CREATIVITY AND SEMANTIC PROCESSING IN THE BRAIN: AN MEG STUDY OF N400

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Creativity is an ability that has a fundamental status in defining human nature. The processes and components of creativity have long been considered mystical and un-researchable, but contemporary studies permit the examination of creative abilities like any other cognitive process. This study examined possible links between creativity and semantic processing in the brain, indicated by N400 event-related potential. Participants (n=8) were university students, aged between 19 and 25. Brain activation was measured with magnetoencephalography (MEG) during a three-word list task, in which half of the lists were congruent (all items semantically related to each other) and half were incongruent (first two words were related, but the last word broke the pattern). Creativity was measured with self-assessment of creative abilities (K-DOCS), Design Fluency Test, and a questionnaire about creative hobbies. Cognitive skills were assessed with parts of Wechsler Adult Intelligence Scale (WAIS). The proposed hypothesis was based on theory about creativity as ease of association. It was assumed that higher creativity is associated with easier semantic association, and hence correlates with more effortless semantic categorization. This was hypothesised to manifest as a smaller semantic N400 effect. Results showed that the presented stimuli created an expected N400 effect; a greater N400 amplitude was seen for incongruent stimuli than to congruent. Self-assessed creativity (average creativity and performance-related creativity) correlated positively with the magnitude of semantic effect in the left hemisphere. On the other hand, hobbies related to music production, Design Fluency Test scores and working memory (WAIS) correlated positively with the semantic effect magnitude in the right hemisphere. Direction of correlations was opposite to what was assumed by the hypothesis: greater scores on creativity tests correlated with greater semantic effect. Hence, more creative people exhibit a larger N400 effect. However, it is possible that more creative people actually require more effort in semantic processing, because they possess a larger semantic network. This study was executed with a small number of participants, and more research is needed to uncover the processes that underlie creativity and how it might be connected to semantic processing.

Keywords: creativity, semantic processing, N400

Luovuus on kyky joka määrittää ihmisluontoa, mutta sen perustaa ja siihen liittyviä prosesseja on pidetty mystisinä ja tutkimuksen ulottumattomissa olevina. Nykyaikainen tutkimus kuitenkin mahdollistaa luovuuden ja siihen liittyvien tekijöiden tutkimisen samoin kuin minkä tahansa muun kognitiivisen kyvyn. Tämä pro gradu -tutkielma tarkasteli luovuuden ja semanttisen prosessoinnin yhteyksiä aivotasolla. Tutkittavat (n=8) olivat yliopisto-opiskelijoita, iältään 19-25 -vuotiaita. Semanttista prosessointia ilmaisevaa N400 herätevastetta mitattiin aivomagneettikäyrällä (MEG) samalla kun tutkittavat seurasivat kolmen sanan listoja. Näistä sarjoista puolet olivat yhteneväisiä (kaikki sanat listalla liittyivät toisiinsa merkityksellisellä tasolla) ja puolet epäyhteneväisiä (kaksi ensimmäistä sanaa liittyivät toisiinsa, mutta viimeinen sana rikkoi sarjan). Luovuutta mitattiin luovuuden itsearviointikyselyllä (K-DOCS), kyselyllä luovista harrastuksista, sekä visuaalisen fluenssin testillä (DFT). Kognitiivisia kykyjä kartoitettiin Wechslerin testistön (WAIS) osatesteillä. Tutkimuksen hypoteesi pohjautui teoriaan luovuudesta assosiaation helppoutena. Korkeamman luovuuden oletettiin tekevän assosiaatiosta helpompaa, ja siten esitettyjen sanojen semanttisesta kategorisoinnista vaivattomampaa. Tämän oletettiin ilmenevän pienempänä N400 efektinä. Tulokset osoittivat, että esitetyt sanalistat loivat aivotasolla näkyvän semanttisen efektin; N400 vaste epäyhteneväisille viimeisille sanoille oli suurempi kuin yhteneväisille. Itsearvioidun luovuuden yleinen sekä esiintymiseen liittyvä taso (K-DOCS) korreloivat positiivisesti semanttisen efektin suuruuteen vasemmalla aivopuoliskolla. Musiikin tuottamiseen liittyvät harrastukset, visuaalinen fluenssi (DFT) sekä työmuisti (WISC) korreloivat positiivisesti semanttisen efektin suuruuteen oikealla aivopuoliskolla. Korrelaatiot olivat suunnaltaan päinvastaisia kuin hypoteesi antoi olettaa: suuremmat pisteet luovuusmittareissa korreloivat suurempaan N400 efektiin. On kutenkin mahdollista, että luovemmat ihmiset tarvitsevatkin suurempaa ponnistelua semanttisessa prosessoinnissa, sillä heidän semanttinen verkostonsa on laajempi. Siten luovuus voisi näyttäytyä suurempana semanttisena efektinä. Tämä tutkimus toteutettiin pienellä osallistujamäärällä, joten lisätutkimusta luovuuden perustana olevista prosesseista sekä niiden yhteyksistä semanttiseen prosessointiin tarvitaan.

Avainsanat: luovuus, semanttinen prosessointi, N400

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INTRODUCTION

Creativity is a cornerstone of what makes us human (Dietrich & Kanso, 2010, p. 1). It is one of the few qualities that define human nature (Lindell, 2010). Creative innovations have enriched lives, prolonged life, and helped relieve suffering (Heilman, 2016, p. 285). Creative thinking and imagination enable people to go beyond what was previously stored in memory; hence, it lays the basis of such important cognitive activities as future thinking, planning and idea generation (Benedek et al., 2018, p. 93). The importance of creativity for human kind can also be seen from an evolutionary point of view - how did creativity enhance survival or reproduction? For example, the innovation of weapons most likely evolved as a creative response to a need for protection. Creativity can also enhance a group's social cohesion: especially music of our earliest ancestors played an important role in creating and manipulating social relationships through the impact on emotional states (Gabora & Kaufman, 2011). Since creativity is so important for humans, it seems vital to understand the processes and factors behind it. In the past, the processes and components of creativity were considered mystical and un-researchable, but the contemporary studies permit the examination of the creative abilities like any other cognitive process (Kenett, Anaki, & Faust, 2014, p. 1). In this thesis I will examine creativity conceptualised as associability, and the underlying neural processes. More specifically, I will focus on the neural signatures of semantic associability and their linkage with creativity as trait characteristics.

Semantic processing refers to the processing of meanings; this processing occurs when we encounter any stimulus with meaning (words, symbols, pictures etc.). The stimulus is placed to a context and related to other objects with similar meaning. Semantic processing is one of the higher cognitive processes: it requires the person to encode the meaning of the stimulus at an abstract level. (Craik & Lockhart, 1972.) There is surprisingly little research about the links between creativity and semantic processing. Studies have looked into creativity's links to sensory gating (Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), personality, and many other traits, but there is a need for additional research, especially in neuroscience (Abraham, 2016; Dietrich & Kanso, 2010). Semantic processing includes associating stimuli to other stimuli with similar meaning. In this thesis I will use associativity as the link that connects creativity and semantic processing.

Associativity indicates a mental connection between ideas, events, or mental states that usually stem from specific experiences (Klein, 2014). Mental Association, or Association of Ideas, expresses the conditions under which representations arise in consciousness (Chisholm, 1911). The term was first used by John Locke, and it refers to connections between experiences and ideas. “Ideas” in this case can refer to all kinds of mental content: thoughts, sensations, memories. In the simplest view of association, one idea serves to recall another which resembles it, or which was contiguous to it in former experience. The manner in which association operates follows the laws of similarity (or resemblance) and contiguity: an idea brings forward either an idea that resembles it semantically, or an idea that has been experienced in close conjunction (spatially or temporally). (Warren, 1921.)

Defining creativity

Creativity can be viewed from several different angles. We can stress the outcome or the creative process, the social environment or the creative agent (Mayer, 1999). Different definitions and aspects of creativity include divergent thinking, imagination, artistic creativity, insight, and pragmatic creativity, just to name a few. It links closely imagination, daydreaming, problem solving, finding unusual meanings or solutions, and creating something new. Dietrich & Kanso (2010) categorize creativity into three categories: divergent thinking, artistic creativity, and insight. Heilman (2016, p. 286) proposes four stages of creativity: preparation, incubation, illumination, and production. In common sense, it usually refers to creative activities, such as music, arts or poetry. Among all these approaches, the most common definition for creativity is “to create something new and useful”. For example, Abraham (2016, p. 4197-4198) defines creativity as the ability to generate ideas that are both original (novel, unique) and appropriate (relevant). These ideas arise from reintegration of existing material, but when completed it contains something new. (Abraham, 2016, p. 4204.)

