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Neural correlates of creative thinking: Conceptual expansion processing

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List of Abbreviations

ACC	Anterior Cingulate Cortex
ANOVA	Analysis of Variance
AUT	Alternate Uses Task
BA	Brodmann area
EEG	Electroencephalography
ERP	Event-related potential
fMRI	Functional magnetic resonance imaging
HULA	High unusual, low appropriate
HUHA	High unusual, high appropriate
IFG	Inferior frontal gyrus
LUHA	Low unusual, high appropriate
PFC	Prefrontal Cortex
RAT	Remote association test
ROI	Region of Interest
TOP	Temporal, Occipital, Parietal

Abstract

In contemporary scientific discourse, creative thinking is seen as arising from a medley of normative cognitive processes that are not exclusive to highly creative people.

Following this modern continuum-based view, one functional magnetic resonance imaging (fMRI) study and one event-related potential (ERP) study, implementing a novel task design, were carried out to investigate the neural correlates of conceptual expansion, acritical facet of creative thinking. Conceptual expansion is one of the core processes in the invention of creative ideas and describes the ability to widen the boundaries of existing semantic concepts beyond conventional limits. The new task design used a modified version of the alternate uses task and required subjects to rate a given object and a described use for this object into one of three possible categories: High-unusual and low-appropriate (nonsense), low-unusual and high-appropriate (common), and high-unusual and high-appropriate (creative). Brain activation during trials rated as high-unusual and high-appropriate (creative) reflected conceptual expansion processing and were contrasted with trials reflecting pure novelty processing (nonsense object-use combinations) or appropriateness processing (creative and common uses)

As hypothesized, the fMRI results showed conceptual expansion related activation in a semantic and conceptual integration network comprising the frontopolar cortex, anterior inferior frontal gyrus, anterior cingulate cortex and the temporal poles.

The ERP study investigated whether conceptual expansion related activation could be observed in the N400-time window. Results showed a post-N400 effect, differentiating conceptual expansion specific processing from the processing of mere novelty or appropriateness, implicating semantic integration brain mechanisms.

Both studies together led to the uncovering of relevant brain networks and cerebral time flow of conceptual expansion processing. These studies illustrate a new and viable approach by which to investigate predefined facets of creative thinking using neuroscientific methods, which allowed for more consistent and specific results to surface compared to prior creativity research.

1 General Introduction

Creativity is one of the most fascinating human cognitive abilities. It is the foundation that enables the emergence of innovative power and cultural progress of human societies.

The creativity concept has undergone a long history of development starting with the earliest mystical concepts about geniuses being vessels of the divine spirit, to the beginning of separation of the genius from the supernatural in the Renaissance, to Galton´s first attempts to measure individual differences using empirical methods. But it was not until Joy Paul Guilford´s APA Presidential Address (Guilford, 1950) that the research focus slowly shifted away from the investigation of extraordinarily gifted people with remarkable social achievements to the investigation of creative thinking in ordinary individuals (Albert & Runco, 1999). Different research approaches were developed to get a grasp on this topic, each with its own advantages and disadvantages. However, despite being a fascinating ability, creativity often did not receive the same attention as other constructs like intelligence or memory, for example. Although Guilford managed to greatly strengthen this research area, it nonetheless remained a marginal research topic in psychology (Guilford, 1950).

1.1 Creativity - Conceptualization

One of the reasons for this lack of research impetus was likely the immense complexity of the topic, which is evidenced by the fact that one can investigate creativity from many different perspectives (Rhodes, 1961). It is possible to examine the factors that define a person or a product to be creative, the process of being creative, the neurophysiological correlates of creative thinking, or, for example, environmental factors such as the sociocultural context in which creativity takes place. The fact that many researchers look from many different angles on creativity tells us that the construct is heterogeneous and complex.

This leads to another problem, that such a construct is easily confounded with other factors. For example, the fine arts are sometimes regarded as the home of creative production and many artists are widely admired and eventually become historical prominent persons. It is the field of arts from which creativity got most of its mystical and fascinating glamour. But a stricter consideration could come to the conclusion that art has much more to do with extraordinary skill rather than originality or creative thinking (Abraham, 2012). A pianist for example shines through because of his remarkable piano skills. Proficiency is the basis for being an artist.

Another example is the historical confounding of creativity with intelligence. Joy Paul Guilford stated “Some of you will undoubtedly feel that the subject of creative genius has not been as badly neglected as I have indicated, because of the common belief that genius is largely a matter of intelligence and the IQ” (Guilford, 1950). Creativity and intelligence are often positive correlated and a threshold-effect stating that creativity and intelligence are positive correlated only to the extent of normal levels of intelligence has been discussed in detail (Benedek et al., 2014). A good example for the obvious possibility of a confound between creativity and intelligence is the domain of problem solving. Certain solutions to problems are regarded as a new and appropriate, and they are therefore classified as creative. But it is hard to imagine that the process of problem solving has nothing to do with intelligence, regardless of whether the solution calls for creativity or not.

Given such difficulties one could be led to believe that creativity cannot exactly be defined. Nonetheless, over the course of several decades, the research community has agreed upon a product based working definition of creativity. This definition states that a creative product has to be novel and appropriate (Runco & Jaeger, 2012; Stein, 1953). Many different words are exchangeably used for the two defining characteristics of creative products in the literature, such as original, statistically rare, unique or new instead of novel, or significant, utilizable, applicable, relevant or fitting instead of appropriate.

Despite this seemingly straightforward definition, different research approaches such as the psychometric approach, the neuroscientific approach or the biographical approach (Mayer, 1999), and different methodologies adopted within each of these approaches has resulted in a myriad of findings, which often seem unlinked and are challenging to integrate into a common theoretical framework (Abraham, 2013a).

The emergence of newer neuroscientific techniques like functional and structural neuroimaging has resulted in even more scattered and unclear results over the past

15 years. Difficulties in examining creativity in an artificial and unspontaneous laboratory environment certainly contribute to this high diversity of results.

The current doctoral project focused on a specific cognitive process that is called upon during creative thinking. In doing so, creative cognition approach (Finke et al., 1992; Smith et al., 1995) using two different neuroscientific methods (functional magnetic resonance imaging and electroencephalography) was employed. The following sections will give an overview of the most prominent cognitive theories, cognitive processes and neuroscientific findings related to creative thinking, as well as a short introduction to these neuroscientific techniques.

1.2 Cognitive Theories - From past to present

J.P Guilford´s work on creativity and especially his APA Presidential Address were a turning point in the history of creativity research in multiple respects. He tackled many questions that are still discussed today and blazed a trail for the empirical investigation of individual differences regarding creative thinking. He argued for a separation of creativity from intelligence testing, conducted empirical investigations with ordinary people and formulated so called “primary abilities” that he assumed to underlie creative thinking. Based on these primary abilities he also argued for the existence of “different kinds of creative abilities”, specialized for different domains of creativity. As primary abilities he outlined the factors: “sensitivity to problems”, “fluency”, “flexibility”, “novelty”, “synthesizing”, “reorganization”, “complexity” and “evaluation” (Guilford, 1950). “Sensitivity to problems” enables people to realize discrepancies which can lead to new insights or solutions. “Fluency” describes the ability to produce a larger number of ideas, which enhances the chances of producing something creative. “Flexibility” means the ability to leave old thinking paths. “Novelty” stands for originality or uncommonness of ideas. “Synthesizing” is the “organizing of ideas into larger, more inclusive patterns”. “Reorganization” stands for example for the ability to transform an existing object into a new design. And finally, “evaluation” is necessary to decide which ideas are suitable.

Later, Guilford focused on his well-known “Structure-of-intellect-model” (SOI-model) to capture the intellectual abilities which are fundamental for creative thinking processes. The SOI-model consists of “contents”, “products” and “operations”.

Guilford argued that especially “divergent production” and the product called “transformation” were essential for creativity (Guilford, 1975). With “transformation” he described “any kind of change in an item of information” which provides us with flexibility. “Divergent production” became much more prominent in further research endeavours in relation to creativity and was later mostly referred to as “divergent thinking”. This term represents the retrieval of stored information through a broad search procedure. It is often used in situations in which several possible answers exist. Guilford described “divergent production” with “the generation of logical alternatives”. Logical because these alternatives are not meant to be inappropriate or irrational (Guilford, 1975). The concept of divergent thinking is very important for this doctoral thesis, as the alternate uses task (AUT), which was used in a modified version in the reported studies, in its original form is a divergent thinking task (Wallach & Kogan, 1965).

Another theory of creativity was proposed by Kris (1952) who postulated that creative people were better in switching between primary and secondary process cognition. Primary process thinking is characterized through free-association, imagery, alternate states of consciousness etc., whereas secondary process thinking comprises logical, analytical and conscious thinking. The primary process thinking mode was believed to facilitate the generation of possible creative products. In contrast, secondary process mode allowed for the analysis and verification of potentially creative results from primary process mode.

Sarnoff Mednick developed another influential framework regarding a domain-general interpretation of creative thinking in associative terms. He defined the creative thinking process as “the forming of associative elements into new combinations which either meet specified requirements or are in some way useful” (Mednick, 1962). He further described three ways to reach this new and useful combination of associative elements: “serendipity”, “similarity” and “mediation”. A creative solution to a problem would be one which combines two previously remotely connected elements to an appropriate result. As one important reason for individual differences in the production of creative solutions, Mednick´s theory assumes differences in the organization of associations. Accordingly, flat associative hierarchies will promote creative solutions due to access to more widely distributed associations, whereas steep hierarchies hinder the same because of fewer original associations being dominant. A demonstrative example could be taken from the remote association test (RAT) which was designed to measure individual differences in creativity. In this test, participants are given three words and their task is to find a fourth word which is strongly associated to all three other words. For example, the fourth word to be found for the given words “rat”, “blue” and “cottage” would be “cheese” (Mednick, 1962). Mednick´s theory fits well in later developed ideas about spreading activation type search processes in semantic networks (Collins & Loftus, 1975).

Mendelsohn (1976) developed this idea further but held that the well-established link between RAT scores and external criteria of creative performance was based on attentional processes and not associative organizations. He based his thesis on findings that the RAT performance could be improved by using instruction cues which narrowed down the possible search areas, such as ten solutions will be types of animals. These results were interpreted as an evidence for the importance of search strategies for higher performances while performing the RAT. Greater or broader internal attentional capacities would therefore allow for simultaneous search in memory storages and increase the chance of a new combination of remotely associated elements.

This parallel search was later described to take place in a state of “defocused attention” (Kaufman et al., 2010; Martindale, 1995; Martindale, 1999) which is thought to be reflected in lower levels of cortical activation. In this mental state a large number of elements of a neural network can be activated simultaneously, which increases the probability that connections between weakly related elements are strengthened. The idea of unconscious parallel search processes fits well with modern neurosc*i*entific views (Dietrich, 2004; Dijksterhuis & Meurs, 2006). Cognitive disinhibition is thought to facilitate creative thinking through the reduction of constraining effects (higher cortical activation levels). This relation is today however regarded as having a kind of inverted-U function, meaning that some degree of top down cognitive control is necessary to think creatively (Abraham, 2014b).

Dietrich (2004), following some of the aforementioned considerations, proposed in a newer theoretical framework that one should differentiate between two processing modes, the “deliberate mode” and the “spontaneous mode”, which can both lead to creative insights. The spontaneous mode is described as a mental state of reduced or altered attentional focus, parallel processing, free-associations, unguided and uncontrolled by prefrontal regions. Dreaming is regarded as the extreme form of the spontaneous mode. Its origin is assumed to be located in temporal, occipital and parietal areas (TOP), with an additional involvement of basal ganglia. The deliberate mode, in contrast, which is thought to be initiated by the prefrontal cortex (PFC), serves for controlled attentional search and processing. It brings the continuous activity in TOP into working memory which enables further manipulation and conscious processing of information and at the same time inhibits other not task-relevant activations. While there is an astonishing similarity between Dietrich`s suggestions and Kris (1952) earlier explanations, Dietrich did not refer to Kris's ideas explicitly in his work. There is also considerable overlap between these theories and the Geneplore model, which will be introduced in the next section.

1.3 Creative Cognition approach

One fundamental question in the investigation of creative thinking is: Are there two modes of human thinking, one creative and the other normative? Or is there just one mode and creative thinking takes place if certain contextual factors come into play (Abraham, 2013a)? The creative cognition approach states that creative thinking is essentially normative cognition unfolding within situations in which generation processes are needed. Contextual factors like task demands are therefore held to orchestrate the interplay of normative cognitive processes (Abraham, 2014a). Evidence of the human capacity to be generative can be seen in day-to-day acts where everyone can create concepts out of experiences and build new linguistic constructions through the flexible use of language. People do not have to create masterpieces of art to be considered creative as creativity can be found in all aspects of human life in lesser scales (Ward et al., 1999).

In the tradition of experimental cognitive psychology, the creative cognition approach seeks to investigate the normative human cognitive operations which underlie creative thinking. In doing so it assumes that there are different cognitive processes which contribute to creative thinking and that these processes can be investigated using experimental methods. For instance, under the Geneplore model (Finke et al., 1992), which served as an early heuristic model for the creative cognition approach, creative products are presumed to result from an alternation between the generation of preinventive structures and exploratory processes of these structures. Examples of generative processes would be the retrieval of existing knowledge, the formation of simple associations, the synthesis of new structures, analogical transfer of information and so on (Ward et al., 1999). Exploratory processes include the search for potential functions of the structures, the interpretation of structures as representing possible solutions to problems, and the search for various practical or conceptual limitations that are suggested by the preinventive structures. The acknowledgement that creative thinking comprises of different cognitive processes opened up the possibility of examining those varied processes using specific experimental tasks. These include conceptual expansion, creative imagery, overcoming the constraints of examples, and insight. Of special interest for the research presented in this work is the process called conceptual expansion which will be introduced in more details.

1.3.1 Conceptual expansion

Conceptual expansion is the core cognitive component of interest which was investigated in the reported studies of this doctoral thesis. Humans possess large semantic brain networks which contain stored information about real-world perceptions as well as abstract thoughts (Binder et al., 2009). A concept can be thought of as a container comprising strongly associated information under one label. For instance, the concept of a football includes several attributes – that it is round, that it can be kicked through the air, that it is used for sports, and so on. The advantage of concepts is that it structures our detailed experiences into larger and easier to handle information units. Semantically related concepts are more likely to be activated jointly as the distance in a semantic network between both concepts is rather small. Conceptual expansion refers to the process of widening or loosening the boundaries of an existing concept. For example, one manner in which to expand the concept of a football is that it could be used as a sunhat after cutting it into two halves. Conceptual expansion renders it possible to establish a relation between too previously unrelated concepts in a semantic network and thus generate creative ideas. T.B. Ward introduced the term “conceptual expansion” in a series of behavioral experiments investigating how people imagine a new member of a given concept (Ward, 1994). In these experiments subjects were supposed to draw animals from another planet very different from earth. Drawings were rated as being more novel if they shared less features with existing animals, like bilateral symmetry or typical sense organs or appendages. The drawing results showed many common features of earth like animals even if participants were explicitly instructed “to use their wildest imaginations”. Thus there was a clear tendency to rely on features of prior category members which hindered more creative solutions. This less laborious generation style was called the “path of least resistance”. Smith and colleagues could demonstrate a similar effect in an experiment in which subjects were asked to invent as many new toys as possible in a given time. Solutions were less creative if some exemplars of possible toys were shown during the introduction phase of the experiment (Smith et al., 1993). This effect also remained when subjects were explicitly told to generate toys which are very different from the shown exemplars (“path of least resistance”). Ward therefore concluded, that the “the heightened accessibility of an initially retrieved or presented example makes alternative examples less retrievable” (Ward, 1995). Ward could also demonstrate that the structuring of imagination could be influenced by task demands. Subjects were more likely to imagine innovative features of imagined animals from another planet, when the environment of the planet was described (e.g. a planet with seas of molten rocks and just a few solid islands). Thus creative solutions can be promoted when starting new ideas from a more abstract level rather than concrete existing examples.

