that music has similar priming effect on language as words (Koelsch *et al.*, 2004). It could be further studied if for example training one type of semantic modality improves the other.

Research on semantics requires effort from the scientific and philosophical community in a multidisciplinary manner. Objectivistic and constructivist views are no longer under much debate, once cognition role in semantics has been proved with accumulating results. What these debates still provide for us, is another perspective on understanding human ability for abstract thinking and language. Yet, there is a continuous discussion on how language is processed in the brain: maybe this question cannot be answered while contradictive ideas are strongly against each other but finding an answer that would go along with the spectrum of theories in the field. Maybe we process language in a way no one has ever thought yet but is still to be discovered. The answer might lie somewhere else than in the battlefield of opposing ideas.

Conclusions

This study discovered how narrative listening is represented in the brain and more specifically, what are the neural correlates of semantic processing in a narrative context. According to ISC, wide brain areas are recruited in language comprehension suggesting different cognitive modalities having a role. Their recruitment is dependent on the content of the language and the situation in which language is perceived. Results from ridge regression show semantic processing to be distributed across hemispheres in superior, middle and medial frontal, inferior and medial parietal cortices and cerebellum, but also visual and temporal cortices showed involvement in the task. Results suggest narrative context recruiting both hemispheres in semantic processing, and that these processes occur in an associative manner in distributed cortical areas. That is to say, words associate in for example sensory and motor areas depending on the features they have, and semantics lie in these connections in the brain. These results showed areas that are often found in studies considering semantics, suggesting computational approach word2vec to be suitable for extracting detailed information from functional brain data.

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