The neural mechanisms of creativity are poorly understood (Dietrich & Kanso, 2010, p. 1), but some of the most essential brain areas include the Default Mode Network, semantic cognition network (Abraham 2016, p. 4201; 4204), dorsolateral frontal lobe and ventral medial PFC (Heilman, 2016, p. 288-293). Neurotransmitters play a role in creativity as well: a lesser amount of noradrenaline in the brain correlates with higher creativity. Depression, relaxation and non-REM sleep reduce noradrenaline (Heilman, 2016, p. 288-293). Creativity had long been associated with the right hemisphere, but Dietrich & Kanso (2010) state that creativity is not particularly associated with the right hemisphere, or any single brain region, the prefrontal cortex excluded.

How can a mysterious concept like creativity be measured? There is a great deal of diversity in how creative thinking is measured (Kröger et al., 2013). Some common measurement tools require a person to solve problems in a creative way; tests such as divergent thinking tasks (eg. Dietrich &

Kanso, 2010; Mayseless & Shamay-Tsoory, 2015), conceptual expansion tasks, and alternate uses task (Kröger et al., 2013) measure the ability to think creatively in a specific situation. Also creative writing (Lotze, Erhard, Neumann, Eickhoff, & Langner, 2014), real-world creative achievements (Zabelina et al., 2015), and questionnaires about creative abilities are used to measure creativity. The methods used in this study to measure creativity were a self-evaluation of creative abilities (K-DOCS), a questionnaire about creative hobbies, and Design Fluency Test.

Associativity theory of creativity

Marupaka, Iyer & Minai (2012) state that all thought is combinatorial and associative: ideas are combinations of existing concepts or ideas. New ideas are born in association with currently active ideas or concepts, creating the “train of thought”. This is a central theme in most theories of creativity. Mednick (1962) has looked at creativity from the perspective of associativity. He proposed a model of creativity which says that more creative people have richer and more flexible associative network, and hence can more fluently combine remote associative elements. He developed the concept of “associative hierarchies”, which refers to the individual’s ability to connect concepts to each other. Levels of the “hierarchy” are determined by the word’s distance of a concept (for example, if the concept is “table”, then “chair” is closer in hierarchy than “fork”). His study states that creative people have more flat associative hierarchies – meaning that when presented with a word and asked to produce other words that are in association with it, they produce a wide variety of answers, not dominated by the most obvious one. Hence, creativity also requires inhibition of obvious solutions. Consequently, less creative people have steep associative hierarchies, meaning that their answers are concentrated on a small number of stereotyped associative responses.

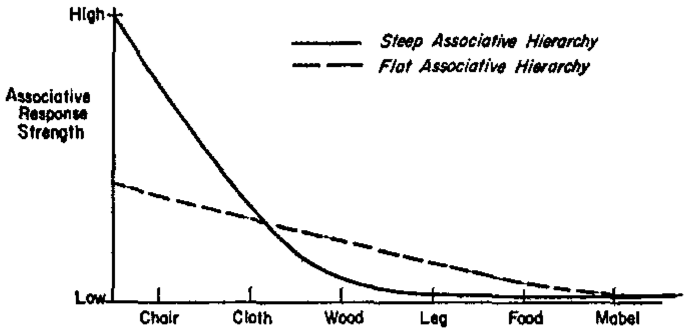

FIGURE 1. Associative hierarchies around the word “table”. According to the theory, more creative people have flatter hierarchies. (Mednick, 1962, p. 223.)

Benedek & Neubauer (2013) tested Mednick hypothesis in their study of “associative hierarchies”. In a continuous free association task, participants wrote down all arising associations for a given stimulus word within a time period of 60 s. Associative hierarchies were compared between groups of low and high creativity. They found support for Mednick’ hypothesis for associative fluency and associative uncommonness: highly creative people generated responses of higher average uncommonness than low creative people. They also found that the group effect obtained for associative uncommonness may largely be explained by individual differences in associative fluency (amount of associative responses). Hence, the study revealed clear support for Mednick’s hypotheses that creative people show higher fluency and uncommonness of associations. However, the model assuming differences in associative hierarchies did not get support from the study, since according to the hypothesis, the association strength for highly common responses should be lower with creative people than non-creative people (the curve of the associative strength being flatter), and vice versa for less common responses. This did not occur in the study, even though the more creative people generated more uncommon responses on average.

Kenett and colleagues (2014) found support for Mednick’s theory in their study of the structure of semantic networks. In a free association task, the group of high creativity people generated significantly more unique responses than the low creativity group. The result was verified even when effect of fluency was eliminated by examining only the first ten answers. They also found that semantic networks of more creative people were less modular, meaning that their responses were less clustered around few “obvious” answers – which is in parallel with Mednick’s “flat” associative hierarchy of creative people.

These studies and Mednick's theory are about semantic associations and networks – but how exactly does semantic processing happen and what does it mean? The next paragraph is going to look into semantic processing and how it is indicated on brain level.

Semantic processing indicated by N400

Associating concepts to one another is abled by semantic processing. In this processing we encode the meaning of a word or other stimulus and associate it to others with similar meaning. On brain level, semantic processing is indicated by the N400 response. The N400 is an event-related potential (ERP) which appears after a person is presented with a stimulus that is meaningful (or potentially meaningful), peaking at 400 milliseconds after the stimulus onset. Kutas & Hillyard (1980) discovered the N400 by researching the response to unexpected words in sentences. Test subjects read seven-word-sentences of which some were congruent sentences (e.g., I shaved off my moustache and beard.), while some ended "oddly" with an improbable word (He planted string beans in his car.) or a wholly anomalous one (I take my coffee with cream and dog.). This yielded a large negativity with a broad scalp distribution, peaking around 400 ms; it then became to be known as the N400 (Kutas & Hillyard, 1980, 2). This sustained response to any meaningful stimuli is called the N400 *response*, while the term N400 *effect* (or semantic effect) is usually - and in the present study - used when referring to the difference between responses to congruent versus incongruent stimuli; the mismatch between perceived object and the expectation.

Kutas and Federmeier (2011, p. 2) point out that unlike many other ERP responses, the N400 is not named for its function, and its functional characterization is in a state of fine-tuning. Lotze, Tune, Schlesewsky and Bornkessel-Schlesewsky (2011) have proposed that the N400 reflects the degree of matching between top-down and bottom-up processes, so that a mismatch results as a higher N400 amplitude. Studies have found that there is no N400 response to physically unexpected ending to a sentence (capital vs. small letters), or to simple grammatical violations. Other studies have confirmed that the ERPs to all sentence final words – even congruent ones – are characterized by some degree of N400 activity, and further demonstrated that N400 amplitude is highly correlated with eliciting word's expectancy. N400 effects have also been observed in lexical priming paradigms, where a target word is or is not somehow related (e.g., identically, associatively, semantically, categorically, and perhaps phonologically) to an immediately preceding (prime) word; in all cases, related items show reduced N400 amplitudes relative to unrelated items across a number of different tasks. As the N400 came to be characterized, it quickly became clear that it is the amplitude of the response that is most sensitive to manipulation (becoming smaller when the presented information is more expected, and thus easier to process). N400 latency, by contrast, is generally quite stable. Characterizing N400 topography across the scalp has proven more difficult. A very important notion is that the N400 generalises across input modalities, including spoken words, American Sign Language and even movement or actions; Reid & Striano (2008) found that if a concluding action of an action sequence is unanticipated, a larger N400 component is induced than in the case of an expected concluding action. This suggests that neural systems rapidly discern semantic information within human movements, and that these systems are related to the N400 component. Overall, the data suggests that the N400 indexes something fundamental about the processing of meaning and hints that the meaningful/nonmeaningful dimension may be more important than the linguistic/non-linguistic dimension. (Kutas & Federmeier, 2011.)

Kröger and colleagues (2013) studied the N400 using modified conceptual expansion. Conceptual expansion means the ability to widen the usual conceptual boundaries of an object, to create novel dimensions for it, and it is usually used for measuring creativity. In this modified test, subjects had to decide whether a shown use for an object is unusual, appropriate, or both. Thus, the uses were categorised into three outcomes: creative uses (high unusual and appropriate), nonsensical uses (high unusual, low appropriate) and common uses (low unusual, high appropriate). The N400 was generally responsive to unusualness of the stimuli: the amplitudes for creative and nonsensical uses were higher than for common uses. There was no difference in N400 between nonsensical and creative uses, which implies that N400 reflects semantic violations. (Kröger et al., 2013, p. 190-191.) From this it can be interpreted that the N400 reflects expectancy at a conceptual level; the “high unusual” uses are in contrast to what is expected of the object (for example, using a shoe as a flowerpot). The “high appropriate” uses are common, customary uses for the object, so they do not generate as strong response.