Beside the aforementioned structured imagination task and the novel toy task, the process of conceptual expansion can also be assessed using psychometric tests like the alternate uses task (Wallach & Kogan, 1965). In this task, subjects are asked to name as many uses for a given everyday object as possible (divergent thinking task). Subjects reach higher scores if they are able to generate a high number of different responses (fluency) and responses which are statistically infrequent in the sample (original). For example using a shoe as a plant pot associates two more distantly related concepts and would therefore certainly result in a higher original score than the use of a shoe as foot protector. Thus this task necessitates an active expansion of existing concepts.

1.4 Neuroscientific findings regarding creative thinking

In the past decade, there have been three influential reviews that have summarized the neurophysiological findings regarding creative thinking or aspects of creativity in detail (Arden et al., 2010; Dietrich & Kanso, 2010; Sawyer, 2011). Unfortunately, all three reviews concluded that there was very little empirical consensus regarding the neural correlates of creative thinking.

The following sections will provide a concise overview of different approaches and results of studies that have investigated different aspects of creative thinking, following a brief introduction to neurophysiological methods used in these studies as well as the reported studies of this doctoral thesis, namely functional magnetic resonance imaging (fMRI) and electroencephalography (EEG).

1.4.1 Creativity and fMRI

Functional magnetic resonance imaging (fMRI) is a well-established, non-invasive method to examine the location and dynamics of brain activity (Goebel & Kriegeskorte, 2005). It is based on the measurement of a signal which depends on the oxygenic level in the blood, the so called BOLD (blood-oxygenation-level-dependent) signal. The underlying principle is that neuronal activity leads to a local change in the blood flow and thus to a change in the blood oxygenation. In order to measure this variation, subjects who participate in an fMRI experiment are brought into a strong magnetic field. They are then irradiated with electromagnetic waves in a radio frequency spectrum leading to a measurable magnetic echo, which is dependent on the magnetic properties of the respective tissue in the brain. These signals are then used to reconstruct three dimensional images of the subject’s brain, which are either anatomical or functional dependent on the specific measurement settings. Anatomical and functional images are then aligned to display dynamic changes in brain activity on detailed anatomical maps. FMRI offers a maximum spatial resolution of about 2 mm voxels and a time resolution of a few seconds. The advantage of this non-invasive neuroscientific technique lies in the high spatial resolution it affords, whereas its relative disadvantage is the limited time resolution and the indirect measurement of brain activity which makes it impossible to separately measure single neuronal events.

Over the past 15 years many different paradigms and tasks have been adopted to investigate the neural correlates of creative thinking using fMRI and older neuroimaging methods (Dietrich & Kanso, 2010).

The earliest approach was to investigate difference in brain activity between highly creative and low creative people. Carlson et al. (2000) found more bilateral frontal brain activation when performing the alternate uses task in the high-creative group in contrast to unilateral left frontal activation in the low-creative group. More recently, Chávez-Eakle and colleagues (2007) who also contrasted high and low creative groups found higher cerebral blood flow within the right precentral gyrus, right frontal rectal gyrus, left orbital gyrus, left inferior gyrus and cerebellum in the high-creative group while performing tasks from the Torrance Tests of Creative Thinking.

Another approach is to investigate active creative performances in a laboratory setting. For example, Shah and colleagues (Shah et al., 2011) let their subjects pass through a scanning procedure consisting of covert reading of a text for 60 seconds, copying the first 35 words of a text for 60 seconds, brainstorming following the presentation of the first 30 words of the previous text to generate a possible creative continuation of the story for 60 seconds, and engaging in creative writing for 140 seconds to physically write down a creative continuation of the story. The written stories were rated by ten German teachers following a standardized rating procedure. The brain activation resulting during creative writing when subtracted from the activation elicited by the control copying condition was located in the temporal pole (BA 38), hippocampus and posterior cingulate cortex (BA 31). A further correlation analysis of this activation and the creativity ratings showed a positive correlation between brain activation levels and creativity index in temporal pole (BA 38) and left inferior frontal gyrus (BA 45). These areas are known for their involvement in semantic retrieval and integration processes.

Other studies tried to implement widely employed psychometric methods like the alternate uses task (AUT) in neuroimaging paradigms. For example, Fink and colleagues (2009) administered four different tasks in their fMRI study: the alternate uses task (generate as many uses as possible for a given object), the (object characteristic task (list the many characteristics of a given everyday object), invent names task (make up an unusual name to given two-letter abbreviation), and the words end task (complete the given suffixes). Brain activation specific to the alternate uses task was found in the left angular gyrus.

In a similar vein, Chrysikou and Thompson-Schill (2011) conducted an fMRI experiment consisting of three different tasks. In one task, the subjects had to report aloud the common use of a seen everyday object (common use condition). Another task required subjects to call aloud a new generated use for a seen everyday object. A control task was also included where subjects saw scrambled everyday objects and were supposed to call aloud “yes” if a black box was superimposed on the image and “no” if it was not. The results showed an activation of lateral prefrontal cortex during the common use task, whereas the uncommon use task activated occipito-temporal cortex. The authors interpreted these findings with the need of “heightened attention to visual aspects of the object” during the uncommon use task. In contrast the “common use task” required controlled semantic retrieval which could account for the PFC activity.

Green and al. used an analogical reasoning task to study creativity (Green et al., 2012). The stimuli consisted of word pairs, of the form “A is to B as C is to ?”, with varying semantic distance. Analogical mapping of word pairs with higher semantic distance was rated as more creative than stimuli with less semantic distance between the word pairs. The results revealed parametrical covariation of frontopolar cortex (BA 10) activity with semantic distance. Thus higher demands to link two distantly related concepts with each other led to higher involvement of the frontopolar cortex. This relationship also remained after controlling for task difficulty.

FMRI studies on insight problem solving have resulted in the most consistent findings so far. Insight problem solving most often activates the superior temporal gyrus (STS) and the anterior cingulate cortex (ACC). The role of prefrontal areas seems to be much more inconclusive as some studies reported an activation of frontal areas, whereas other studies did not find such activations (Dietrich & Kanso, 2010).

Taken together the multitude of approaches, paradigms and results associated with neuroimaging based investigations on creativity, it should not be surprising that a clear cut picture about the neuronal correlates of creative thinking is still lacking.

1.4.2 Creativity and EEG

EEG is a traditional neurophysiological method to capture electrical activity changes of neuronal ensembles at the scalp surface via electrodes. Synchronously firing neuronal ensembles with similar spatial orientation leads to measurable EEG signals. In EEG studies, different parameters are often reported like for instance amplitude changes or power and synchrony changes of EEG signals. Amplitude means the magnitude of voltage differences between different electrodes. Power describes the frequency spectrum of a signal and synchrony how signals from different electrodes correlates to each other. Of special interest for many creativity studies was the so-called alpha synchrony, which refers to the synchronous occurrence of EEG signals at a frequency range from about 7 to 14 Hz at different electrodes. This alpha frequency usually reflects relaxed brain states in the awake brain.

Repeated application of time-locked experimental stimuli under continuous measurement renders it possible to average EEG signals and separate stimuli related signal changes from baseline activity. This procedure is called event-related potentials (ERP). ERPs are a powerful tool to investigate brain activity associated with cognitive processes. EEG and ERP come with the advantage of neuronal measurement in milliseconds resolution. On the other hand, these methods offer only limited spatial resolution, which complicates the mapping of observed neuronal activity to specific brain structures.

Although EEG research has a long tradition Dietrich (2010) pointed out that until the late 1990s, just three EEG studies had been conducted in the field of creative thinking. Following from the ideas of the aforementioned theories about defocused attention and lesser cortical arousal during creativity, EEG studies tended to concentrate their efforts mainly on the examination on synchrony changes and hemispheric asymmetry (Arden et al., 2010). In one of their studies, for example, Martindale et al. (1984) compared brain activation of high- and low-scorers on the AUT and RAT during three different speech tasks. Creative subjects showed “high-levels of right hemisphere activation during creative production”.

Fink et al. (2009) conducted an EEG experiment using the above already described tasks (section 1.5.1). They reported higher levels of alpha synchronization during the alternate uses task, especially over frontal brain regions. Subjects who produced more original ideas during the alternate uses task displayed a stronger right-hemispheric alpha synchronization over centro-parietal to parieto-occipital regions. This hemispheric asymmetry could not be observed in the low-originality group.

However, the meta-analyses conducted on findings within the field (Arden et al., 2010; Dietrich & Kanso, 2010) summarized that EEG studies could not sufficiently prove the claim of a special role for the right brain hemisphere during creative thinking. The role of alpha synchronization during creative thinking also remained unclear.

There is a notable lack of ERP studies in the field of creativity. Only a few exceptions bear noting here of ERP studies specifically investigating the process of insight. For example, Qiu et al. (2008) found a positive signal deflection in a time window of 200 – 600 ms for insight solutions originating from left superior temporal gyrus and posterior cortices. Further successful solutions elicited a negative ERP ongoing between 1500 and 2000 ms relating to the anterior cingulate cortex (ACC). In a second experiment, the authors were able to demonstrate that a positive ERP deflection during the preparatory phase of insight solutions was linked to the ACC.

Taken together, compared to neuroimaging studies, EEG studies on insight provided a relatively more consistent picture as they often observed decreases in alpha power during insight and a consistent involvement of the ACC (Dietrich & Kanso, 2010).

1.4.3 Methodological obstacles

The aforementioned conceptualization problem regarding creativity could explain the many scattered findings regarding creativity to some extent. But some of the studies reported in previous sections may serve to illustrate which special problems arise if one tries to translate creativity experiments into neuroscientific settings.

First of all, it is debatable whether creativity is suitable to be examined under laboratory conditions. Some researchers have argued that the nature of creativity involves spontaneity and freedom which contradicts laboratory constraints (Runco & Sakamoto, 1999). But even when adopting a less ideological focus, it is a noteworthy challenge to develop experimental paradigms in which the time point of the investigated creative process of interest can be reliably determined. Merely instructing subjects to be creative on cue is not sufficient.

A second constraint, which maybe contradictory to genuine creative generation, is that in order to reach a sufficient number of trials in ERP and fMRI experiments, the creative process of interest has to be repeatedly elicited and is therefore is not allowed to last too long. Otherwise the complete experimental duration would become too overdrawn. So open-end tasks are not suitable for such settings. A sufficient number of trials is mandatory for reaching the necessary statistical power to be able to detect small neurophysiological changes. Long task durations would also complicate the interpretation of any elicited brain activation as these would always reflect a mixture of different cognitive processes.

A third problem arises from the susceptibility of fMRI and EEG measurements to movement, whether it comes from verbal speech or limb movements. The described study by Shah et al. (2011) may serve as a good example for this. In many experiments the possibilities for creative expression or responses are limited. Some researchers ask their subjects to avoid any overt response as, for instance, in the study of Green et al. (2012). In this experiment, the subjects had to indicate any generated solution via a button press. After this, the correct solution was displayed and subjects had to indicate whether their solution matched the experimenter determined solution word. Such procedures or any post-experimental questionnaire certainly avoid movement artefacts and measurement of neurophysiological activity purely related to the cognitive process prior to execution of the response. On the other hand, it comes with the risk that subjects do not sufficiently follow the task instructions or simply invent new responses in post-experimental phases because they forgot their original solution.

One further serious challenge is the conception of suitable control tasks. To avoid any confound that could reduce the validity of a measurement or its interpretation, it is necessary to eliminate or control other relevant factors that could cloud the pattern of findings. Task difficulty would be such a factor in creativity experiments which renders it necessary to introduce a control task of at least equal task difficulty.

This brief presentation of possible obstacles in the investigation of creativity using neuroscientific methods should illustrate that these problems lead to a somewhat artificial manner of investigation and certainly contributed to the diversity of experiments, tasks and lastly results in the past 15 years (please refer to Abraham 2013 for a detailed analysis of such issues).

1.5 The present studies

This section will introduce details of the studies that were conducted within this doctoral thesis. These studies were designed to approach creativity as a multidimensional construct. Following the creative cognition approach, the presented studies focused on one described cognitive operation involved in creative thinking, which is conceptual expansion. The consideration behind this approach was that breaking creativity down into its underlying processes should enhance consistency of results across studies using a similar paradigm and facilitate the interpretation of the resulting brain activations for future investigations. This new approach was strictly oriented at the common definition that the factors of novelty and appropriateness jointly contribute to a creative product. Other creativity studies emphasized the originality factor and did not adequately account for the appropriateness factor (Fink et al., 2010). A new paradigm was also developed in order to prevent some of the methodological shortcomings of previous studies, like insufficient trial numbers or movement inducing task instructions. As the same paradigm was conducted with two different neuroscientific methods (fMRI, ERP), the task design for both studies is the same and will be introduced in the following section.

1.5.1 Task design

A modified version of the alternate uses task (Wallach & Kogan, 1965) was adapted for use in both studies. While the original task involves active conceptual expansion on the part of the subject, the modified alternate uses task invokes passive conceptual expansion. Subjects were presented with word-pairs consisting of an everyday object and a suggested use. Their task was to evaluate the object-use combination along two dimensions. First, they indicated whether they found the suggested use to be unusual or unique. Second, they then indicated whether they deemed the object-use combination to be appropriate or fitting. The question “unusual” was aimed at assessing the novelty factor whereas the question “appropriate” assessed the appropriateness factor. This evaluation led to each object-use combination falling into one of three possible categories. Object-use combinations could be rated as low-unusual and high-appropriate (common uses), high-unusual and low-appropriate (nonsense uses), and high-unusual and high-appropriate (creative uses). The fourth classification of low-unusual and low-appropriate did not exist, as a common object-use combination is inherently appropriate. Object-use combinations judged to be novel and appropriate (creative uses) were trials in which conceptual expansion processing was supposed to occur, as in these trials the classic concept of a given object is expanded in a novel manner beyond its customary boundary.

The presented studies therefore investigated conceptual expansion via a passive task which brought multiple advantages with it. First, motion artefacts, which would occur to a greater extent in an active generation task, are reduced or entirely absent. Also, any necessity of post-experimental survey of self-created solutions is avoided. These surveys are often compromised in active generation tasks and are also susceptible to false-memory effects. Second, it was possible to ensure that comparable number of trials across the three possible categories or conditions (common uses, nonsense uses, creative uses) were maintained across participants. An active generation task could lead to the problem that too few creative uses (novel and appropriate) would be generated. Also, an active generation task would necessitate the introduction of a further control task, which would lead to an overall increase of experimental duration. Third, this passive approach facilitates the analysis of brain activation relating to one of the three categories. An active generation task would result in brain activation that reflects a mixture of processes during object generation rather than separately assessing processing related to novelty, appropriateness and conceptual expansion, which is only possible using a passive paradigm. The passive paradigm also allows for the time point of interest for data analysis to be narrowed down more precisely.

A major advantage of this innovative task design is also that it does not rely on experimenter determined judgments and therefore leaves room for inter-individual differences regarding the evaluation of the seen object-use combinations. This is extremely important given the differences between subjects in terms of how conceptual networks are organized. An association that seems novel for one participant may not be novel for another participant. This paradigm allows for individual variability to be accounted for.

This passive approach certainly also has some shortcomings. The ecological validity, which is a standard problem in laboratory studies, is even more reduced with a passive task. When undertaking a creative enterprise, people would expand concepts actively. In a passive paradigm, factors like volition and stronger inhibition requirements are to some extent left out. On the other hand, given that the conceptual network being expanded upon in active or passive paradigms is one and the same, there are strong grounds to argue for largely overlapping mechanisms in both cases. There are therefore few grounds to presuppose that active and passive conceptual expansion recruit entirely different brain networks. The hypotheses of the reported studies regarding the specific brain areas expected to be involved in conceptual expansion processing will be outlined in the next section.

1.5.2 fMRI hypotheses

It was hypothesized that brain activation as a function of conceptual expansion will not be limited to a single brain area but will rather engage a brain network consisting of prefrontal areas BA 45, BA 47 (anterior and middle inferior frontal gyrus) and BA 10 (frontopolar cortex), as well as BA 38 (temporal pole) in the temporal lobe. BA 45 and BA 47 are well-known to be involved in semantic retrieval and selection processes (Badre et al., 2005; Thompson-Schill, 2003) and are likely to be activated when subjects encounter two unrelated concepts and have to search for a link between both in their semantic networks. This is the same reason the temporal pole was expected to be activated, as this region plays a crucial role in semantic cognition as a possible hub region underlying amodal semantic representations (Rogers et al., 2004; Patterson et al., 2007b; Lambon Ralph et al., 2010). All these areas involved in semantic processing were also expected to be strongly recruited in trials classified as “nonsense uses” for the same reason as the creative uses. Creative uses, however, were expected to also additionally involve the frontopolar cortex (BA 10) for subserving the process of integration of the new discovered previously weakly related concepts into an expanded concept. This is because the frontopolar cortex has been demonstrated to be involved in relational integration processing (Bunge et al., 2005; Green et al., 2010; Kroger et al., 2002).

1.5.3 ERP hypotheses

The ERP hypotheses were focused on the well-established N400 component. This component describes a negative deflection between 200 to 600ms, which peaks around 400ms (Kutas & Federmeier, 2011), and was first described in the processing of semantic incongruent sentence endings (Kutas & Hillyard, 1980). Later it could be demonstrated that this component is also sensitive to a wide range of other factors reaching from pure bottom-up stimuli like unusual word capitalization (Lotze et al., 2011) to top-down stimuli like world knowledge violations (Hagoort et al., 2004). As ERP studies regarding other creative processes beside insight are missing, the hypothesis of the presented study was derived from findings in related research domains. A N400 component was expected following nonsensical uses compared to common uses as this would represent the classic example of semantic incongruent stimuli.. However, the interesting case in point would be the N400 pattern in relation to creative uses. If the N400 indexes processing relevant for conceptual expansion, a smaller N400 should be observable in the case of the creative uses relative to that of the nonsensical uses. If there were no differences between creative uses and nonsensical uses in the N400 time-window, conceptual expansion related processing could possibly be reflected in later ERP time-windows.

The following sections will now describe the conducted studies in detail.

2 Study 1

Using a shoe as a plant pot: Neural correlates of passive conceptual expansion.

Published in: Brain Research

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2.1 Abstract

Conceptual Expansion is a key process that underlies our ability to think creatively. In the present event-related fMRI study, a modified Alternate Uses Task was used to identify brain regions involved during passive conceptual expansion and thereby separately assess the effects of the two defining elements of creative output: Originality (unusualness) and Relevance (appropriateness). Participants viewed word pairs consisting of an object and a use and indicated whether the given use was unusual and/or appropriate for the given object. Trials with object-use combinations judged as unusual and appropriate (HUHA) were contrasted against trials judged as just unusual but inappropriate (HULA) or just appropriate but not unusual (LUHA). As hypothesized, conceptual expansion related activation (HUHA) was found in the bilateral inferior frontal gyrus (BA 45, 47), left temporal pole (BA 38) and left frontopolar cortex (BA 10). We discuss the specific contributions of these regions with reference to semantic cognition.

Keywords: fMRI, creative cognition, conceptual expansion, alternate uses task, BA 47, BA 45, BA 10, BA 38, divergent thinking.

2.2 Introduction

Although the study of creative thinking has a long scientific tradition, little is known about the underlying neurocognitive mechanisms. This lack of knowledge is due to conceptual problems as well as technical limitations and suboptimal experimental paradigms for the neuroscientific investigation of creative thinking (Dietrich, 2004; Dietrich & Kanso, 2010). One of the more critical problems is that creative thinking has mainly been examined as a unitary construct but with a range of tasks that are not comparable to one another. This has led to a multitude of scattered findings. A recent review summarized that the only reliable conclusion from neuroimaging studies to date is that creative thinking leads to changes in prefrontal brain activation (Dietrich & Kanso, 2010). Unfortunately, this is also a very unspecific claim given that the prefrontal cortex is a large structure which is known to underlie a wide range of functions from cognitive control to mental state reasoning (Amodio & Frith, 2006; Badre, 2008). The lack of consistency in neuroscientific findings related to creative thinking highlights the necessity to develop new paradigms where the construct of creativity is investigated in terms of its component processes.

In comparison to the neuroscience of creative thinking, there is a substantial agreement about the definition of creativity from the psychological domain. Creativity is typically defined from the product perspective in that a creative product has to be original or unusual as well as relevant or appropriate in a certain context (Hennessey & Amabile, 2010; Runco, 2004). The first theoretical approach which stressed the multifaceted nature of creativity was the creative cognition approach (Finke et al., 1992). Unlike the tradition of early cognitive models of creativity (Mednick, 1962; Mendelsohn, 1976), which focused on individual differences in creative ability, this approach examined normal cognitive processes which underlie our ability to think creatively. Several types of mental operations are held to be involved in creative thinking that are not qualitatively different from normal cognitive processes (Smith et al., 1995).

The aim of the current study was to disentangle the multifaceted construct of creativity by identifying brain regions involved in the processing of one critical facet of creative thinking, namely the process of conceptual expansion. This process is one of the core features of creative thinking in that it involves broadening the existing definitions or boundaries of a concept beyond its usual characteristics and therefore aids the development of new ideas (Smith et al., 1995; Ward, 1994). In the original conceptual expansion task, subjects were asked to imagine and draw an animal living on another planet which is very different from Earth (Ward, 1994). In other words what was required in this task was to expand the original concept of what an animal can look like while still be definable as an animal. The drawings were evaluated with respect to deviations from ordinary Earth animals in terms of fundamental features like bilateral symmetry and the presence of sense organs. Interestingly, subjects revealed a tendency to rely on generic exemplars of animals, even when instructed not to do so. This “path-of-least-resistance” strategy or the tendency to adopt the least cognitive demanding approach that is possible in a given situation is commonly observed when performing generative tasks (Finke, 1990; Ward, 1994). Despite its significance, no neuroimaging studies have so far explicitly assessed conceptual expansion.

The original conceptual expansion task cannot be directly implemented in an fMRI setup due to problems that would arise from technical difficulties such as drawing responses and inadequate number of trials. To overcome some of the difficulties which are typically encountered when trying to combine neuroimaging with active engagement in creativity tasks, a novel paradigm was developed in the current study to induce conceptual expansion. For this purpose we used a modified version of the alternate uses task (AUT, Wallach & Kogan, 1965), a classic creative thinking task in which conceptual expansion is assessed (Abraham & Windmann, 2007). The AUT tests the ability to generate as many uses as possible for common objects (e.g., a shoe) and thereby necessitates that the subject expands the usual conceptual boundaries in which the object is customarily used (e.g., foot protection). While the classic AUT does not dissociate the originality (or unusualness) component from the relevance (or appropriateness) component of creativity, the current modification of the paradigm enables the concurrent consideration of both these components separately (originality OR relevance) as well as together (originality AND relevance).

In this modified version of the AUT, subjects view word pairs of a common object together with a described use for this object and have to decide on a trial-by-trial basis whether they find the use for the given object unusual (U), appropriate (A) or both. Trials in which subjects judge a particular object use combination to be highly unusual and highly appropriate (HUHA) or unfamiliar but fitting are trials in which the subjects were induced to loosen the classic boundaries of the presented concepts thereby allowing for the conceptual expansion and conceptual integration of the previously unrelated concepts. This is in contrast to trials in which subjects decide that a particular object use combination is only unusual but not appropriate (high unusual and low appropriate – HULA) or only appropriate but not unusual (low unusual and high appropriate – LUHA). In this manner, a creative object use combination that is unusual and relevant (HUHA) can be separated from a purely unusual but irrelevant combination (HULA) as well as from purely relevant but common combination (LUHA). This allows for the assessment of the separable effects of originality and relevance from that of creative conceptual expansion. Instead of just relying on pre-determined conditions, the great advantage of this procedure is that the experimental design is individually validated by each participant on a trial by trial basis.

Unlike in the classic AUT, participants in the current study do not have to generate a creative (unusual AND appropriate) use for a given object by themselves, but are instead presented with a solution to a problem that they judge as being creative. The fact that they recognize the bringing together of the two concepts (the object and its use) as being unusual but appropriate is proof of passive conceptual expansion taking place as they passed such a judgement only when an object-use combination was unfamiliar but fitting. Although we expect quantitative as well as qualitative differences in brain activation between an active and a passive conceptual expansion paradigm due to factors like volition and a stronger directed memory search process in case of the passive conceptual expansion, we assume that the type of conceptual expansion induction (volitionally induced in the AUT versus externally induced in the current modified AUT), would not affect the general manner in which conceptual structures are expanded upon in the human brain. After all, the conceptual structures being expanded within either scenario would be one and the same. By doing away with the volitional side though, we are able to systematically assess the neural underpinnings of passive conceptual expansion without the added confounds of increased cognitive difficulty during creative thinking, unpredictability in generating creative responses upon cue, and so on.

We expect to find passive conceptual expansion related activation in three brain areas namely the frontopolar cortex (BA 10), the anterior and middle inferior frontal gyrus (IFG: BA 45, 47), and the temporal pole (BA 38). This is because bringing two concepts together which were previously only weakly or not at all related to one another necessitates the activation of these concepts and searching for their associative links, both of which require controlled semantic retrieval and selection mechanisms. Such processes are known to involve the IFG (Badre et al., 2005; Thompson-Schill, 2003). The temporal pole which has also been referred to as the “semantic hub” of the brain (Patterson et al., 2007a) has been implicated in the extraction of amodal conceptual information and may therefore also play a role in search processes in semantic networks. With regard to the separable factors of originality (or unusualness) and relevance (or appropriateness), the IFG and temporal pole regions would also be expected to be responsive as a function of unusualness given the higher demands on semantic selection and retrieval during novelty processing.

One further process that is also needed when expanding an existing concept by linking it with another previously unrelated concept is the integration of the detected relations between the two previously weakly related or unrelated concepts to form an expanded new concept. We hypothesize that this aspect of the conceptual expansion processing should engage the lateral frontopolar cortex (BA 10). Although the exact function of this brain area is a matter of ongoing debate (Ramnani & Owen, 2004), there is substantial evidence that it is involved in relational integration processing (Bunge et al., 2005; Green et al., 2010; Kroger et al., 2002), where multiple relations have to be considered simultaneously in order to infer the correct solution of a problem as, for instance, in the Raven’s Progressive Matrices test (Christoff et al., 2001). This makes it a candidate region for the integration processes during passive conceptual expansion.

2.3 Experimental procedures

2.3.1 Participants

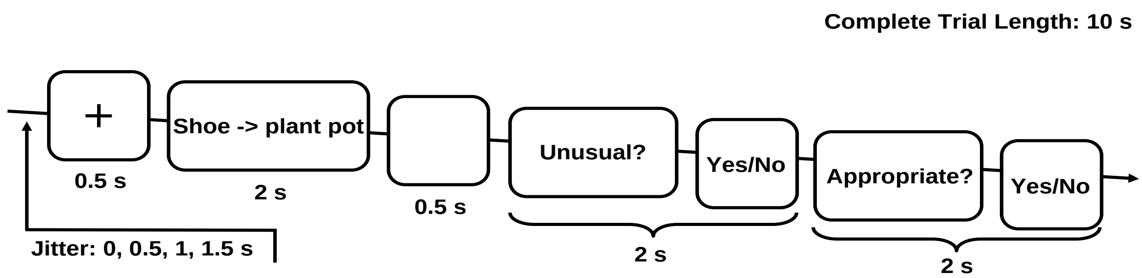
Twenty-six right-handed native German-speaking subjects either received a 15 Euro payment or a course credit for their participation in the experiment. Six subjects had to be excluded from further analysis because they did not meet the minimum inclusion criterion of at least 30 trials per condition. One additional subject had to be removed due to extensive movement during data acquisition. The final sample therefore comprised 19 subjects (10 women; age range = 19-31 years, mean = 22.68) with normal or corrected-to-normal vision. None of the participants had a history of neurological or psychiatric illness or was taking drugs. All gave informed consent before participation. The experimental standards were approved by the ethics committee of the German Society of Psychology (Deutsche Gesellschaft für Psychologie, DGPs).

2.3.2 Task Design

We employed an event-related fMRI design. During each trial (Fig. 1), subjects viewed a pair of words for 2 s consisting of a common object and a described use for this object in each trial. After the presentation of a blank screen for 500 ms, subjects were asked to evaluate whether in their opinion the described use for the object was unusual or not (Unusual?) and whether it was appropriate or not (Appropriate?).

This was done by giving a yes/no answer to each of these questions by pressing either the left or the right button of a response box. Participants were instructed that a use was to be classified as “Unusual” if it was novel or unfamiliar and “Not Unusual” if it was known or familiar. They were also instructed that a use was to be classified as “Appropriate” if it was fitting or relevant and “Not Appropriate” if it was unfitting or irrelevant. Each stimulus was categorized as belonging to one of three possible conditions based on the participant’s response. The three possible conditions were: high-unusual and high-appropriate (HUHA, yes-yes response), high-unusual and low-appropriate (HULA, yes-no response) and low-unusual and high-appropriate (LUHA, no-yes response). Subjects were told that a no-no response (low unusual and low appropriate) would not make sense as a low appropriate response is always highly unusual.

Each question was shown for 1.5 s followed by a 500 ms blank period so that subjects had 2 seconds per question to respond. Each trial started with a jittered blank screen (0 – 1.5 s, jittered in steps of 500 ms) followed by a 500 ms fixation period consisting of the presentation of a fixation cross for 300 ms and a 200 ms blank screen. With a trial length of 10 s and a total of 149 trials (including 14 null events), the experimental session lasted 24.83 min.



Shoe ->			
	…plant pot	High unusual and high appropriate	(HUHA)
	…piece of clothing	Low unusual and high appropriate	(LUHA)
	…electronic device	High unusual and low appropriate	(HULA)
Toilet seat ->			
	…picture frame	High unusual and high appropriate	(HUHA)
	…seating	Low unusual and high appropriate	(LUHA)
	…golf club	High unusual and low appropriate	(HULA)

Figure 1. Trial Overview (above) and Examples of the stimuli used in each condition (below). The temporal jitter at the start of each trial led to a variable inter stimulus interval of 1.5 to 4.5 seconds (steps of 500 ms) due to the constant trial length of 10 seconds. The 0.5 s fixation period consisted of 300 ms fixation cross and 200 ms blank screen.

2.3.3 Materials

Stimuli were pretested in behavioral experiments with another set of subjects. 45 experimenter-determined word pairs per condition were used to ensure the high likelihood of there being a minimum of 30 subject-determined trials in each condition. Each object was used in all three conditions (HUHA, HULA and LUHA) in combination with a described use for this object. Objects and uses were all single words.

The behavioral pilot studies indicated that some variability was unavoidable when using subject-determined trial classifications as, for instance, what one participant considers to be an unusual and appropriate object-use combination (HUHA) may be classified by another subject to be unusual but inappropriate (HULA). A minimum inclusion criterion of 30 trials per condition for each subject was therefore set as it was imperative that the fMRI analyses were not unduly influenced by widely varying trial-condition distributions across subjects. While the subject-determined trial classification is a major strength of the current paradigm, it comes with a cost of having to exclude all participants who did not meet the strict inclusion criterion.