Aims of the study

Several studies have examined semantic processing in form of the N400 paradigm, and also creativity has been a topic of interest for many researchers. However, links between semantic processing and creativity, as well as the brain mechanism of creativity, remain less studied. In current study I aim to examine, whether associative creativity is linked with the brain’s processing of semantic meanings.

This would verify Mednick's theory of creativity as ease of associations in the brain level. The possible influence of general cognitive skill level was also evaluated, as it might underly the possible association between creativity and brain correlates of semantic processing.

Research questions. This paper will focus on the following questions: 1. Does the brain activation indicate sensitivity to semantic information (in the form of an N400 response) in this three-word list task? 2. Do the participant's cognitive abilities or creativity (based on subjective reports or objective tests on creative thinking) have correlation to brain semantic activation (N400 response)? These individual aspects will be measured with questionnaires and cognitive tests. The N400 response will be measured with magnetoencephalography, during a picture-list task. The hypothesis is, in correlation with Mednick's theory, that individuals with higher self-evaluated and objectively tested score on creativity associate concepts with more ease, and hence have smaller semantic N400 effect.

METHODS

This study is part of a larger project which examined conceptual level processing in the brain, by using congruent and incongruent lists of words and pictures. In this thesis I will focus on the words only. Brain activity was measured with Magnetoencephalography (MEG) while participants viewed these lists. Participant's creativity and cognitive skills were assessed with questionnaires and cognitive tests.

Participants

The participants of this study consisted of eight university students of ages 19 to 25 (1 male, 7 females). The participants were recruited through email lists of student associations of University of Jyväskylä. In order to achieve variation in the scores of creativity, subjects were recruited from a variety of majors in "creative" fields, including cultural anthropology, musicology, languages and literature. Since the present study was conducted with Magnetoencephalography (MEG), candidates with any metal in their head area (e.g. braces) were excluded from the study due to possible disturbances to the magnetic field of the MEG. Candidates with neurological conditions (e.g. epilepsy) were also excluded. All the volunteers gave an informed consent to the study.

Materials

In the research project, a comprehensive battery of behavioural tests and questionnaires was conducted, but for this thesis only the ones related to the research questions were chosen for examination.

K-DOCS. Five different domains of participants' self-assessed creativity were measured with Kaufman Domains of Creativity test. The test was translated to Finnish, as the participants were Finnish speakers. The K-DOCS measures five domains of self-assessed creative behaviours: Self/Everyday, Scholarly, Performance (encompassing writing and music), Mechanical/Scientific, and Artistic. While some other creativity surveys emphasize the frequency of certain creative behaviours, or levels of creative accomplishments, the K-DOCS is more focused on self-beliefs about one's abilities than a simple reporting of participation. In this way, the K-DOCS also incorporates the idea of creative self-efficacy. The domain-specific nature of the K-DOCS allows an in-depth instrument for studying beliefs, perceptions, and metacognition. In addition, it gives multiple scores instead of one overall number. (Kaufman, 2012.)

Creative hobbies. To examine participants' exposure to creative activities, a questionnaire was created for this study. In the questionnaire, the participants reported if they had creative hobby/hobbies in the following fields: music production (e.g. singing, playing an instrument, composing), writing (novels, poems, diary etc.), producing art (painting, photographing etc.), performing arts (e.g. dancing, acting), or other. They were also asked to report how long they had participated in these hobbies.

DFT. Creative abilities were further tested with Design Fluency Test (DFT: Jones-Gotman & Milner, 1977). In this test the task is to create novel designs out of one's imagination, drawing as many of them as possible in the given time. The test consists of two conditions: first one is the free condition (five minutes), where there are no rules, and the fixed condition (four minutes), where the participant can only use four lines for one design. Repetitions of the same design, designs with incorrect amount of lines (in fixed condition) and designs that can be named (resembling something real) are excluded from the score.

WAIS. To measure the effect of cognitive skills, parts of The Wechsler Adult Intelligence Scale (WAIS) were used to test the participants level of cognitive abilities (block design, digit span and vocabulary).

Magnetoencephalography procedure

The MEG measures were conducted in the MEG laboratory of Jyväskylä Centre of Interdisciplinary Brain Research with a 306-channel neuromagnetometer (Elekta Neuromag Oy, Finland). This MEG equipment measures magnetic fields using 102 magnetometers and 204 planar gradiometers. Magneto- and gradiometers placed in a helmet around the participant's head measure the amplitude, timing and distribution of a change in magnetic fields generated by brain activity. Before starting the experiment, all metal objects (e.g. earrings, keys) were taken off so they would not affect the measurement.

After making sure there was no metal on the participant, Isotrak 3D digitizer (Polhemus, USA) was used to draw three marking points on nose and ears, as well as five Head Position Indicators (HPI-coils). Three of the HPI-coils were placed on the forehead and two behind ears. After this, other points were drawn to better determine the position of the head. In addition to the marking points made with Isotrak, a set of electrodes were glued to the participant. Four electrodes were attached across the eyes, and three under collar bones. These electrodes measured eye movement (electro-oculogram, EOG) and heartbeat (electrocardiogram ECG), so that artefacts related to eye movements and heartbeat could be corrected later in data analysis.

After the preparations, the participant’s resting brain activity was measured four minutes with eyes open and four minutes eyes closed. After that, we began the experiment procedure, which consisted of showing 195 different three-word lists in Finnish. The stimuli words were adapted from a study of Vartiainen, Parviainen & Salmelin (2009). The words were short, two or three syllables long, and were of average frequency in Finnish language. First two of the words in a list were always related to each other, in order to create an expectation in the participant. The third word was either in correlation with the expectation, or it broke the expected pattern. Creating an expectation of the meaning of the stimuli is integral in adducing the semantic processing of the brain. Thus, half of the lists were congruent: all the words were of the same category. In other words, they were semantically related to each other, for example rose-tulip-lily. Other half of the lists were incongruent: they had two related concepts, but the third word was not clearly related to the other two (e.g. rose-tulip-computer). In other words, the setting of the experiment created expectancy, and the difference in the congruence of the last word of the list created N400 effect (semantic effect).

KIELO	LUMME	SUKSI	?

FIGURE 2. The stimuli, example of an incongruent list. First two are related to each other (both are flowers) and the last one is not (a ski).

Presentation version 18 (build 6.9.2015) (Neurobehavioral Systems, Inc.) program was used to present the stimuli. The resolution of the presented stimuli was 1920x1080x32 (60 Hz). Participants sat in a chair under the MEG helmet so that the distance between their eyes and the screen was approximately 105 cm. On the screen, the participants viewed the words one by one, in chains of three. The words were approximately 6x4 cm by size. Each word was shown for one second, and between words participants would see a black screen with a cross as a fixation point for the eyes. Between first and second word the pause with the fixation point was 1.5 seconds, and between second and third word the pause was 1.8 seconds (to give the participant a little more time to prepare for the last word). Between the chains of three-word lists, the fixation cross was shown for two seconds. They were asked to pay attention to whether the third word was congruent with the two first ones or not. After a random number of lists, the participant was asked about the congruence/incongruence of the last word with a question mark. The question mark was shown for maximum of two seconds. To answer, the participant had to press one of two buttons in a response pad. The experiment took 60 minutes with small breaks in between (including similar paradigm with pictures, which is not included in this study).

Data analysis

Data was acquired with 1000 Hz sampling frequency and highpass filter of 0.10 and lowpass filter of 330 Hz. MaxFilter (Elekta Neuromag Oy, Finland) was applied to remove disturbances from the data; it uses signal space separation method to remove signals coming from outside the head. Data was downsampled to 250 Hz**.** Maxfilter was also used to apply spatiotemporal signal space separation method (tSSS) and head movement correction to the data. Artefacts caused by muscle activity (e.g. heartbeat and eye movements) were removed by using independent component analysis (ICA). Data was low-pass filtered with 40 Hz. Meggie, an in-house built graphical user interface for MNE Python script -based analysis of EEG and MEG data was used for applying offline filters.