2.3.4 Imaging Session

Participants were placed on the scanner bed in a supine position. A two-button response box was placed under the right hand, so that the right index and middle fingers were positioned on the appropriate response buttons. Stimuli were presented under computer control using Presentation® software (Version 0.70, www.neurobs.com), in black font (size = 28) on grey background and projected with an LCD projector onto a screen in a resolution of 800x600 pixel. Subjects viewed this screen through a mirror that was mounted onto the head coil. Prior to the imaging session, participants were given written instructions and performed a 5-minute practice session on a computer outside the scanner. After the imaging session, subjects received a post-experimental survey as well as a list of stimuli which they had just seen in the experiment and were asked to rate on a 5-point scale whether they had already known the object use combinations prior to the experiment. [1]

2.3.5 Data Acquisition

Functional MRI was acquired via whole-body 1.5 Tesla Siemens Symphony scanner (Siemens, Erlangen, Germany) with a standard head coil at the Bender Institute of Neuroimaging. A single-shot gradient echo planar imaging (EPI) sequence was used

[1] Results of the post-experimental survey are not presented here because of a memory bias which occurred due to the prior presentation of the stimuli in the experiment. Participants who were confronted with the stimuli during the fMRI session tended to rate the object-use combinations as more familiar in the post-fmri session than participants in a control group who did not participate in the main experiment. We postulate that the engagement with the stimuli during the fMRI session and the successful integration of unusual but appropriate object-use combinations into existing semantic networks led to this memory bias.

with the following parameters: 25 axial slices; repetition time (TR), 2500 ms; echo time (TE), 55 ms; flip angle (FA), 90^{o}; field of view (FOV), 192 mm; voxel size, 3x3x3 mm; slice thickness, 5mm; gap, 1mm; volumes: 614. A detailed T1-weighted anatomical *MP-RAGE* (magnetized prepared rapidly aquired gradient echo) sequence consisting of 160 volumes (1mm slice thickness) was conducted with the same spatial image orientation as the functional data.

2.3.6 fMRI Data Analysis

Data were preprocessed and analyzed using SPM 8 routines (Wellcome Department of Cognitive Neurology, London, UK). The preprocessing procedure consisted of a realignment to the first image, slice time correction, coregistration of functional and anatomical data, segmentation and normalization to the standard brain of the Montreal Neurological Institute and smoothing with a Gaussian kernel with a full width at half maximum (FWHM) of 9 mm. Low-frequency signal changes and baseline drifts were removed using a high-pass filter set at 150 seconds.

Event-related BOLD responses were analyzed using the general linear model with a canonical hemodynamic response function combined with time and dispersion derivatives time-locked to the onset of the event. The design matrix included one regressor for each condition (HUHA, HULA, LUHA, null events), one regressor for each question (Question 1: unusual, Question 2: appropriate, together with the reaction time of the button press as a parametric modulation parameter), and the six movement parameters from the realignment procedure. The regressors for each condition were determined individually according to the individual responses of each participant. Pairwise T-contrasts between the three conditions were computed and the resulting contrast images were used for second level analysis.

The main focus centred on three second-level conjunctions which were computed for whole brain analysis as well as a priori defined regions of interest via paired T-Test routines. These revealed which brain regions were commonly activated across contrasts as a function of a particular process of interest. First Conjunction (Conceptual Expansion): **HUHA** > HULA ∩ **HUHA** > LUHA. Second Conjunction (Unusualness): **HU**HA > LUHA ∩ **HU**LA > LUHA. Third Conjunction (Appropriateness): HU**HA** > HULA ∩ LU**HA** > HULA.

For both the whole brain and the ROI analysis a family-wise error (FWE) of $p < .05$ was applied to correct for multiple comparisons. The ROI analyses were performed for a priori predicted regions (BAs 10, 45, 47, 38, 21) using the WFU Pickatlas toolbox version 2.5.2 for SPM (Maldjian et al., 2003; Maldjian et al., 2004).

2.4 Results

2.4.1 Behavioral Findings

We carried out a 3 x 2 repeated measures ANOVA to check for differences in reaction times between the three types of conditions (HUHA, HULA, LUHA) and two types of questions (Question 1: unusual, Question 2: appropriate). We found significant main effects for the condition type (F (2,38) = 8.173 p = .001) and question type (F (1,19) = 40.576 p < .001) as well as a significant interaction (F (2,38)= 6.684 p= .003). Bonferroni corrected (p < .05) post hoc T-tests revealed that subjects significantly took longer to respond to the second question (appropriate) in the HUHA condition compared to the second question in the HULA (p = .001) and the LUHA condition (p = .004). Additionally subjects responded significantly faster to the second question compared to the first question, independent of type of condition. See Table 1 for mean reaction times and standard deviation.

Table 1. Reaction times (mean and standard deviation in milliseconds) for all three conditions.

Conditions	Unusual (Question 1)		Appropriate (Question 2)	
	Mean	SD	Mean	SD
HUHA	688.68	115.06	622.53	123.97
HULA	691.12	120.82	544.81	91.35
LUHA	653.09	96.30	546.09	93.70

2.4.2 fMRI Findings

Whole brain and region of interest analysis for a priori defined regions BA 10, BA 47, BA 45 and BA 38 were carried out. We also did exploratory analysis to reveal additional activated regions. All activations reported were FWE-corrected for multiple comparisons ($p < .05$).

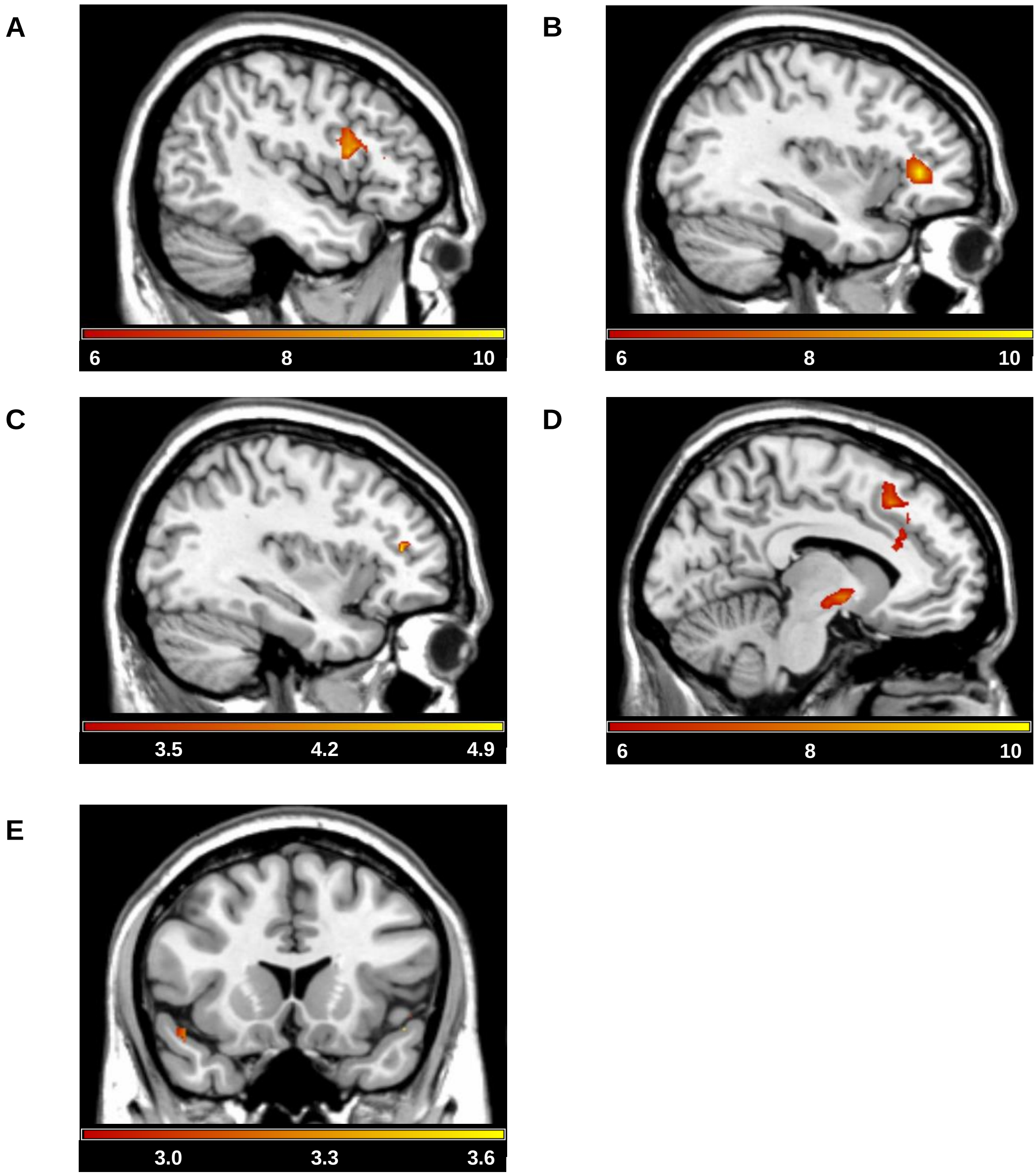


Figure 2. Passive Conceptual Expansion related activation in A: IFG (BA 44/45), B: anterior IFG (BA 47), C: Frontopolar Cortex (BA 10, ROI analysis, p < .005 uncorrected), D: dorsal ACC (BA 32/ BA 8), E: Temporal Poles (BA 38, ROI analysis, p < .005 uncorrected). Color bars represent T-values.

2.4.3 Passive Conceptual Expansion

To determine which brain regions were activated during passive conceptual expansion (HUHA), a conjunction analysis was conducted (**HUHA** > HULA ∩ **HUHA** > LUHA) (Results in Table 2). Consistent with our prediction, passive conceptual expansion related activation was found in left inferior frontal gyrus (IFG) with activation peaks in BA 47 and BA 44 while also extending into BA 45.

Table 2. Passive Conceptual Expansion: Whole Brain Analysis and Region of Interest Analysis. Anatomical Specification, MNI coordinates, number of voxels (l.m.: another local maxima in the cluster above), maximum T-value of the significantly activated areas in the HUHA > HULA ∩ HUHA > LUHA conjunction analysis. All results were corrected for multiple comparisons (FWE) at *p* < .05.

Area	**BA**	**Side**	**x**	**y**	**z**	**Cluster size**	**T-value**	**p**
Conceptual Expansion Whole Brain Analysis								
Inferior Frontal Gyrus	47/45/10	L	-36	35	4	56	12.43	.000
Inferior Frontal Gyrus	44/45	L	-45	11	16	76	10.76	.000
Inferior Frontal Gyrus	46/45	R	51	38	4	12	9.82	.000
Inferior Frontal Gyrus	47	R	27	29	-11	5	9.52	.000
Inferior Frontal Gyrus	47	L	-27	23	-14	3	7.33	.021
Inferior Frontal Gyrus	45	R	51	26	1	1	6.86	.046
Superior Frontal Gyrus (med)	32/8	L	-9	23	46	27	9.58	.000
Superior Frontal Gyrus	8	L	-21	14	52	l.m.	7.30	.022
Anterior Cingulate Cortex	24	L	-6	23	19	1	7.38	.019
Anterior Cingulate Cortex	32	L	-9	26	22	1	7.29	.023
Anterior Cingulate Cortex	32	L	-9	29	28	1	7.19	.027
Anterior Cingulate Cortex	32	L	-6	32	31	1	6.82	.048
Subthalamic Nucleus		R	9	-13	-8	14	9.95	.000
Hypothalamus		L	-9	-5	-1	23	9.15	.001
Subthalamic Nucleus		L	-6	-10	-8	l.m.	8.01	.005

Area	BA	Side	x	y	z	Cluster size	T-value	p
Conceptual Expansion Region Of Interest Analysis								
Lateral Frontopolar Cortex	10	L	-36	38	13	7	6.02	.003
Inferior Frontal Gyrus	47	L	-27	26	-14	48	6.95	.000
		L	-36	29	-2	l.m.	6.28	.001
		L	-42	20	-11	l.m.	5.43	.005
		L	-33	14	-20	1	4.71	.022
		L	-39	26	-17	1	4.71	.022
		L	-42	41	-8	1	4.60	.028
		L	30	23	-8	1	4.46	.038
		R	51	26	1	2	6.86	.000
		R	54	26	-5	1	6.59	.000
		R	27	32	-8	7	6.19	.001
		R	51	23	-8	5	5.26	.007
		R	48	35	-2	1	5.10	.009
Inferior Frontal Gyrus	45	L	-51	17	16	24	7.06	.000
		L	-54	11	19	2	5.79	.001
		L	-36	26	7	4	5.50	.002
		R	51	35	4	2	9.81	.000
		R	51	26	1	2	6.86	.000
		R	51	26	22	4	4.69	.011
Temporal Poles	38	L	-48	20	-11	2	4.72	.017
		L	-45	17	-14	1	4.39	.036

Although no peak activations were found in the frontopolar cortex or temporal pole in the whole brain analysis, the results of the region of interest analysis showed passive conceptual expansion related activation in the left frontopolar cortex (BA 10) and the left temporal pole (BA 38), as well as in the bilateral IFG (BA 45, 47). The whole brain analysis also revealed the involvement of the left rostral cingulate zone (BA 32, 8, 6).

2.4.4 Unusualness and Appropriateness

The conjunction analysis for unusualness (**HU**HA > LUHA ∩ **HU**LA > LUHA) did not reveal the predicted involvement of the IFG or the temporal poles. Brain regions that were instead found to be activated for the unusualness conjunction included the left supramarginal gyrus (BA 2/40) (Table 3).

Table 3. Unusualness: Whole Brain Analysis and Region of Interest Analysis. Anatomical Specification, MNI coordinates, number of voxels (l.m.: another local maxima in the cluster above), maximum T-value of the significantly activated areas in the HUHA > LUHA ∩ HULA > LUHA conjunction analysis. All results were corrected for multiple comparisons (FWE) at $p < .05$.

Area	**BA**	**Side**	**x**	**y**	**z**	**Cluster size**	**T-value**	**p**
Unusualness: Whole Brain Analysis								
Supramarginal Gyrus	2/40	L	-63	-31	40	12	8.58	.000
Unusualness: Region Of Interest Analysis								
Lateral Frontopolar Cortex	10	L	-39	38	16	2	5.31	.012
Inferior Frontal Gyrus	47				No activation found			
Inferior Frontal Gyrus	45				No activation found			
Temporal Poles	38				No activation found			

The appropriateness conjunction (HU**HA** > HULA ∩ LU**HA** > HULA) resulted in significant activations mainly in posterior and anterior cingulate gyrus (BA 31, 24, 32) and in parts of the frontomedian wall (BA 9, 32) (Table 4).

Table 4. Appropriateness: Whole Brain Analysis and Region of Interest Analysis. Anatomical Specification, MNI coordinates, number of voxels (l.m.: another local maxima in the cluster above), maximum T-value of the significantly activated areas in the HUHA > HULA ∩ LUHA > HULA conjunction analysis. All results were corrected for multiple comparisons (FWE) at $p < .05$.

Area	BA	Side	x	y	z	Cluster size	T-value	p
Appropriateness: Whole Brain Analysis								
Posterior Cingulate Gyrus	31	L	-6	-55	22	29	9.84	.000
Medial Frontal Gyrus	9	L	-6	44	34	21	8.54	.002
Medial Frontal Gyrus	9	L	-9	53	31	l.m.	7.99	.006
Anterior Cingulate Gyrus	24	R	3	35	7	38	8.31	.004
Anterior Cingulate Gyrus	32	L	-3	44	10	l.m.	8.15	.005
Middle Temporal Gyrus	21	L	-60	-7	-20	3	7.71	.010
Middle Temporal Gyrus	21	L	-60	-16	-11	3	7.52	.015
Middle Temporal Gyrus	21	L	-63	-10	-14	1	7.51	.015
Middle Temporal Gyrus	21	L	-54	-16	-20	1	7.03	.037
Angular Gyrus	39	R	57	-58	28	5	7.82	.009
Angular Gyrus	39	L	-54	-64	28	2	7.25	.024
Appropriateness: Region Of Interest Analysis								
Lateral Frontopolar Cortex	10	L	-9	47	10	71	7.64	.000
		L	-3	59	28	l.m.	6.46	.001
		L	-3	53	-2	l.m.	5.96	.003
		R	3	53	10	41	5.99	.003
		R	6	53	-2	l.m.	5.98	.003
		R	3	47	-8	1	4.90	.030
Inferior Frontal Gyrus	47				No activation found			
Inferior Frontal Gyrus	45				No activation found			
Temporal Poles	38	L	-48	17	-17	6	5.67	.002
		L	-42	8	-29	1	4.44	.032
		L	-51	14	-20	1	4.31	.042

2.5 Discussion

Using a novel paradigm, the aim of this study was to disentangle the multifaceted construct of creative cognition by investigating our capacity to engage in passive conceptual expansion which involves the bringing together of original and relevant semantic connections. The paradigm enabled us to dissociate the brain responses associated with passive conceptual expansion (unusual and appropriate) compared to the processing of purely unusual (only original) or purely appropriate (only relevant) responses and was individually validated by each subject on a trial by trial basis.