It was possible to consider the brain activation’s sensitivity to semantic information only from the responses to the last words, where congruent and incongruent stimuli became contrasted. Hence, only the data from the last (third) words were used for the analysis. Epochs were created for the responses to these last words. They were created separately for congruent and incongruent stimuli. The time frame for each epoch was -0.200 s to 1.00 s. Epochs with bigger amplitude than the following thresholds were excluded from the analysis: for gradiometers the threshold was 3000.00 FT/cm and for magnetometers 4000.00 FT/cm. A script was used to select desired channels of all the available ones. The greatest interest was directed to sensors over temporal lobes, where the N400 is most robust, so the channels of the right and left temporal lobe were selected for further analysis. After this, the processing of the data from selected channels continued with Excel 2016 program. Each gradiometer pair's vector sum was calculated. An average of the vector sums was calculated for each participant, separately for left and right hemispheres, and for congruent and incongruent stimuli.

After this, analysis continued by calculating the average and maximum amplitudes of the N400 for each participant, separately for congruent and incongruent stimuli and for left and right temporal areas. These variables were used to examine the existence of a N400 response in the word list -task. To examine the semantic effect created by the congruent versus incongruent property of the item, the difference in the amplitudes for congruent versus incongruent stimuli was calculated. This N400 effect was used for analysing the correlation between creativity and semantic processing. Hence, for later analysis there was three types of MEG variables: mean amplitudes, maximum amplitudes, and the semantic effect represented by the difference between congruent and incongruent amplitudes.

For visualisation, an average across all participants was calculated (figures 3 and 4). The average waveform was used to specify a narrower time window of the N400 response (as the time window of the epochs was quite wide, from -200 ms to 1000 ms). Figure 3 shows the average responses in the left hemisphere. First, early sensory reaction can be seen, and then the N400 response starts around 200 ms after the stimulus onset, peaks at 400 ms and ends around 600 ms. For congruent stimuli the N400 response was not as clear, but same specified time windows were used. Figure 4 shows the responses in the right hemisphere.

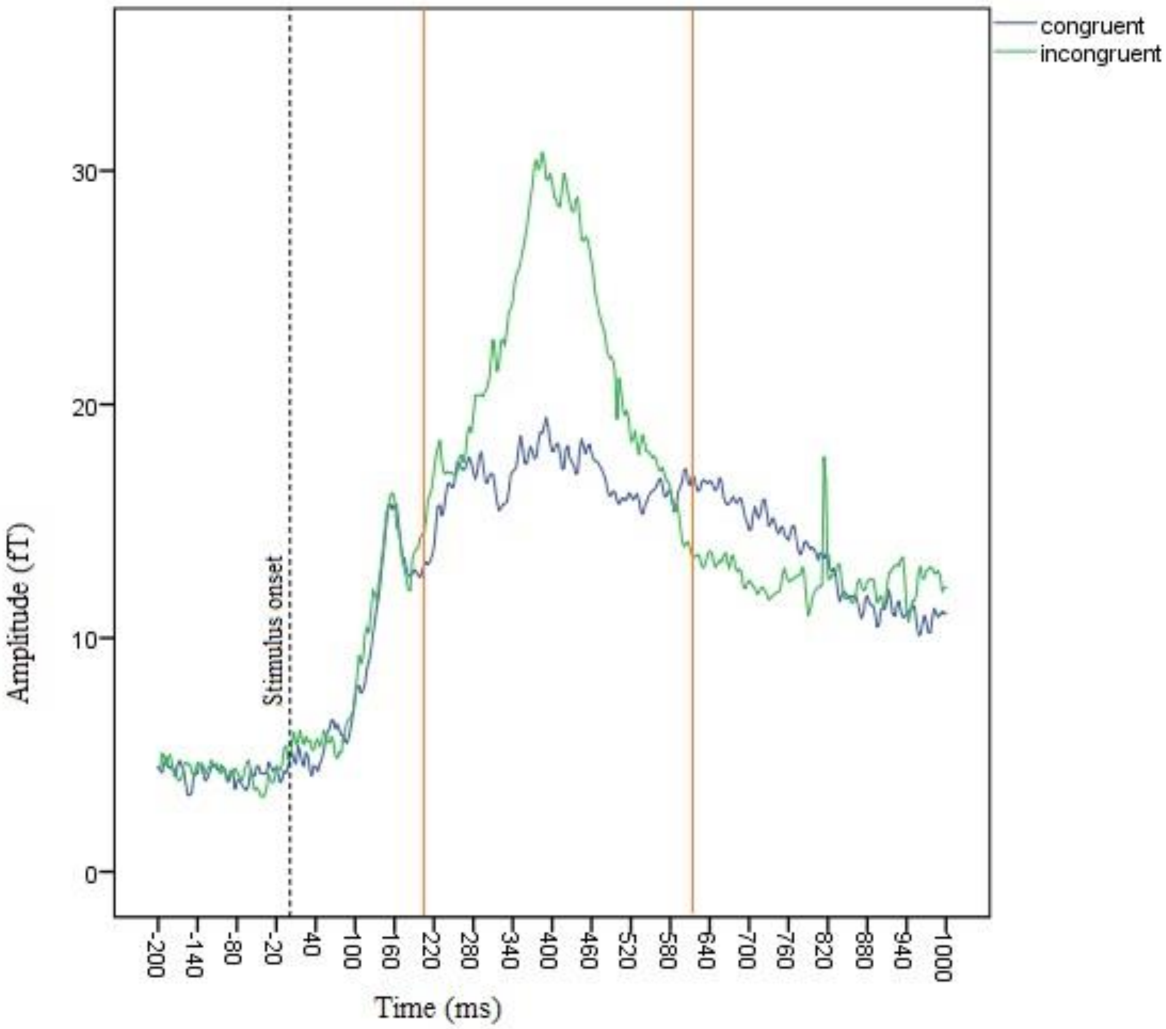

FIGURE 3. MEG-data from the left hemispheres (averaged across all participants) shows the N400 response for congruent and incongruent stimuli. Orange lines show the specified time-window used for analysis.

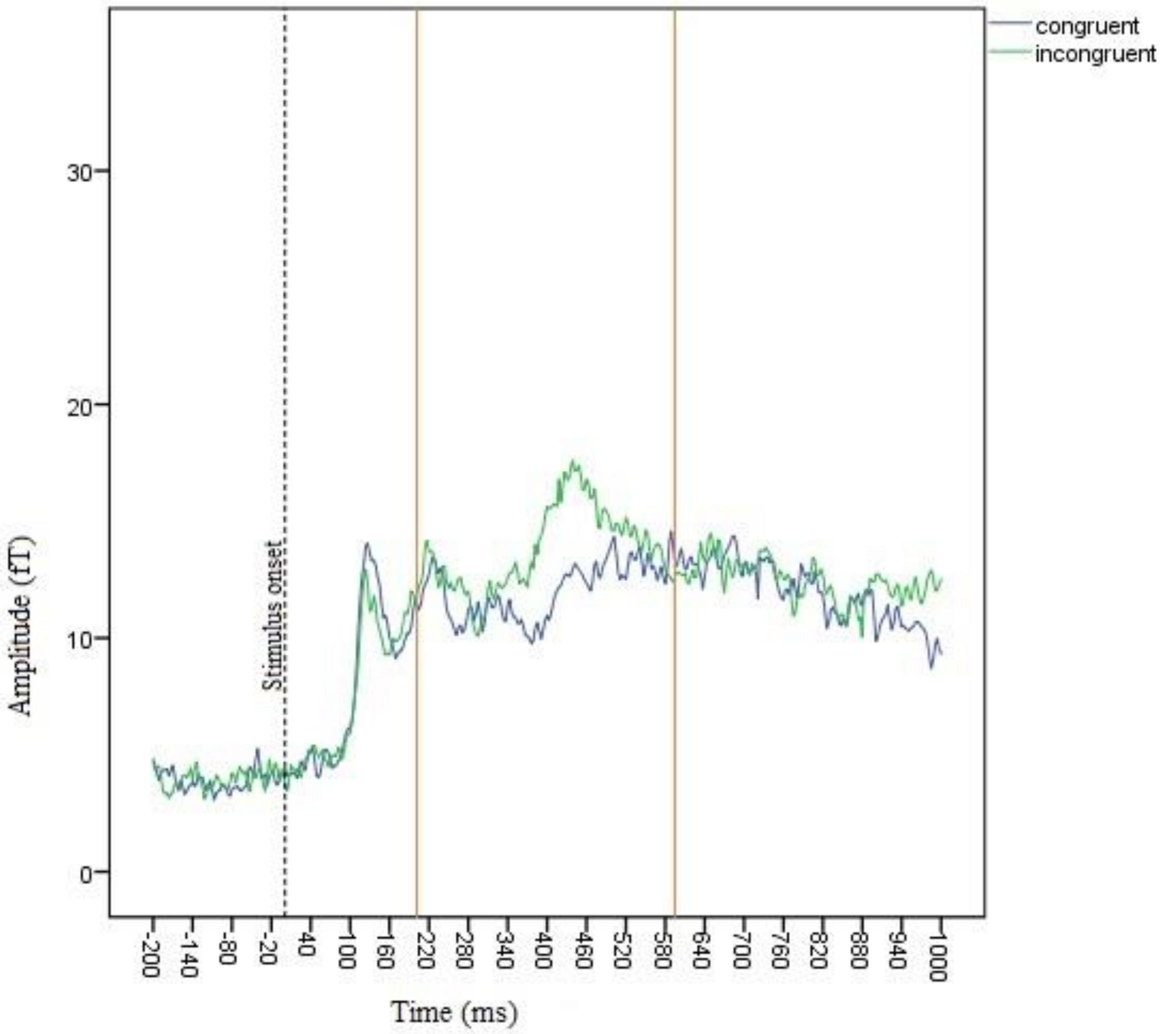

FIGURE 4. Responses to congruent and incongruent stimuli in the right hemisphere. Orange lines show the specified time-window used for analysis.