2.5.1 Passive Conceptual Expansion

In order to identify brain regions selectively involved in the process of passive conceptual expansion, we compared trials judged as high unusual and high appropriate (HUHA) against trials rated as high unusual but low appropriate (HULA) as well as low unusual and high appropriate trials (LUHA). In line with our predictions, passive conceptual expansion related activation was found in the frontopolar cortex (BA 10), inferior frontal gyrus (IFG: BA 45, 47) and temporal pole (BA 38).

The IFG activity is likely to reflect higher semantic retrieval and selection demands due to the effort incurred by searching for the link between the weakly associated concepts presented in the object-use combination. This region is known to be involved in semantic processing (Bookheimer, 2002; Binder et al., 2009), exhibits stronger BOLD responses to concepts with low associative strengths, and is sensitive to semantic distance between concepts during analogical reasoning (Green et al., 2010; Bunge et al., 2005). More specifically, it has been proposed that the anterior portion of the IFG (BA 47) plays a major role in controlled semantic retrieval, whereas the middle IFG (BA 45) is more involved in the selection of retrieved semantic representation (Badre & Wagner, 2007) .

Stronger passive conceptual expansion related activation was also expected to be found in the so-called “semantic hub” region of the brain in the temporal poles (BA 38) given its role in the storage of amodal conceptual knowledge. This has been shown in experiments using rTMS that disrupted neural processing in this area as well as in semantic dementia patients with atrophy of this region (Lambon Ralph & Patterson, 2008; Lambon Ralph et al., 2009).

The lateral frontopolar cortex was expected to play a key role in the integrational processing demands that arise during passive conceptual expansion. This brain area is engaged during relational reasoning on the most abstract level (Badre, 2008) as well as in monitoring and integration of subgoals during working memory tasks (Braver & Bongiolatti, 2002), and during active processing of self-generated or inferred information (Christoff et al., 2003; Christoff et al., 2004). Activity in the frontopolar cortex has also been shown to co-vary parametrically with increasing semantic distance between items in an analogical reasoning task (Green et al., 2010) as well as with relational complexity, which corresponds to the number of relations simultaneously kept in mind while inferring conclusions (Kroger et al., 2002). In an effort to bring together the diverse task-related findings in this region into a more task-independent general description, Ramnani and Owen (2004) argued that the frontopolar cortex is required for integration of output results from multiple cognitive operations while following a higher behavioral goal. Taken together the data fit very well with the idea that the lateral frontopolar cortex is involved in passive conceptual expansion as this process demands the integration of two previously weakly related or unrelated concepts.

2.5.2 Active versus Passive Conceptual Expansion

It must be noted that our study investigated the processing of passive conceptual expansion which we expect to differ from a situation in which a person has to actively expand an existing concept on a generative basis. We assume that beside other relevant factors such as a stronger convergent memory search process during a passive conceptual expansion task, the most obvious difference between a passive and an active approach would lie in the volitional side of bringing about the expansion. Nevertheless we would postulate that the actual expansion of the concept would be expected to involve similar structures related to semantic cognition in the brain regardless of whether it was initiated volitionally or induced automatically. This is because information processing demands on the access, selection, retrieval and integration of semantic information would be necessary regardless of whether the conceptual expansion was actively or passively induced. It would be expected that volitionally induced or active conceptual expansion will engage similiar brain areas to a greater extent compared to passively-evoked conceptual expansion (quantitative changes). Several further structures (such as hypothetical reasoning, inhibitory control and extended cognitive control related brain regions) would also be expected to be involved during active conceptual expansion (qualitative differences).

Some studies have inadvertently investigated active conceptual expansion without explicitly referring to such a process (Chrysikou & Thompson-Schill, 2011; Fink et al., 2010). For example in a fMRI study from Chrysikou et al. (2011) one group of participants were required to actively retrieve the common use of an everyday object while another group were required to generate a creative use. Common use generation activated the lateral prefrontal cortex, whereas the creative use generation led to activations in occipito-temporal cortex. Unfortunately these results are not directly comparable to the results derived from the paradigm used in the current study due to critical differences in the paradigms such as not distinguishing between unusual and appropriate uses (as creative uses are defined) from merely unusual but inappropriate uses. The same limitation in integrating the current results with those in the literature applies to the study by Fink et al. (2010) in which the active generation of original ideas was associated with higher activation in the anterior supramarginal gyrus. We found a similar region (almost the same MNI coordinates) to be significantly activated during unusualness processing in general, but not during passive conceptual expansion. The fact that we accounted for both originality and appropriateness of the association might explain the divergence between the findings.

2.5.3 Unusualness and Appropriateness

The processing of unusual object use combinations was also expected to lead to activations in the IFG and the temporal pole given the literature on semantic memory retrieval and storage processing, as well as the responsiveness of this region with reference to semantic associative strength (Bunge et al., 2005). The results of the current study however did not support these hypotheses. One possible interpretation of the results is to align it to what is known about semantic processing with regard to spreading activation in semantic networks (Collins & Loftus, 1975). In the HUHA and LUHA trials, a semantic connection between the concepts could be forged because of a strong (LUHA) or weak (HUHA) overlap of the activated associated semantic nodes. However, because the stimuli cannot be related to one another in the HULA trials, there would be no overlaps in the associated activated semantic nodes in the network that would enable the linkage of the two concepts. The semantic search process in the case of HULA could therefore be readily aborted because of the speed of the spontaneous spreading activation in semantic networks. The current behavioral data lends some support to this interpretation as the subjects responded “No” to the appropriateness question in the HULA condition with comparable speed as they did “Yes” to the appropriateness question in the LUHA condition. This indicates an equally prompt processing of the stimuli in both the HULA and LUHA condition with respect to the appropriateness question. The reported activation of the supramarginal gyrus in the HULA condition is in line with results from other studies investigating the active generation of unusual object uses (Fink et al., 2010).

The appropriateness conjunction yielded activation in posterior cingulate (BA 31) and parts of the frontomedian wall (BA 9/32), regions that are known to be involved in declarative memory retrieval (Abraham et al., 2008). In a more recent fMRI study, medial prefrontal cortex activation was shown to be associated with enhanced memory retrieval of information congruent with prior knowledge (van Kesteren et al., 2010). This corresponds partially with the current observations of appropriateness-related activations in medial prefrontal regions as information judged to be appropriate was either congruent with prior knowledge (LUHA) or could be added to existing knowledge (HUHA).

All in all the evidence suggests that the information processing of sheer unusualness or novelty recruits posterior brain regions, whereas appropriateness and conceptual expansion related information processing necessitates the involvement of frontal regions in the brain.

2.5.4 Other relevant findings

Our exploratory analysis revealed that apart from the IFG activation, the second main frontal activation cluster found during passive conceptual expansion comprised the dorsal ACC (BA 32) and parts of BA 8 and BA 6 (rostral cingulate zone). These areas are customarily thought to be involved in detection of errors or conflicts between competing representations as a form of action monitoring during decision making and the consequent recruitment of cognitive control mechanisms and adjustments in motor behavior (Botvinick et al., 2004; Carter & van, V, 2007; Mars et al., 2005; Rushworth et al., 2004; Ullsperger & von Cramon, 2004). This fits well with the considerations about what subjects actually had to do during the HUHA condition. We presume that the decision conflict was higher in the HUHA condition compared to the other two conditions (HULA, LUHA) given that the subjects had to initiate controlled search in semantic networks, select between competing representations and to adjust their decision outcome as a consequence of the successfully retrieved conceptual links between the presented object-use pair. Such demands could render the engagement of the rostral cingulate zone necessary. This region has indeed been reported in other neuroimaging studies of creative thinking, especially in insight problem solving experiments (Aziz-Zadeh et al., 2009; Jung-Beeman et al., 2004).

2.5.5 Summary and Conclusions

In summary, a novel neuroscientific paradigm was successfully developed to investigate one mental operation underlying our ability to think creatively, namely passive conceptual expansion. In doing so, we overcame traditional approaches in the field of creativity research which dealt with the creativity construct as a unitary entity. This study is also the first to dissociate the brain activity relating to the conjoined and separable effects of originality versus relevance, the two defining components of creativity. The next step in investigating operations underlying creative conceptual expansion would be to compare the current findings with those ensuing from an active conceptual expansion paradigm in terms of both qualitative and quantitative differences. Future neuroimaging research on creative thinking should also consider the role played by other relevant mental operations, such as creative imagery and the constraining influence of examples (Abraham & Windmann, 2007)

The findings of the present study show that a better understanding of the neural correlates of creative thinking is enabled when paradigms are developed that are optimised for neuroscientific investigations and where the construct of creative thinking is broken down into its underlying processes. Moreover, the findings highlight the need to integrate the literature on the neuroscience of creative thinking with that of “normative” cognition and to generally do away with the conviction that creative operations are qualitative different from other mental processes.

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Author Contributions

SK and AA wrote the paper. AA conceived of the study. SK carried out the study and the analyses. SK, BR and AA developed the final experimental design. SW and BR provided theoretical and methodological expertise at several stages of the project. RS and CH provided methodological expertise and laboratory settings to carry out the study.

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2.7 Supplementary material

List of stimuli used in the experiment and the proportion of classifications among all subjects.

Object -> Use	HUHA	HULA	LUHA	Error
Kaugummi -> Atemfrische	0	0	100	0
Kaugummi -> Dünger	16,8	84,2	0	0
Kaugummi -> Spachtelmasse	84,2	16,8	0	0
Küchenschere -> Packungsöffner	5,3	0	94,7	0
Küchenschere -> Zahnbürste	0	100	0	0
Küchenschere -> Pizzaschneider	94,7	0	5,3	0
Stromkabel -> Steckdosenverbindung	10,5	0	84,2	5,3
Stromkabel -> Strickwolle	26,3	68,4	5,3	0
Stromkabel -> Springseil	94,7	5,3	0	0
Kunstrasen -> Fußballrasen	0	0	100	0
Kunstrasen -> Fernseher	0	100	0	0
Kunstrasen -> Badvorleger	89,5	10,5	0	0
Wodka -> Cocktailzutat	5,3	0	89,5	5,3
Wodka -> Essigersatz	42,1	57,9	0	0
Wodka -> Brillenputzmittel	89,5	10,5	0	0
CD-ROM -> Datenträger	0	0	100	0
CD-ROM -> Reifen	5,3	94,7	0	0
CD-ROM -> Untersetzer	84,2	5,3	10,5	0
Kissenbezug -> Bettwäsche	0	5,3	94,7	0
Kissenbezug -> Einkaufswagen	26,3	68,4	0	5,3

Kissenbezug -> Salatschleuder	52,6	36,8	10,5	0
Kaffeefilter -> Kaffeezubereitung	0	0	100	0
Kaffeefilter -> Tasse	5,3	78,9	10,5	5,3
Kaffeefilter -> Mundschutz	84,2	15,8	0	0
Schwimmflossen -> Schwimmhilfe	0	0	100	0
Schwimmflossen -> Toaster	0	100	0	0
Schwimmflossen -> Ventilatorblätter	73,7	26,3	0	0
Kokosnuss -> Nahrung	5,3	0	94,7	0
Kokosnuss -> Tastatur	0	100	0	0
Kokosnuss -> Bocciakugel	89,5	10,5	0	0
Babybett -> Schlafmöglichkeit	0	5,3	94,7	0
Babybett -> Rakete	15,8	78,9	0	5,3
Babybett -> Hasenstall	89,5	5,3	5,3	0
Duschkopf -> Wasserspender	10,5	0	89,5	0
Duschkopf -> Kochlöffel	36,8	63,2	0	0
Duschkopf -> Hammer	84,2	15,8	0	0
Schlittschuh -> Eislaufen	0	0	100	0
Schlittschuh -> Feuerlöscher	0	100	0	0
Schlittschuh -> Hackmesser	89,5	10,5	0	0
Scheckkarte -> Zahlungsmittel	5,3	0	89,5	5,3
Scheckkarte -> Monitor	0	94,7	0	5,3
Scheckkarte -> Buttermesser	84,2	15,8	0	0
Nagelfeile -> Maniküre	0	0	94,7	1
Nagelfeile -> Klebeband	0	94,7	5,3	0
Nagelfeile -> Möhrenschäler	57,9	42,1	0	0
Paddel -> Ruderhilfe	0	0	94,7	5,3

Paddel -> Würfel	0	100	0	0
Paddel -> Brotschieber	73,7	21,1	5,3	0
Schuh -> Kleidungsstück	0	0	100	0
Schuh -> Computer	0	100	0	0
Schuh -> Blumentopf	68,4	26,3	5,3	0
Nylonstrumpf -> Frauenkleidung	0	0	100	0
Nylonstrumpf -> Luftballon	0	100	0	0
Nylonstrumpf -> Staubfilter	89,5	10,5	0	0
Toilettenpapier -> Hygieneartikel	5,3	0	94,7	0
Toilettenpapier -> Locher	7	94,7	7	5,3
Toilettenpapier -> Kissenfüllung	100	0	0	0
Tennisschläger -> Sportgerät	0	0	100	0
Tennisschläger -> Duschvorhang	0	100	0	0
Tennisschläger -> Nudelsieb	78,9	21,1	0	0
Skateboard -> Skaten	0	0	100	0
Skateboard -> Schornstein	0	94,7	0	5,3
Skateboard -> Topfuntersetzer	78,9	10,5	5,3	5,3
Eiswaffel -> Eiskugelbehälter	0	0	100	0
Eiswaffel -> Heckenschere	0	100	0	0
Eiswaffel -> Sandförmchen	78,9	15,8	5,3	0
Stricknadel -> Handarbeit	0	0	100	0
Stricknadel -> Zigarre	0	100	0	0
Stricknadel -> Essstäbchen	94,7	0	0	5,3
Plattenspieler -> Musikabspielgerät	0	0	100	0
Plattenspieler -> Waage	5,3	89,5	0	5,3
Plattenspieler -> Töpferscheibe	89,5	5,3	0	5,3

Trampolin -> Turngerät	0	0	100	0
Trampolin -> Motorroller	0	100	0	0
Trampolin -> Bett	84,2	5,3	10,5	0
Bügelbrett -> Bügelunterlage	0	0	100	0
Bügelbrett -> Wasserkocher	0	100	0	0
Bügelbrett -> Wandregal	57,9	42,1	0	0
Gabel -> Essen	0	0	100	0
Gabel -> Hundehütte	0	100	0	0
Gabel -> Kamm	94,7	0	5,3	0
Zuckerguss -> Kuchenglasur	0	0	100	0
Zuckerguss -> Bodylotion	21,1	78,9	0	0
Zuckerguss -> Haarstyling	57,9	31,6	10,5	0
Thermoskanne -> Kaffeewärmer	5,3	0	89,5	5,3
Thermoskanne -> Schuh	5,3	94,7	0	0
Thermoskanne -> Vase	94,7	0	0	5,3
Streichhölzer -> Anzünder	0	0	100	0
Streichhölzer -> Radkappe	0	94,7	0	5,3
Streichhölzer -> Käsespieße	94,7	0	5,3	0
Bierkasten -> Flaschentransport	10,5	0	89,5	0
Bierkasten -> Teleskop	0	100	0	0
Bierkasten -> Nachttisch	89,5	0	10,5	0
Klobrille -> Sitzfläche	10,5	5,3	84,2	0
Klobrille -> Golfschläger	15,8	84,2	0	0
Klobrille -> Bilderrahmen	78,9	15,8	0	5,3
Tür -> Durchgang	5,3	0	94,7	0
Tür -> Schubkarre	5,3	94,7	0	0