Statistical analysis

Analysing data continued in IBM SPSS program. Existence of a N400 response to the last words of the lists was determined with Wilcoxon signed rank test. This non-parametric test was chosen because the data did not meet the assumption of normality acquired for parametric tests. The test measured the differences in average amplitudes of responses to congruent versus incongruent stimuli. Another Wilcoxon test was done to examine the differences in the N400 response in left and right hemispheres. These sets of tests (congruent versus incongruent and left versus right hemisphere) were first done with the mean amplitude to the last words of the lists, and then with maximum amplitudes.

Next, the correlations of the semantic effect (difference between responses to incongruent and congruent stimuli) and the participants' creativity was studied. To study the correlation between semantic effect and cognitive and creativity scores, Spearman's correlation was calculated. Correlation was calculated between semantic effect and K-DOCS, DFT, WAIS, and the hobby questionnaire. Outliers were detected visually from scatter plots, and then the effect of excluding the outliers was examined. Finally, Spearman's correlations were calculated for correlations between different creativity and cognitive skill measures in order to consider these possible correlations in the interpretation of the results.

RESULTS

The results concern 1. the sensitivity of brain activation to semantic information in left and right hemispheres during the word-list task, and 2. The correlation of individual creativity and general cognitive skill level with the semantic activation in the brain.

The brain activation to semantic information

The MEG measurements presented an existence of a normal N400 response. The amplitude of the N400 was greater for incongruent than for congruent words, showing that the brain activation was sensitive to the semantic information. Figures 3 and 4 (see methods) present the averaged responses in left and right hemispheres. The N400 response started approximately 200 ms after the appearance of the stimulus and peaked at approximately 400 ms. The response was seen more clearly in the left hemisphere.

The N400 effect (i.e. the difference in amplitudes between responses to congruent versus incongruent stimuli) and the hemispheric differences were further examined with Wilcoxon's signed rank test. The test was done for both mean and maximum amplitudes. Table 1 shows the Wilcoxon ranks for mean amplitude data. There was a significant ($p < 0.05$) difference between the congruent and incongruent final words, but only in the left hemisphere. All the ranks between incongruent and congruent stimuli were negative, meaning that the responses to incongruent stimuli are bigger than to congruent stimuli (mean rank = 4.50, $p = 0.012$) – which indicates the existence of an N400 effect. In the right hemisphere there was no significant difference ($p = 0.208$). Comparisons between hemispheres showed that the response in the right hemisphere was generally smaller (mean rank = 5.0, $p = 0.017$) than the response in the left hemisphere (negative ranks).

Same set of tests was done for maximum amplitudes. The results are shown in table 2. The results show similar outcome as the average data. Responses to incongruent stimuli are significantly greater than to congruent stimuli in the left hemisphere (mean rank = 4.5, $p = 0.012$). In the right hemisphere there was no significant difference ($p = 0,779$). The responses were significantly smaller in the right hemisphere for incongruent stimuli (mean rank = 4.5, $p = 0.012$).

TABLE 1. Ranks of the Wilcoxon’s signed rank test for mean amplitude of the N400.

		N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Congruent vs. incongruent Left hemisphere	Negative Ranks (cong<incong)	8	4.50	36.00	-2.521	0.012
	Positive Ranks (cong>incong)	0	0	0		
	Ties	0				
	Total	8				
Congruent vs. incongruent Right hemisphere	Negative Ranks	5	5.40	27.00	-1.260	0.208
	Positive Ranks	3	3.00	9.00		
	Ties	0				
	Total	8				
Right vs. Left hemisphere	Negative Ranks (right<left)	7	5.00	35.00	-2.380	0.017
Incongruent stimuli	Positive Ranks (left<right)	1	1.00	1.00		
	Ties	0				
	Total	8				
Right vs. Left hemisphere	Negative Ranks	6	5.33	32.00	-1.960	0.050
Congruent stimuli	Positive Ranks	2	2.00	4.00		
	Ties	0				
	Total	8				

TABLE 2. Ranks of the Wilcoxon’s signed rank test for maximum amplitudes of the N400.

		N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Congruent vs. incongruent Left hemisphere	Negative Ranks (cong<incong)	8	4.50	36.00	-2.521	0.012
	Positive Ranks (cong>incong)	0	0	0		
	Ties	0				
	Total	8				
Congruent vs. incongruent Right hemisphere	Negative Ranks	3	5.33	16.00	-0.280	0.779
	Positive Ranks	5	4.00	20.00		
	Ties	0				
	Total	8				
Right vs. Left hemisphere	Negative Ranks (right<left)	8	4.50	36.00	-2.521	0.012
Incongruent stimuli	Positive Ranks (left<right)	0	0	.0		
	Ties	0				
	Total	8				
Right vs. Left hemisphere	Negative Ranks	5	4.60	23.00	-0.700	0.484
Congruent stimuli	Positive Ranks	3	4.33	13.00		
	Ties	0				
	Total	8				

Correlation between semantic effect and cognitive and creativity scores

Table 3 shows all significant correlations between semantic effect and cognitive and creativity scores. Numbers in brackets present the correlations when outliers were excluded. In the left hemisphere, two factors had statistically significant ($p < 0.05$) correlation with the magnitude of the N400 effect: the average score of the K-DOCS ($p = 0.009$), and the score of domain three (performance-related creativity, including music and writing) of the K-DOCS ($p = 0.047$). The correlations were positive, meaning that the higher the test score, the bigger the semantic effect.

In the right hemisphere there were three significant correlations, all of which were positive: hobbies related to music production ($p = 0.005$), the fixed condition of Design Fluency Test ($p = 0.015$), and the working memory test from WAIS ($p = 0.027$). As the hobbies related to music - variable is nominal (the participants answered either "no hobbies" or "one or more hobbies"), it's not appropriate to examine the correlation, but it is examined here as a descriptive variable.

TABLE 3. Spearman Correlation coefficients and p-values of the significant correlations. Numbers in brackets show the results when outliers were excluded.

Left hemisphere semantic effect	**Average creativity**	0.838 p = 0.009	(0.757) (p = 0.049)
	Performance-related creativity	0.714 p = 0.047	(0.786) (p = 0.036)
Right hemisphere semantic effect	**Hobbies related to music production**	0.873 p = 0.005	
	Design Fluency Test (fixed condition)	0.807 p = 0.015	(0.709) (p = 0.074)
	WAIS (digit span)	0.766 p = 0.027	

Outliers were detected visually, and their effect was examined for correlations of performance-related creativity, average creativity, and Design Fluency Test. The results are shown in table 3 in brackets. Correlations of performance-related and average creativity stayed significant after the exclusion of outliers, but for Design Fluency Test the correlation was not significant anymore. To visualise the significant correlations, scatter plots were drawn for each pair. Figures 5-9 illustrate the relationships between semantic effect and scores in creativity and cognitive measures.

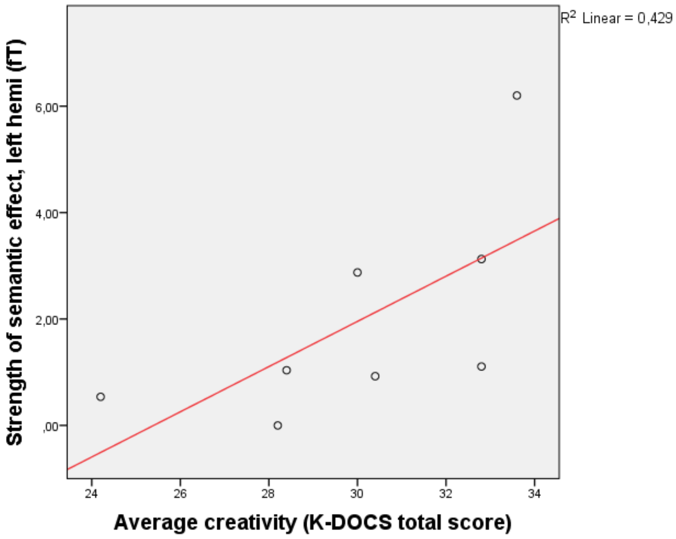

FIGURE 5. Scatter plot of average self-reported creativity and N400 effect in the left hemisphere.