Tür -> Tischtennisplatte	84,2	15,8	0	0
Surfbrett -> Wellenreiten	5,3	0	89,5	5,3
Surfbrett -> Kochtopf	0	100	0	0
Surfbrett -> Bügelbrett	89,5	5,3	5,3	0
Gießkanne -> Gartengerät	0	0	100	0
Gießkanne -> Hut	21,1	0	78,9	0
Gießkanne -> Weinkaraffe	94,7	5,3	0	0
Strohhalm -> Trinken	68,4	26,3	0	5,3
Strohhalm -> Rasierer	0	100	0	0
Strohhalm -> Pipette	68,4	26,3	5,3	0
Pfannenwender -> Küchenutensilie	0	0	100	0
Pfannenwender -> Fernbedienung	5,3	94,7	0	0
Pfannenwender -> Spachtel	89,5	0	0	10,5
Spaghetti -> Pastagericht	0	0	100	0
Spaghetti -> Wattebausch	0	100	0	0
Spaghetti -> Mikado	89,5	10,5	0	0
Billardkugel -> Billardspiel	0	0	100	0
Billardkugel -> Hängematte	0	100	0	0
Billardkugel -> Türknauf	94,7	5,3	0	0
Zollstock -> Messinstrument	0	0	100	0
Zollstock -> Ball	0	100	0	0
Zollstock -> Gardinenstange	84,2	10,5	0	5,3
Kronkorken -> Flaschenverschluss	0	0	100	0
Kronkorken -> Zahnbürste	0	100	0	0
Kronkorken -> Ausstechform	84,2	10,5	0	5,3
Wattebausch -> Abschminken	0	0	100	0

Wattebausch -> Laterne	5,3	89,5	0	5,3
Wattebausch -> Christbaumschmuck	78,9	5,3	15,8	0
Kanu -> Boot	0	0	89,5	10,5
Kanu -> Telefon	0	100	0	0
Kanu -> Badewanne	100	0	0	0
Löffel -> Besteck	0	5,3	94,7	0
Löffel -> Portemonnaie	0	94,7	5,3	0
Löffel -> Blumenschaufel	94,7	5,3	0	0
Geweih -> Wandschmuck	5,3	5,3	84,2	5,3
Geweih -> Degen	52,6	47,4	0	0
Geweih -> Kleiderhaken	94,7	0	5,3	0

3 Study 2

An ERP study of passive creative conceptual expansion using a modified alternate uses task.

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3.1 Abstract

A novel ERP paradigm was employed to investigate conceptual expansion, a central component of creative thinking. Participants were presented with word pairs, consisting of everyday objects and uses for these objects, which had to be judged based on the two defining criteria of creative products: unusualness and appropriateness. Three subject-determined trial types resulted from this judgement: High unusual and low appropriate (nonsensical uses), low unusual and high appropriate (common uses), and high unusual and high appropriate (creative uses). Word pairs of the creative uses type are held to passively induce conceptual expansion. The N400 component was not specifically modulated by conceptual expansion but was, instead, generally responsive as a function of unusualness or novelty of the stimuli (nonsense = creative > common). Explorative analyses in a later time window (500 – 900 ms) revealed that ERP activity in this phase indexes appropriateness (nonsense > creative = common). In the discussion of these findings with reference to the literature on semantic cognition, both components are proposed as indexing processes relevant to conceptual expansion as they are selectively involved in the encoding and integration of a newly established semantic connection between two previously unrelated concepts.

Keywords: creativity; ERP; N400; conceptual expansion; alternate uses task, divergent thinking; semantic cognition

3.2 Introduction

3.2.1 Current state of creativity research

Ever since brain based investigations of creative thinking emerged around two decades after Joy Paul Guilford gave his Presidential Address about creativity to the American Psychological Association in 1950 (Arden et al., 2010; Guilford, 1950), many efforts have been made to investigate our ability to think creatively. While neuroscientific investigations of creativity primarily employed EEG based methodologies, the past 10-15 years have also witnessed a great surge of neuroimaging studies on creative thinking. However, we are still far from understanding the specific neural underpinnings of creative cognition as what has emerged after four decades of creativity research are a multitude of scattered results and few consistent conclusions (Arden et al., 2010; Dietrich & Kanso, 2010). This is due to many factors such as a great deal of diversity in how creative thinking is measured, as well as a high variance regarding appropriate control tasks. In addition, the neuroscientific study of creativity is also challenging as it is often difficult to determine the exact time point of the process of interest, as well as to obtain enough trials to reach sufficient statistical power, or, for instance, to prevent movement inducing responses which could lead to artefacts (Abraham et al., 2012b; Abraham, 2012).

One further challenging problem is that there is a tendency to investigate creativity as though it is a unitary construct (Dietrich & Kanso, 2010). In an effort to go against such trends, new paradigms have been adopted in recent neuroimaging studies where select operations of creativity, such as conceptual expansion, have been targeted (Abraham et al., 2012a; Abraham et al., 2012b; Rutter et al., 2012b; Kröger et al., 2012) Conceptual expansion describes the ability to broaden the defining boundaries of semantic concepts beyond their usual characteristics (Smith et al., 1995; Ward, 1994) This is a process that is vital in the generation of novel ideas and it has been investigated in fMRI studies using paradigms that call for active generation (Abraham et al., 2012b) or passive induction (Rutter et al., 2012b; Kröger et al., 2012) of conceptual expansion. Few ERP studies, however, have been conducted thus far to assess conceptual expansion or indeed any other aspect of creativity.

3.2.2 Previous ERP research on creativity

Traditionally, EEG studies in the field of creativity research have focused on either amplitude or synchronization changes associated with creative performance, but seldom have ERP components been explored in relation to creative cognition (Arden et al., 2010; Dietrich & Kanso, 2010). Until recently, the only exception to this case were a handful of investigations on insight problem solving (Lang et al., 2006; Lavric et al., 2000; Luo et al., 2011; Qiu et al., 2008).

In a recent study conducted by Rutter and colleagues (2012a), a novel and promising way to investigate creative thinking using ERP methods was established. In this study, conceptual expansion was successfully linked to the well-known N400 component. Rutter et al. (2012a) used metaphorical statements as stimuli and compared creative (unusual and appropriate), nonsensical (unusual and inappropriate) and literal phrases (usual and appropriate) which were classified as such by subjects on a trial-by-trial basis. One of their findings was that the N400 and a late ERP component were modulated as a function of the unusualness of the stimuli.

The N400 component is a well-documented ERP component which is characterized as a negative-going waveform between 200 and 600 ms, which peaks around 400 ms after the critical event. It usually shows a centro-parietal distribution and a slight right-hemisphere bias (Kutas & Federmeier, 2011). This ERP component was first reported as a brain response to semantically incongruent sentence endings, such as “He took a sip from the *transmitter* (Kutas & Hillyard, 1980). The authors proposed that a higher N400 signalled an interruption of on-going sentence processing and a search for meaning in the sentence. Following the original discovery, several studies have investigated the N400 using a variety of paradigms. This ERP component is held to be highly relevant for indexing lexical and semantic aspects of language processing as well as semantic memory and recognition memory (Kutas & Federmeier, 2011; Lau et al., 2008).

3.2.3 The present study

To investigate the link between conceptual expansion to the N400 component, this present study adapted a paradigm used in an fMRI study by Kröger et al. (2012) where conceptual expansion was induced using a modified version of the alternate uses task (Wallach & Kogan, 1965). The original alternate uses task requires the generation of as many uses as possible for common objects (e.g., a shoe) and thereby necessitates that the subject expands the usual conceptual boundaries in which the object is customarily used (e.g., foot protection) to include novel dimensions (e.g., plant pot, ashtray). The responses in the classic alternate uses task are not differentiated in terms of the degree to which they encompass the two defining components of creativity, which are Originality (novel, unique) and Appropriateness (relevant, meaningful) (Runco & Jaeger, 2012). The current modification of original paradigm, however, enables the concurrent consideration of both these components separately (originality OR appropriateness) as well as together (originality AND appropriateness).

In this experimental task (Figure 1), subjects were shown word pairs consisting of an everyday object and a potential use for this object. Subjects had to decide on a trial-by-trial basis whether they found the use for the given object to be unusual appropriate or both.

Three different trial outcomes were possible: object use combinations rated as highly unusual and highly appropriate (creative uses), or highly unusual and low appropriate (nonsensical uses) or low unusual and highly appropriate (common uses). Subjects were informed that the fourth trial outcome of a no-no response (low unusual and low appropriate) was not possible and would not make sense because a low appropriate object-use combination is always highly unusual. This experimental design therefore allowed each trial to be individually validated by each participant as belonging to one of the three conditions (creative uses, nonsensical uses, common uses). Trials in which subjects judged a particular object use combination to be highly unusual and highly appropriate (creative uses) are trials in which conceptual expansion was passively induced. This is because subjects needed to loosen and expand the conceptual boundaries of the object in order to make a new semantic connection between the previously unrelated object-use concepts.

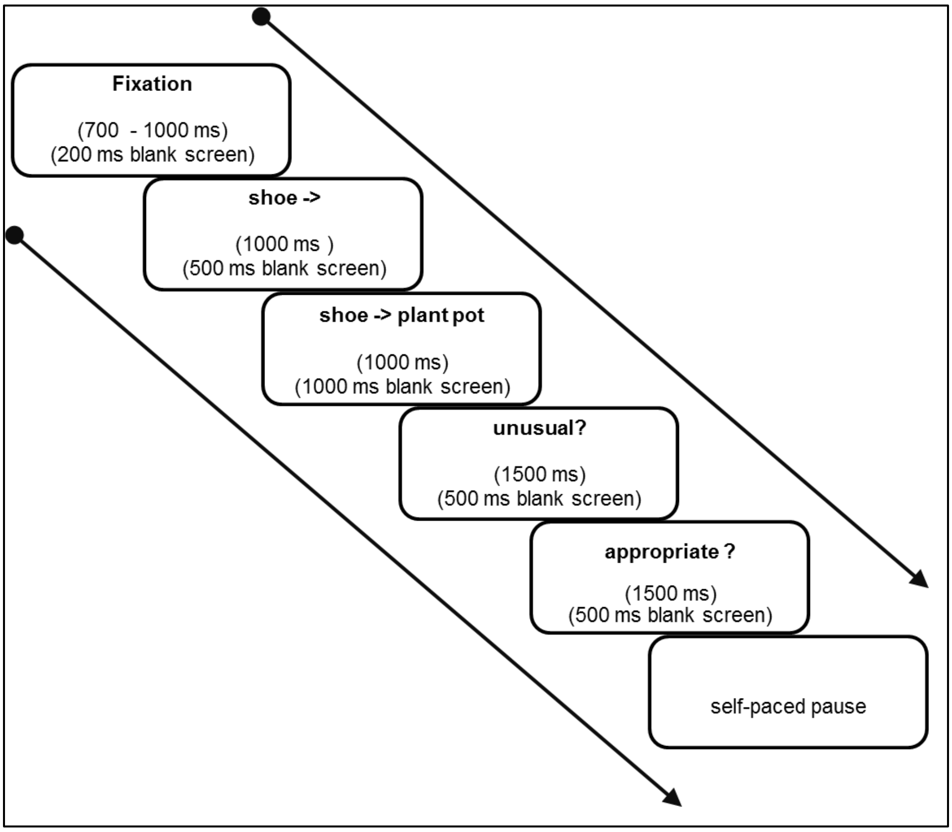

Figure 1. Experimental trial overview: The fixation period lasted between 700 ms and 1000 ms (steps of 100 ms). Total trial length from fixation cross to onset of the break thus varied between 8400 and 8700 ms.

In line with the literature, we expect a modulation of the N400 as a function of the semantic congruence of the given object-use combination. Trials judged as low unusual and high appropriate (common uses) should result in a reduced N400 amplitude as no violation of prior world knowledge occurred (Hagoort et al., 2004). This would be in contrast to trials judged as high unusual and low appropriate (nonsensical uses), which should show a strong N400 amplitude. The interesting case would be the N400 pattern associated with the trials judged as highly unusual and highly appropriate (creative uses), where conceptual expansion was induced as novel but fitting associations were made. On the one hand, a semantic mismatch or incongruence occurs as the subject is exposed to a wholly novel semantic association. Thus, just as in the case of the nonsensical uses, the N400 associated with the creative uses is expected to be significantly higher than that of the common uses. On the other hand, unlike the nonsensical uses, creative object use combinations can be successfully integrated into existing semantic networks. Rutter et al. (2012a) reported a graded effect in the N400 time window with the highest amplitude for nonsensical metaphors and more positive amplitudes for creative metaphors, followed by literal phrases (N400: nonsense > creative > common).

If the N400 reflects solely semantic or world knowledge violations, we expect the N400 to be undifferentiated between the creative uses and nonsensical uses. However, if the N400 is also responsive to the successful integration of novel semantic association into existing knowledge structures, we expect the N400 amplitude to be smaller in the case of creative uses compared to nonsensical uses, in line with the findings of Rutter et al. (2012a).

3.3 Materials and Methods

3.3.1 Participants

Twenty-four right-handed students either received a 15 Euro payment or course credit for their participation in the experiment. Handedness was assessed using the German version of the Edinburgh Inventory of Handedness (Oldfield, 1971). Four subjects had to be excluded from further analysis because they did not reach the minimum inclusion criterion of at least 30 trials per condition (see Data Analyses section for further details). The final sample therefore comprised 20 native German-speaking subjects (11 women; age range = 20-27 years, mean = 22.55, SD = 2.1) with normal or corrected-to-normal vision. None of the participants had a history of neurological or psychiatric illness, and none were taking drugs according to self-report. All gave written informed consent before participation. The experimental standards were approved by the ethics committee of the German Society of Psychology (Deutsche Gesellschaft für Psychologie).

3.3.2 Task Design/Procedure

Participants were seated in front of a computer monitor in a separate room that was isolated from that of the experimenter and the computers. After applying the electrodes the participants were given task instructions and performed a 10-minute practice session on a computer with another set of stimuli. Stimuli were presented using Presentation software (Neurobehavioral Systems, Inc., Albany, CA) and consisted of black letters (size = 28) on a grey background. During each trial, subjects viewed two consecutive words consisting of a common object (first word) and a described use for this object (second word).

Each trial (see Figure 1) started with a fixation cross presented in the middle of the screen, lasting between 700 and 1000 ms, which was jittered in steps of 100 ms. After a 200 ms blank screen, the first word (common object) was shown for 1000 ms followed by a 500 ms blank screen and the second word (described use, further referred to as critical word) lasting for another 1000 ms. We chose to present the two words one after another to prevent any overlap between ERP components. Following a 1000 ms blank screen, the questions “Unusual” and “Appropriate” each appeared for 1500 ms, separated by a 500 ms blank screen. Subjects were asked to give a yes/no answer to each of these questions by pressing either the left or the right arrow key of a computer keyboard with the index finger and the ring finger of their right hand.

Participants were instructed to decide whether they found a given object use combination to be unusual and/or appropriate. To prevent misunderstandings with what was meant with the words “unusual” and “appropriate”, they were told that a use was to be classified as “unusual” if it was novel or unfamiliar to them and “not unusual” if it was known or familiar. They were also instructed that a use was to be classified as “appropriate” if it was fitting or relevant and “not appropriate” if it was unfitting or irrelevant. Each stimulus was categorized as belonging to one of three possible conditions based on the participant’s response. The three possible conditions were: high-unusual and high-appropriate (creative uses, yes-yes response), high-unusual and low-appropriate (nonsensical uses, yes-no response) and low-unusual and high-appropriate (common uses, no-yes response). Subjects were also informed that a no-no response (low unusual and low appropriate) would not make sense as a low appropriate object-use combination is always highly unusual.