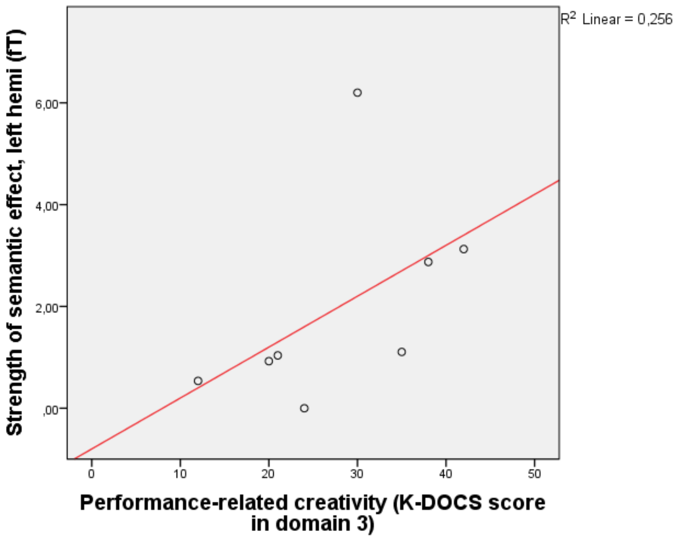

FIGURE 6. Scatter plot of self-reported creativity related to performance (including writing and music) and N400 effect in the left hemisphere.

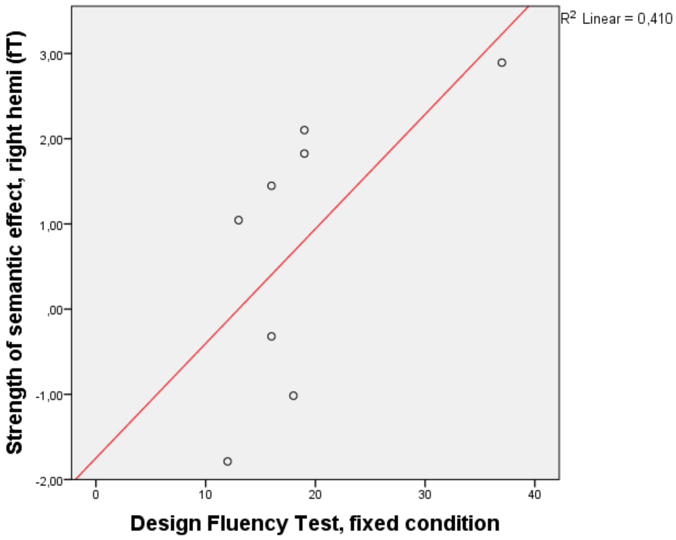

FIGURE 7. Scatter plot of design fluency score and N400 effect in the right hemisphere.

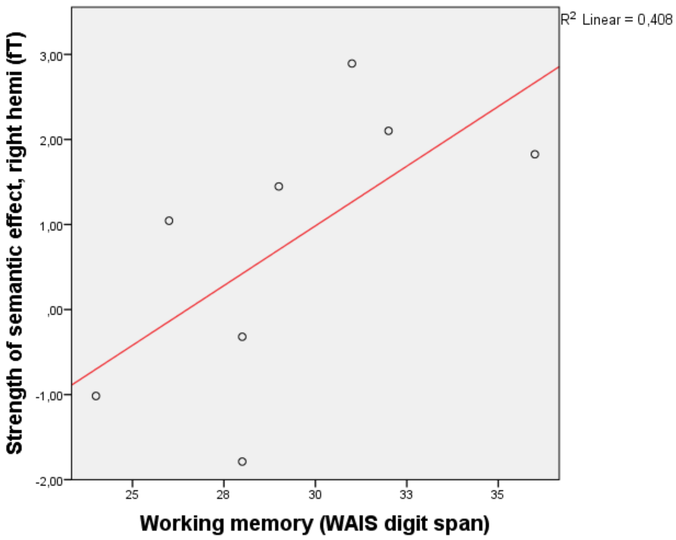

FIGURE 8. Scatter plot of WAIS working memory test score and N400 effect in the right hemisphere.

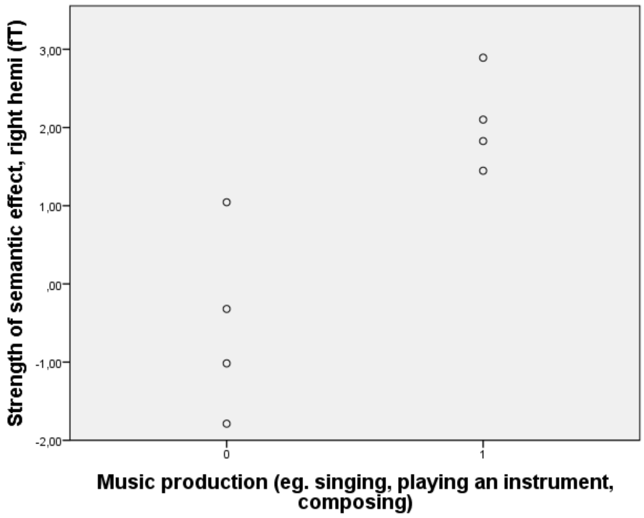

FIGURE 9. Scatter plot of hobbies related to music production and N400 effect in the right hemisphere. (0= Does not have a hobby in this field, 1= Has at least one hobby in this field)

In order to consider the effect of correlations between cognitive skill scores and creativity measures, these correlations were examined with Spearman's correlation. Table 4 presents the significant correlations between the different measures. Hobbies related to music production correlated to performance-related creativity ($p = 0.027$), working memory ($p = 0.004$), and Design Fluency Test fixed condition scores ($p = 0.045$). Amount of different creative hobbies correlated to average creativity ($p = 0.013$) and block design ($p = 0.005$). Self/everyday creativity (K-DOCS domain 1) correlated to working memory ($p = 0.038$) and vocabulary ($p = 0.026$), while scholarly creativity correlated to average creativity ($p = 0.002$) and block design ($p = 0.031$). Average creativity correlated to block design as well ($p = 0.015$).

TABLE 4. Correlations of creativity and cognitive skill measures

	Spearman's correlation coefficient	Sig. (2-tailed)
Hobbies related to music production x Performance-related creativity	0.764	0.027
Hobbies related to music production x Working memory	0.878	0.004
Hobbies related to music production x DFT fixed condition	0.718	0.045
Amount of creative hobbies x Average creativity	0.820	0.013
Amount of creative hobbies x WAIS block design	0.872	0.005
Self/everyday creativity x Working memory	0.733	0.038
Self/everyday creativity x Vocabulary	0.770	0.026
Scholarly creativity x Average creativity	0.898	0.002
Scholarly creativity x WAIS block design	0.755	0.031
Average creativity x WAIS block design	0.807	0.015

DISCUSSION

The present study examined possible links between creativity and semantic processing in the brain, indicated by the N400 event-related potential. The proposed hypothesis was that creativity makes association easier, and hence makes semantic categorisation more effortless. This was hypothesised to manifest as a smaller semantic N400 effect, since the N400 is seen to reflect the brain's effort to process information. Brain activation was measured using magnetoencephalography during a three-word list task. Creativity and cognitive skills were assessed with tests and self-evaluated questionnaires. Results showed that the presented stimuli managed to create an N400 effect; in other words, a greater N400 amplitude was seen for incongruent than for congruent stimuli. Self-assessed creativity correlated with the magnitude of semantic effect in the left hemisphere. Hobbies related to music production, Design Fluency Test scores and working memory scores correlated with the magnitude of semantic effect in the right hemisphere. Contrary to the hypothesis, the correlations were positive, suggesting that semantic processing requires more effort for more creative people.

First part of the results presented the existence of a normal N400 response. The N400 amplitude was bigger for incongruent than for congruent words, showing that the brain activation was sensitive to the semantic information, and indicating that processing of incongruent semantic content requires more effort. The response started approximately 200 ms after the appearance of the stimulus and peaked at approximately 400 ms. The response was seen more clearly in the left hemisphere, and it has been previously stated that the N400 activation is probably stronger in the left hemisphere (Kutas & Federmeier, 2011, p. 629). These results were congruent with previous research by the timing and nature of the response (Kutas & Federmeier, 2011). It has been demonstrated that the N400 amplitude is highly correlated with the eliciting word's expectancy (Kutas & Federmeier, 2011). Lotze and colleagues (2011) have proposed that the N400 reflects the degree of matching between top-down and bottom-up processes, so that a mismatch causes a higher N400 amplitude. In priming paradigms, similar to this study, it has been observed that related items show reduced N400 amplitudes relative to unrelated items. The amplitude of the N400 becomes smaller when the presented information is more expected, regardless of the input modality. Thus, the N400 reflects expectancy at a conceptual level and indexes something fundamental about semantic processing (Kröger et al., 2013; Kutas & Federmeier, 2011).

The results from N400 investigations can be interpreted as indicating that when information is more expected, it becomes easier to process, and that is why the N400 response becomes smaller (Kutas & Federmeier, 2011). It has been assumed that the amplitude of the N400 response increases as a function of the memory requirements necessary for accomplishing the task (Federmeier, McLennan, Ochoa & Kutas, 2002), as the memory requirements grow when the presented information is unexpected. Elmer and colleagues (2014) revealed dampened N400 responses in musicians in their study of the effect of speech and music expertise on categorisation of sounds, and also interpreted these results as representing a reduced cognitive load during the categorisation task. Previous studies have shown that reduced N400 responses are linked to a less demanding engagement of working memory resources and semantic processes. In line with these findings and interpretations, the hypothesis in the present study was that more creative people would find the presented information easier to processes, and hence have smaller N400 effect to the last words of the lists. However, it is also possible that more creative people actually require more effort in semantic processing. Kenett, Anaki & Faust (2014) have proposed that the semantic network of creative people is larger. When a larger number of potentially relevant elements is present, the brain has to do more work in order to make associations, and hence more creative people exhibit a larger N400 effect. (Kenett et al., 2014.) This could explain the results of this study which showed that the creativity and cognitive skill measures correlated positively to the magnitude of the semantic effect.

The second research question of this study asked whether individual creativity or cognitive skills have correlation to the N400 effect (the semantic effect; i.e. the difference between the responses to congruent versus incongruent stimuli). It was found that working memory, average and performance-related creativity, music-related hobbies and Design Fluency Test scores correlated with the semantic effect.

Self-assessed creativity had a positive correlation with the N400 effect in the left hemisphere. This included both the average creativity score and the score in performance-related creativity domain. However, the correlation was opposite to what was assumed; the higher the creativity score, the bigger the semantic effect. The performance-related domain included creativity related to writing and music. Interestingly, hobbies related to music production also had a positive correlation with the N400 effect, in the right hemisphere. Creative hobbies were assumed to reflect creativity in said field, and this assumption was supported by significant correlation between hobbies related to music and performance-related creativity. It does not seem surprising that experience in the field of music correlates with creativity in the same field. Palmiero, Guariglia, Crivello & Piccardi (2020) have found that expertise in music links to higher measured creativity in musical, but also verbal creativity tasks. However, in addition to the correlation between field specific experience and creativity, the results of this study indicate that musical experience has some connection with semantic processing, as does subjective performance-related creativity. The relationship between music and different cognitive processes has been studied plenty. According to Fritz and colleagues (2019), the underlying semantic processing of music and words is similar. So perhaps it is possible that musical experience through hobbies has an influence on the semantic processing of words. Music training has been observed to positively influence different aspects of speech perception and cognitive functions (Asaridou & McQueen, 2013; Besson, Chobert & Marie, 2011; Dittinger et al., 2016). According to Dittinger and colleagues (2016), music training influences semantic aspects of language processing. Musicians in their study learned semantic meanings of new words quicker than non-musicians, and were able to recall the meanings better after five months. Musician's N400 response to new words left lateralised and grew while learning the words, unlike the N400 response of non-musicians. This was interpreted to indicate faster encoding of novel word meaning. According to Beaty, Benedek, Silvia & Schacter (2015), both artistic performance and creative cognition require cooperation of default and semantic networks. The connecting factor might be the goal-directedness of the action. Carey and colleagues (2015) investigated whether musical skills generalise to other cognitive skills. The results were not completely conclusive, but at least the expert musicians outdid non-musicians in auditory processing skills. A study by Elmer and colleagues (2014) provided evidence for a distinctive influence of speech and music expertise on task-related processing modes, and that it may influence the cognitive representations of speech and musical items.

Other domains of the subjective creativity questionnaire (self/everyday, scholarly, mechanical, and artistic) did not correlate significantly with the N400 effect. It is possible that the translation of the test had some impact on the scores. Other types of creative hobbies included in the hobbies questionnaire (writing, art production, and performative arts), or the amount of hobbies did not correlate with the semantic effect either. Could this point to musical experience or musical creativity having some distinct effect on semantic processing? On the other hand, as the number of participants was small, there was only a few people who had art or performance related hobbies, so such claim cannot be made with this material. The durations of the hobby also had no correlation with the N400, which seems peculiar. However, this can also be the result of the small amount of material. There was some variance in the length of the hobby, but the majority of participants were concentrated on the top two categories (having seven or more years of experience with the hobby).

Working memory (measured with WAIS digit span) was positively correlated with the N400 effect in the right hemisphere. The influence of working memory is easy to understand in context of the experimental procedure. The participants had to keep in mind the first two words of the lists (without seeing them) for several seconds. Additionally, the test procedure was long and might affect the ability to focus, although the task to perform was quite easy. But does the N400 require focus or attention? There has been a long standing debate concerning whether the N400 is a controlled process (requires attention) or an automatic process (proceeds without attention or awareness), but the evidence has led to the conclusion that it is controlled, or at least requires that attention is directed to the stimuli (Kutas & Federmeier, 2011, p. 630).

Why does a better working memory correlate with stronger semantic effect? It might be that this connection reflects a general cognitive skill level that could also help to explain the connection between creativity and semantic effect. According to Heilman (2016), a sufficient level of cognitive skills is required for creativity, but the precise relationship between cognitive skill level and creativity remains debated. However, the other cognitive skills tested in this study (vocabulary and block design) did not correlate with the semantic effect. The connection of working memory and the N400 magnitude in this study resulted from a higher N400 response to incongruent words (not from a lower response to congruent ones). This result could support the interpretation that a stronger response reflects the effort that more creative people have to make in order to select an association from a larger network of words. It is noteworthy that cognitive skills and self-assessed creativity correlated significantly. There is a possibility that the working memory and creativity measures partly reflect the same issue, since creativity is known to require working memory (Kenett et al., 2014).

The fixed condition of Design Fluency Test (DFT) had a positive correlation to the N400 effect in the right hemisphere. Previous research shows that patients who have lesions in right frontal and fronto-central lobes are most impaired in DFT: the right hemisphere is critical in this task. Inability in the task lies both in an impoverished novel output and high perseveration. (Jones-Gotman & Milner, 1977.) Performance in the test is relatively stable over one-month retest (Harter, Harter & Hart, 1999. p. 419). Depressive disorder groups are noticed to produce the highest number of novel designs. Depression may increase creativity by decreased noradrenaline production (Heilman, 2016, p. 288-293). DFT has been criticised for overly vague scoring procedure and lack of psychometric data. Individual differences in approach to the task make it difficult to interpret results. However, the unstructured nature of DFT increases the initiation and organisation required from the participant. As expected, interrater reliabilities are higher than test-retest reliabilities. It is notable that according to previous findings, college students have the highest average complexity of designs, which of course limits the number of designs they can produce within the time limit. (Harter, Harter & Hart, 1999, p. 430.) All participants in this study were university students. According to previous studies, the conditions of DFT are correlated with each other despite of the different task structures; this relationship may reflect the similarities among the tasks, the demand to generate unique designs, which is a rather novel requirement in psychological testing. The DFT appears to capture cognitive flexibility or the capacity for divergent thinking. The task places novel and unusual demands on participants. (Demakis & Harrison, 1997.) In this study, the only creativity measure that the DFT scores correlated with was music-related hobbies.