After each trial, participants had the opportunity to take a break and start the next trial at their own pace, via button press of the up arrow key, to prevent extensive blinking and exhaustion. With a trial length of 10 seconds and a total of 135 trials, presented in a pseudo-randomized order, the experimental session lasted approximately 25 minutes (pauses taken by the participants not included).

3.3.3 Materials

The study used a stimulus-set created for a previous fMRI study (Kröger et al., 2012) which was adapted to meet ERP criteria for investigating the N400 component. 45 experimenter-determined word pairs per condition were used to ensure the high likelihood of there being a minimum of 30 subject-determined trials in each condition. Each object was used in all three experimenter-determined conditions (creative uses, nonsensical uses and common uses) in combination with a described use for this object (for examples see Table 1). Words were checked for word length and frequency of occurrence in the German language. A one-way ANOVA revealed that there were no significant differences in word length between the three experimenter-determined conditions (F (2, 132) = 1.37; p = .26). Frequency of occurrence in the German language was computed using the online Vocabulary Database of the University of Leipzig in Germany (http://wortschatz.uni-leipzig.de/). The frequency classes of this database indicate the frequency of the target word in relation to the German definite article “der” (“the”). For example the word “der” (“the”) is 2^9 times more frequent than the word “Ball” (“ball”). A median test comparing the three conditions confirmed that they did not differ significantly regarding the frequency of occurrence (md = 19 for creative uses and nonsensical uses, md = 18 for common uses; p = .7).

Table 1. Example Stimuli for all three conditions (creative uses, nonsensical uses, common uses) in German. English translation is added below the original stimulus.

Condition	Stimulus
Highly unusual and highly appropriate *(creative associations)*	Schuh -> Blumentopf *shoe -> plant pot*
Highly unusual and low appropriate *(nonsensical associations)*	Schuh -> Osterhase *shoe -> Easter bunny*
Low unusual and highly appropriate *(common associations)*	Schuh -> Kleidungsstück *shoe -> piece of clothing*

3.3.4 ERP recording

The electroencephalogram (EEG) was recorded from 64 Ag/AgCl electrodes using an actiCAP system (Brain Products GmbH, Gilching, Germany) and BrainVision recorder software. Data was recorded using an average-reference on-line. The EEG signal was amplified by a QuickAmp amplifier (Brain Products GmbH, Gilching, Germany) and sampled at 500 Hz by a 24 bit analogue-to-digital converter. Impedances were kept below 5 kΩ. Eye blinks and movements were recorded by bipolar EOG electrodes that were placed above and below the right eye, as well as in horizontal position next to both eyes.

3.3.5 Data Analysis

As the subjects determined which trials should be allotted to each condition (creative uses, nonsensical uses, common uses) with their responses, it was important to establish sample homogeneity using a priori inclusion criterion that ensured a minimum number of trials per condition across all subjects in the final sample. Behavioral pilot studies indicated that some variability was unavoidable when using subject-determined trial classifications as participants vary from one another on the evaluation of whether a particular object-use combination should be considered as unusual and appropriate. While the subject-determined trial classification is certainly the major strength of the current paradigm as it ensures the individual validation of the experimental design, it also necessitates the exclusion of all participants who did not meet the strict inclusion criterion of having at least 30 trials per condition.

In order to detect significant differences in reaction times (RTs), a 3 x 2 repeated measures ANOVA was carried out, with the factors Condition (creative uses, nonsensical uses, common uses) and Question (Unusual, Appropriate).

EEG data were analyzed using the Vision Analyzer 2.0 software (Brain Products GmbH, Gilching, Germany). Raw data were initially filtered with a 50 Hz notch and a 0.01 Hz high-pass filter and afterwards segmented into epochs of 1150 ms duration. Each segment started at 150 ms before the onset of the critical word and belonged to one of the three possible conditions (creative uses, nonsensical uses or common uses) based on the participants' responses. Segments were baseline-corrected using the 150 ms time window before onset of the critical word. Eye blinks were removed using an ocular correction procedure based on the Gratton & Coles algorithm (Gratton et al., 1983). A 30 Hz low-pass filter with a slope of 24 db/Oct was applied and artefacts with amplitude exceeding +/-50 μV were removed. ERP waveforms were averaged for each participant and each condition. Subsequently grand-averaged ERPs of all participants were calculated in time windows of interest. An early time window (300-500 ms) and a late window (500-900 ms) were used to capture the N400 effect as well as any late components. This latter time window was chosen on the basis of a former study conducted by Rhodes and Donaldson, who tried to capture any continuation of an observed N400 effect (Rhodes & Donaldson, 2008).

For each time window, a repeated measures ANOVA was computed using the CPz electrode and its eight neighbouring electrodes (C1, Cz, C2, CP1, CP2, P1, Pz, P2) as one factor (electrodes) and the three conditions (creative uses, nonsensical uses, common uses) as another factor (conditions). The electrode sites were chosen on the background of the known centro-parietal distribution of the N400 effect (Kutas & Federmeier, 2011) and in order to explore later ERP components following the N400, after visual inspection of the data.

Pairwise Bonferroni-corrected comparisons were carried out within the repeated measures analysis to assess possible main and interaction effects. In all cases, effects sizes (Cohen's *d* and partial eta squared $\eta 2$) are reported along with significance levels.

The Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) was applied to all ERP repeated measures analyses with more than one degree of freedom because the assumption of sphericity was violated. Corrected p-values with the original degrees of freedom are reported for both ERP time windows.

3.4 Results

3.4.1 Behavioral Findings

The mean concordance between experimenter-determined conditions and subject-determined conditions was highest for common uses (92.8 %) followed by nonsensical uses (88.3 %) and creative uses (80.2 %), showing that, as expected, the creative uses were judged more subjectively than the other uses ($p < .05$).

Table 2 shows the mean reaction times and standard deviations across all conditions to both questions. The repeated measures ANOVA with the factors condition (creative uses, nonsensical uses, common uses) and question (first question = unusual, second question = appropriate) revealed significant main effects for both the factors: condition (F (2,38) = 11.1; $p < .001$; partial eta squared $\eta 2 = .37$) and question (F (1,19) = 71.4; $p < .001$; partial $\eta 2 = .79$).

These main effects indicate that responses to creative uses and nonsense uses were associated with longer reaction times than in the case of common uses and that responses to the first question (Unusual?) were significantly slower than responses to the second question (Appropriate?). A significant interaction effect (condition x question) between both the factors was also found (F (2,38) = 8.5; p = .001; partial $\eta 2 = .31$).

Table 2. Reaction times (Mean and Standard Deviation) for all conditions in milliseconds.

Conditions	**Unusual** (Question 1)		**Appropriate** (Question 2)	
	Mean	SD	Mean	SD
HUHA	712	180	601	183
HULA	751	156	571	167
LUHA	655	153	546	143

Bonferroni-corrected ($p < .05$) post hoc t-tests which were conducted to explore the interaction effect revealed that subjects responded significantly faster to the first question in the common uses condition compared to the first question in the creative uses ($p = .015$; Cohen`s $d = .34$) and nonsensical uses conditions ($p < .001$; $d = .62$). Additionally, subjects responded significantly faster to the second question in the common uses condition compared to the second question in the creative uses condition ($p = .027$; $d = .34$).To further explore this interaction effect, a 2 x 2 repeated measures ANOVA with the factors condition (creative uses, nonsensical uses) and question revealed that even after removing the common uses from the analysis a significant interaction effect remained ($F(1,19) = 21.2$; $p < .001$; partial $\eta 2 = .53$). This indicates that the resulting interaction is due to the fact that responses to the first question (unusual) were slower in nonsensical uses trials than in the creative uses trials, but were faster in nonsensical uses trials following the second question (appropriate)[2].

3.4.2 ERP Findings: General

Grand average waveforms of 36 electrode sites covering the entire scalp are shown in Figure 2. The waveforms of single electrode sites Cz and C2 are depicted in Figure 3 for a closer illustration of the negative going peak around 400 ms (N400) after onset of the critical word. Starting at around 500 ms a positive-shift can be seen in all three conditions which is smaller for nonsensical uses trials compared with creative and common uses trials.

The N400 differences between the conditions were such that creative uses ($p = .038$; $d = 2.48$) and nonsensical uses ($p = .027$; $d = 2.61$) elicited a significantly greater negative mean amplitude in this time window than the common uses. However, the N400 elicited during the processing of creative uses and nonsensical uses did not differ significantly from one another ($p = 1$; $d = .18$) (Figure 4).

[2] Please note that the RT data was derived from the time taken to respond to the question prompts, and not the time taken to respond to the stimuli. However, as information related to the question prompt is assessed prior to the prompt itself, we cannot make any clear claims about how the RT measurements directly relate to the cognitive processes in question. We nonetheless include the RT-related findings in the paper as it may be of interest to researchers in order to understand all the peripheral factors that relate to the implementation of this novel ERP paradigm in the study of creative cognition.

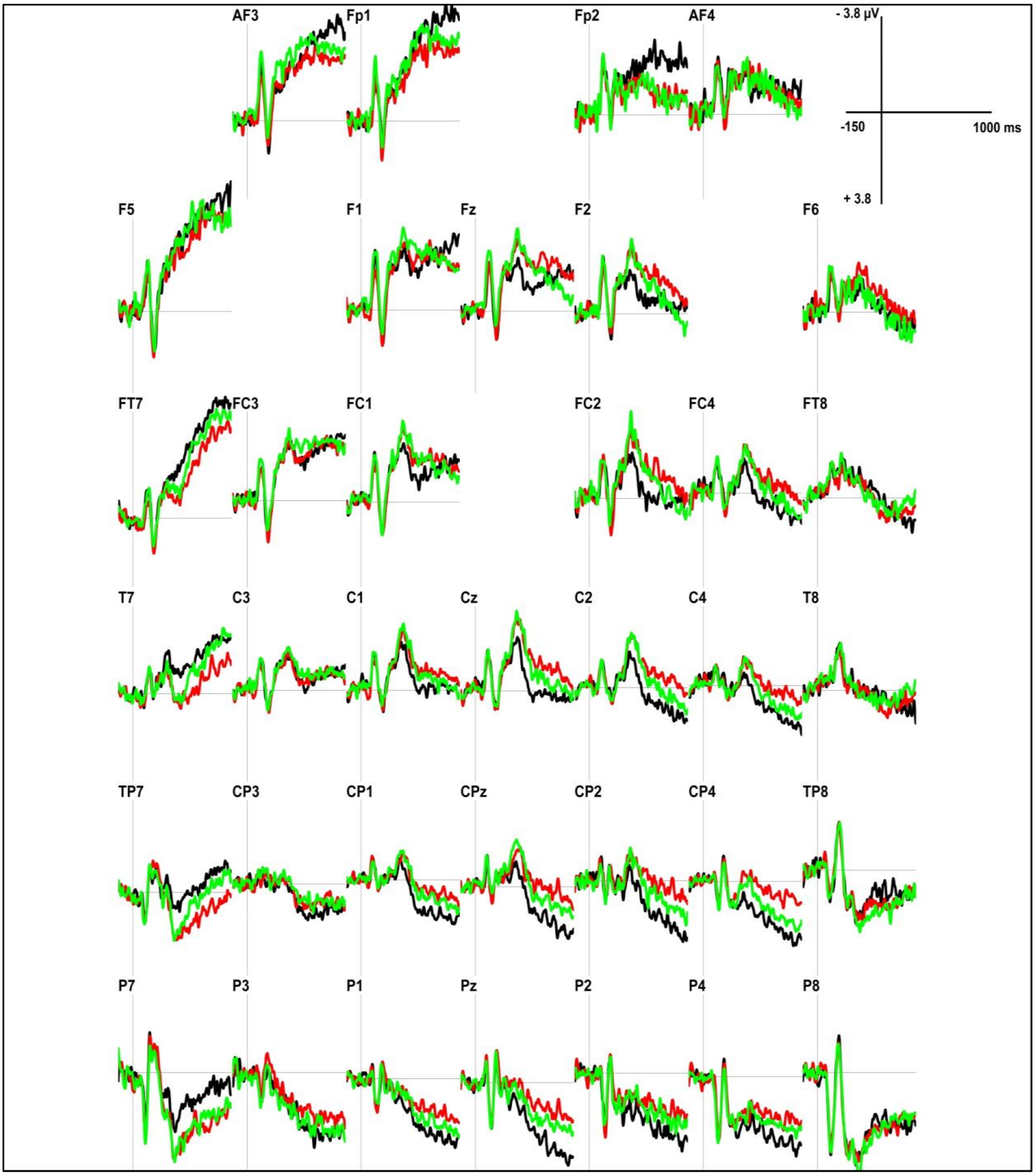

Figure 2. Grand-average ERPs for creative uses (green line), nonsensical uses (red line) and common uses (black line) on 36 electrodes. Vertical line marks onset of the critical word. Negativity is plotted upward.

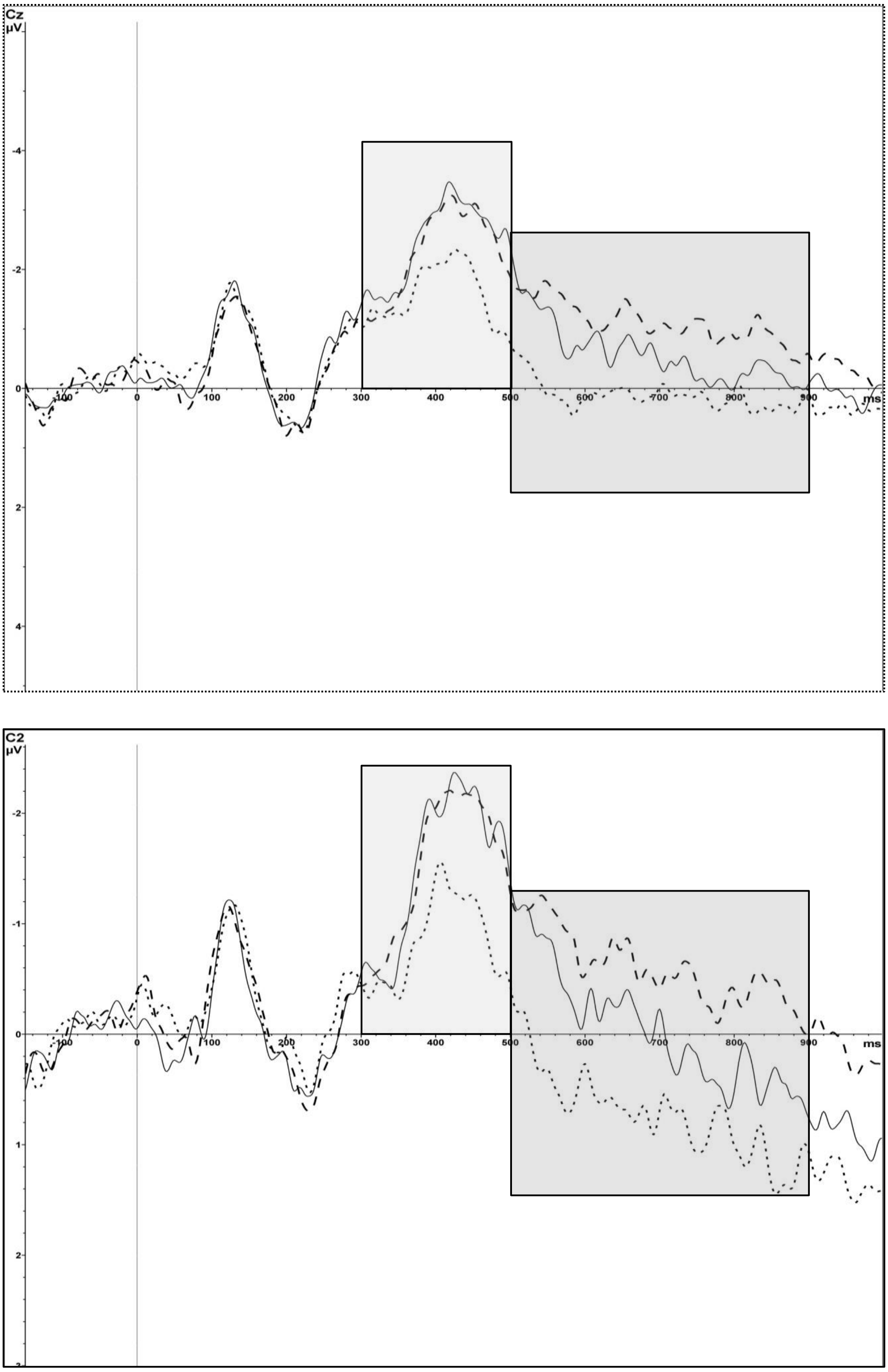

Figure 3. Grand average ERPs on electrode sides Cz and C2 for creative uses (solid line), nonsensical uses (dashed line) and common uses (dotted line). Light-gray box marks early time window (300 - 500ms, N400 analysis). Dark gray box marks late time window (500 - 900 ms, post-N400). Vertical line marks onset of the critical word. Negativity is plotted upward. Timeline in milliseconds.