The hypothesis of this study was based on Mednick's theory about associative creativity, which states that more creative people associate concepts with more ease. The assumption was that higher scores in creativity would correlate with a smaller raise in N400 amplitude to incongruent versus congruent stimuli, ergo a smaller semantic effect. However, the results pointed to the opposite. Why were the correlations between creativity measures and N400 effect positive? As proposed earlier, one theory to explain this is that more creative people possess a larger semantic network, and therefore require more effort when making associations (Kenett et al., 2014.) Previous studies have shown increased N400 responses in speech experts (Elmer, Meyer & Jäncke, 2010; Elmer et al., 2014). One study demonstrated that a better performance in conceptual association task by absolute pitch musicians was achieved through an increased memory load, reflected by enhanced N400 magnitudes (Elmer, Sollberger, Meyer & Jäncke, 2013). It might be possible that participants who showed greater N400 effect (with musical experience, creativity or good working memory), engaged their cognitive resources more strongly.

Marupaka, Iyer & Minai (2012) argue that the difference between creative and mundane thinking arises from the organization of knowledge within the brain. Conceptual combinations arise in the minds of individuals, and hence they must depend in some way on the way these minds organize information. Since it is presumed that ideas arise associatively, the key issue is the structure of associations between mental representations of concepts. Associations are born as the result of experiences. They are encoded in the brain through the long-term modification of synapses between neurons involved in the representation of different concepts. (Marupaka et al., 2012.) However, there is no clear agreement about general principles governing the large-scale structure of semantic memory, or how that structure interacts with memory search processes (Steyvers & Tenenbaum, 2005). How are semantic networks constructed? A variety of different models and theories have been developed, but one widely studied and consolidated is the class of small-world network. Small-world networks are characterised by a high clustering coefficient and a low mean shortest path length. In other words, nodes in small-world networks tend to cluster together and most nodes can be reached from every other node by a small number of steps. It has also been suggested that small-world connectivity in the brain may underlie high creativity in individuals. (Marupaka et al., 2012.)

Steyvers and Tenenbaum (2005) proposed a model where a network, when acquiring new concepts, connects them to a portion of concepts within an existing group, and is likely to choose a specific neighbourhood comparable to its size. The semantic networks they studied shared the statistical features of small-world and scale-free structures: high degree of sparsity, one connected component containing the majority of nodes, short average distances between nodes, high local clustering, and power law degree distribution (a heavy-tailed distribution where the tail is not exponentially bounded; also known as scale-free distribution). Kenett, Kenett, Ben-Jacob & Faust (2011) revealed small-world network features of the Hebrew lexicon, specifically a high clustering coefficient and a scale-free (ergo power law) distribution. Their analysis revealed that balanced dynamics of a network are mainly conducted by a small amount of strong influence nodes (influencing other nodes but not being influenced by any other nodes), and by a relatively grand amount of receiver nodes (that are only influenced by others but do not influence any node). They suggest that the small-world network properties of the Hebrew lexicon, combined with the small world theory of insight, can explain the search processes undertaken in semantic associativity tasks. According to Marupaka and colleagues (2012), many semantic networks have been found to be both scale-free and small-world. They investigated computational models for associative search in semantic neural networks, with five different types of connectivity: random, localised, small-world, scale-free and Steyvers-Tenenbaum (both small-world and scale-free). The random network was most efficient, producing only few ideas but almost all of them unique. However, there was a tendency towards low coherence, which can be seen as bordering on absurdity. In other words, the random network was creative but nonsensical. The small-world network was not very efficient (a great number of ideas, but a large fraction of them were repeated), but produced ideas with a moderate degree of coherence, which can be regarded as sensible but novel, in other words creative. Steyvers-Tenenbaum network also presented a healthy range between creativity and conventionality, and furthermore, it was efficient. The localised network appeared to be inefficient and conventional to the point of obsessive fixation. Scale-free network showed a pattern was a mixture of creative-nonsensical and conventional-fixated. In conclusion, networks that have both small-world features and power law (scale-free) distribution provide the best search performance in associative tasks, small-world connectivity ensuring coherence and power law ensuring efficiency.

Kenett and colleagues (2014) state that semantic networks of semantically creative people may be different than that of less creative people. It is typical for creative thought processes, that memory is searched more widely and in a less-defined manner than during mundane thinking. Thus, the larger the number of potentially relevant elements that are retrieved during processing, the higher the likelihood of generating unusual associations or solutions, and the larger is the pool of novel ideas from which to choose. It may be that more creative people have larger semantic networks, whereupon/therefore there is more potentially relevant items from which to choose. This could require more effort from the brain. (Kenett et al., 2014.) In addition, it has been assumed that the amplitude of the N400 response increases as a function of the memory requirements necessary for accomplishing the task (Federmeier et al., 2002). It could be theorised that when the scope of the semantic network is larger, the memory requirements of the search for associative items increase.

Hence, this could lead to people with high creativity and lager semantic networks producing greater N400 effect.

Mednick's (1962) theory proposes that more creative people have richer associative networks. His study states that creative people have flatter associative hierarchies, compared to steep hierarchies that concentrate on a small number of stereotyped associations. Hence, more creative individuals produce more and broader associations to given stimulus – maybe broader semantic network enables this? High creative individuals may be characterized by having a more complex lexicon network structure. According to this interpretation, the results of this study may be in line with Mednick's theory.

Limitations, implications, and future directions

First notable limitation of this study was the small number and homogeneity of the participants. The study was conducted with only eight participants, all of whom were university students of similar age and background, so they were not a representative sample of the population. To obtain more variance to the cognitive and creativity measures, more research is needed with a more versatile group of participants. Especially comparison between more and less creative groups would be beneficial, as well as groups of high and low cognitive skills. The analysis of this study did not include source modelling of the MEG signals, which would have given a more accurate locations of the signal. There were also some limitations related to the experimental design: the research project to which this study is connected to, included other measures and tests, not all relevant to the study - a more focused study on the connections of creativity and semantic processing in the brain is also needed. Future studies could also utilise a wider spectrum of creativity and cognitive skill measures. More detailed study of the connections between the various creativity measures would also be an interesting aspect to investigate. This study examined creativity as ease of association, but since the theories and types of creativity are various, future research could focus on different forms of creativity. In this study, the role of musical creativity stood out; self-evaluated performative creativity and musical hobbies correlated with the semantic effect. The background of this connection needs more research. The MEG measurement task was fairly simple, and it would be beneficial to do similar testing with different forms of associative/semantic tasks. Previous studies of similar subjects have widely used free association task, but in the present study the participants faced a different kind of assignment, having to decide whether a stimulus word was congruent with previous ones or not. To unveil the possible effect of different task structures, comparative research of the task methods is needed.

This study provided some new information about the connection of creativity and semantic processing, but the underlying cause was left unexplained. Perhaps the biggest suggestion for future study is to clarify the theory of how these two are linked. This study suggests that higher creativity is linked to greater effort of semantic processing in the brain. A possible explanation could be the size of the individual's semantic network – the larger the network, the more effort it takes to go through it. More research is needed to examine the effect of the size of the semantic network to associative creativity and semantic processing, and the connection of the two. It is good to note that the previous studies addressed here have not investigated the size of the semantic network, and present study did not examine it either. More study is needed of the subject.

This research provided new insights about the relationship of creativity and semantic processing, suggesting that, on brain level, more creative people require more effort in semantic processing. Future research can build upon these findings and questions and help to clarify the apprehension of the structures of creativity and processing of meanings. Understanding these processes is a valuable objective, since both semantic processing and creativity are abilities that are fundamental to humans (Dietrich & Kanso, 2010; Lindell, 2010). Creative thinking creates a foundation for many important cognitive functions (Benedek et al., 2018). The processes and components of creativity have long been considered mystical and un-researchable, and the neural mechanisms of creativity are poorly understood (Dietrich & Kanso, 2010; Kenett et al., 2014), but now the time has come to examine the creative abilities like any other cognitive process. More research is needed about the factors that make creativity possible, and how it links to other abilities such as association and semantic processing.

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ANNEX

The hobbies questionnaire

16. Onko sinulla jokin harrastus/harrastuksia, joissa pääset käyttämään luovuutta?

- ☐ Kirjoittaminen (esim. runot, novellit, päiväkirja)
- ☐ Musiikin tuottaminen (esim. laulaminen, soittaminen, säveltäminen)
- ☐ Taiteen tuottaminen (esim. maalaus, valokuvaaminen)
- ☐ Esittävä taide (esim. näytteleminen, tanssi)
- ☐ Muu, mikä? ________

17. Kuinka kauan olet toiminut kyseisen harrastuksen parissa? (Jos useita harrastuksia, ajattele pisimpään jatkunutta)

- ○ Vuoden tai alle
- ○ 2-3 vuotta
- ○ 4-7 vuotta
- ○ 7-10 vuotta
- ○ Yli 10 vuotta