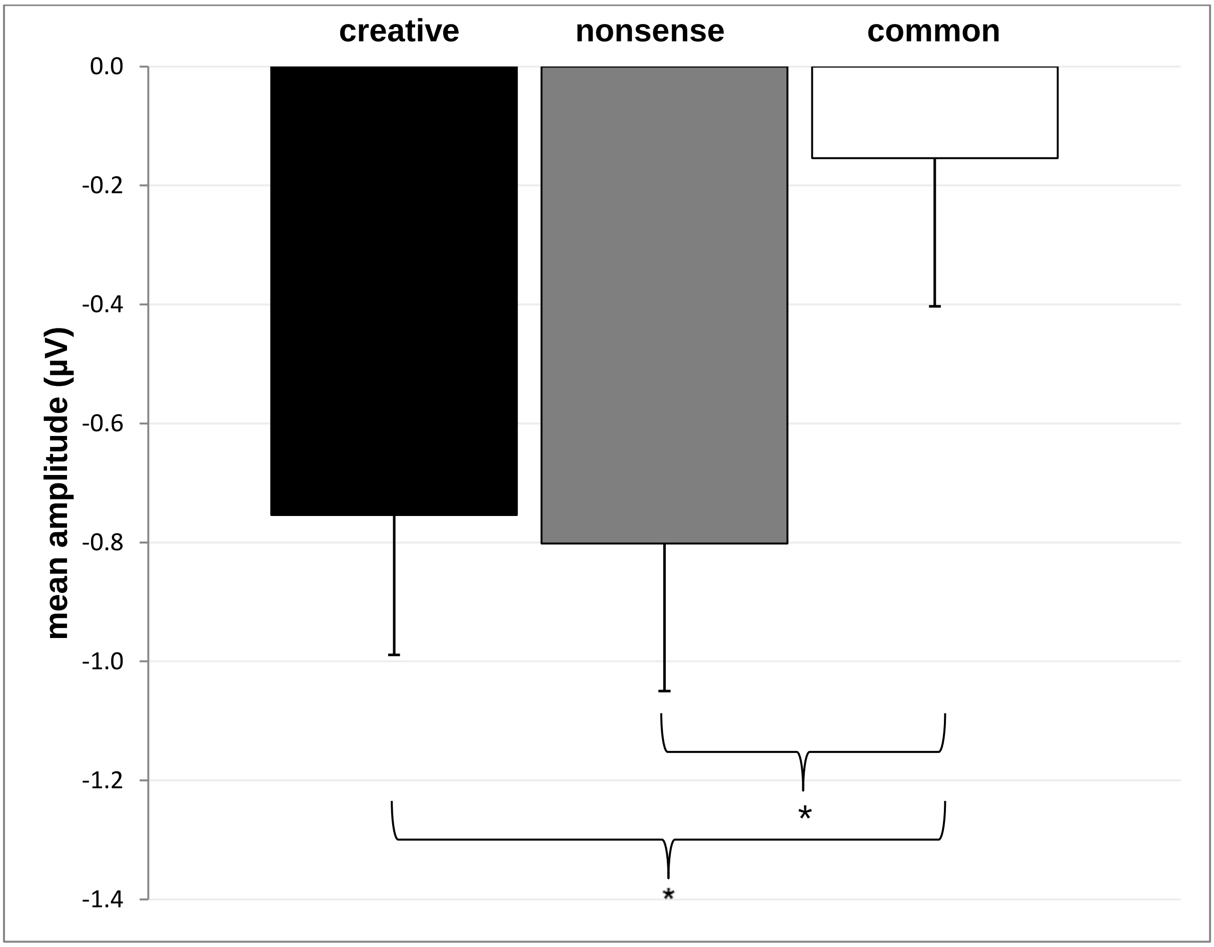

Figure 4. Mean amplitudes from nine electrodes (C1, Cz, C2, CP1, CPz, CP2, P1, Pz and P2) of all three conditions (creative uses, nonsensical uses, common uses) in early time window (300-500 ms, N400 effect). Error bars shown represent standard error of the mean. Significant differences ($p < .05$) are marked with an asterisk.

3.4.3 ERP Findings: Post-N400 late component (Time Window 500-900 ms)

To assess potential differences between the three conditions beyond the N400 time window, an explorative analysis was conducted in the late time window between 500 and 900 ms. As shown at electrode sites Cz and C2 in Figures 2 and 3, waveforms associated with nonsensical and creative uses begin to diverge after 500ms, with a greater sustained negativity for nonsensical uses but a more positive shift in case of creative uses.

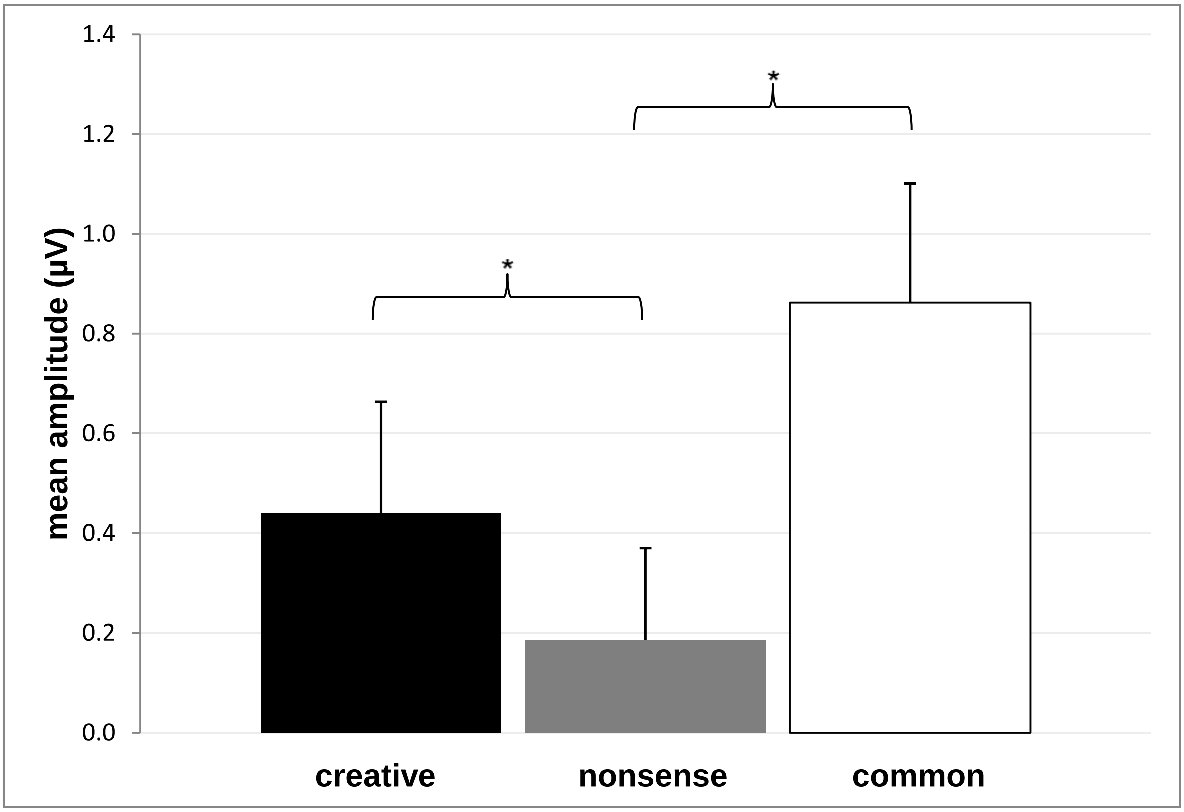

Figure 5. Mean amplitudes from nine electrodes (C1, Cz, C2, CP1, CPz, CP2, P1, Pz and P2) of all three conditions (creative uses, nonsensical uses, common uses) in later time window (500 -900 ms). Error bars shown represent standard error of the mean. Significant differences ($p < .05$) are marked with an asterisk.

The repeated measures ANOVA revealed significant main effects for the factor electrode (F (8,152) = 31.6; $p < .001$; partial $\eta 2$= .62) and condition (F (2,38) = 10.8; p = .001; partial $\eta 2$ = .36) and again no significant interaction of electrodes x condition (F (16,304) = 1.2; p = .3; partial $\eta 2$ = .06).

Moreover, just as in the case of the N400, the difference between waves elicited by the nonsensical uses and common uses in the later time window continued to be significant ($p < .001$; d = 4.32). However, unlike in the case of the N400, the waves elicited during processing of creative uses did not differ significantly from common uses in the late time window (p = .3; d = 1.83). While creative uses and nonsensical uses were undifferentiated in their N400 response, in the post-N400 late time window, the processing of creative uses led to a more positive amplitude shift compared to nonsensical uses (p = .011; d = 2.44) (see Figure 5).

3.5 Discussion

The aim of the current study was to investigate possible modulations of the well-established N400 ERP component alongside later potential ERP components by the creative cognitive process of conceptual expansion when compared to the information processing of mere novelty or appropriateness. A recent ERP study conducted by Rutter and colleagues (2012a) was also conducted to this end. However, in contrast to that study, the employed stimuli in the present study were not metaphors but word pairs consisting of everyday objects and of a described use for this object within a modified alternate uses task paradigm.

In doing so, we implemented several innovations in the investigation of creative thinking using EEG methods. First of all, we chose not to focus on creativity as a unitary entity and instead targeted one crucial mental operation of creative thinking, namely conceptual expansion. We also did not analyze EEG amplitude or synchronization changes but assessed the process of conceptual expansion with reference to specific time-locked ERP components. The experimental paradigm was designed such that each trial of the experiment had to be individually validated by each subject as belonging to a particular condition. Individual differences in the process of conceptual expansion were thus taken into account. This approach also allowed for the assessment of the separable effects of originality and appropriateness from that of creative conceptual expansion which arises from a combination of these factors (Kröger et al., 2012).

3.5.1 Modulation of the N400

The results clearly demonstrate that object-use pairs that were classified by the participants to be high unusual and low appropriate (nonsensical uses) or high unusual and high appropriate (creative uses) associations elicited significantly higher N400 amplitudes than those classified as low unusual and high appropriate (common uses). This fits perfectly with the N400 literature which suggests that the N400 is particularly responsive to semantic deviance. Moreover, the N400 amplitude difference between the nonsensical uses and creative uses was not significant which indicates that the N400 is sensitive to the levels of novelty or unusualness associated with the stimuli but not to differing levels of associated appropriateness of the conceptual combinations. This finding suggests that the mental operations in relation to conceptual expansion are not solely reflected in the N400 component. After all, the pattern of the N400 was not differentiated by the fact that although the creative object-use combination is semantically incongruent at first, unlike the case of the nonsensical object-use combination, the novel semantic association evoked by the creative uses can eventually be successfully integrated into one's knowledge structures.

Defining what the N400 indexes is a matter of on-going debate (Kutas & Federmeier, 2011). While some classify the N400 as a correlate of an early prelexical stage of the comprehension processing stream (Deacon et al., 2000) others associate the N400 with a later postlexical stage (Hagoort et al., 2004). The fact that the N400 is influenced by top-down processes as well as bottom-up processes, led to the recent proposal by Lotze and colleagues (2011), that the degree of matching between top-down processes and bottom-up information is reflected in the N400 modulation, with a mismatch resulting in a higher N400 amplitude. In their study they were able to show, for example, that pure form-based information (uppercase letters) could attenuate the N400 effect of a critical word (Lotze et al., 2011).

Given that the current study was not designed to test the validity of these competing theories, the findings of our study cannot be taken as direct support to any one of these theoretical formulations over another. As the N400 amplitudes were higher upon exposure to both the creative and nonsensical object-use combinations relative to the common object-use combinations in the current study, we postulate that the modulation seen here is likely to reflect a mismatch between expectations or world knowledge and the critical word. This mismatch led to comparable N400 amplitudes in both the nonsensical uses and creative uses condition relative to the common uses condition (nonsensical uses = creative uses > common uses).

The N400 pattern shown in the current study is only partially comparable to the reported N400 pattern in the study of Rutter and colleagues (2012a). Although the reported main effects were comparable in both studies, a linear trend was also discovered in the Rutter et al. (2012) study which suggested a graded effect in the N400 time window, with the highest negative mean amplitude for nonsensical metaphors and less negative amplitudes for creative metaphors, both relative to literal phrases (N400: nonsensical > creative > common). Apart from the many differences in the methodological approach (stimulus material, analysed electrodes, subjects, statistical analysis, etc.) between the two studies, there are also critical differences between the cognitive demands of the two tasks used. When faced with the task employed in the current study, there is a higher need for inference generation to be able to judge whether a given object use combination is unusual and appropriate (e.g. creative uses: shoe → plant pot). In the study of Rutter et al. (2012a) the manner in which the presented concepts could be related to one another was far more obvious as the connection and direction of the association was explicitly stated within the sentence (e.g. creative phrases: The clouds wept over the fields).

We can thus conclude that the manner in which the N400 is modulated in semantically incongruent contexts may be dependent on one or more of these subtle factors, which could in turn lead to discrepancies across studies in this early ERP time window.

3.5.2 Late ERP components (Post-N400: 500 – 900 ms)

As no significant difference was found between the amplitudes elicited by creative uses (conceptual expansion) and nonsensical object-use combinations in the N400 time window, an explorative analysis was run in a post-N400 time window to evaluate whether any differences between these conditions would emerge, as also reported by Rutter and colleagues (2012a). Significant differences between the amplitudes of the three conditions were found in that greater positive mean amplitudes were associated with the processing of creative uses and common uses compared to nonsensical uses. Just as in the case of the N400, the nonsensical object-use combinations continued to elicit a stronger relative negativity in the late window compared to the common object-use combinations. But there was a fascinating switch in the amplitude pattern associated with the creative object-use combinations as the brain activity associated with the processing of creative uses was no longer significantly differentiable from that of the common uses, whereas the difference between the mean amplitude of creative and nonsensical uses was highly significant (nonsensical > creative = common).

These findings also only partially fit with the results reported by Rutter et al. (2012a) in the later time window. They reported a linear trend which showed a graded effect (nonsensical > creative > common) with the lowest mean amplitude for nonsensical metaphors followed by creative metaphors, both relative to literal phrases. However, unlike in the present findings, the ERP waveform differences between the creative phrases and literal phrases was still significant (Rutter et al., 2012a).

On the basis of the pattern of findings in the current study, we postulate that the relative negativity in the nonsensical uses condition results from the continued failure to integrate the nonsensical object-use combination into existing semantic networks, whereas the positive shift found in the creative uses condition (and the common uses condition) could be indicative of a successful semantic integration process. As few ERP studies have been conducted to investigate creative thinking, we refer to findings from other related cognitive domains to aid our interpretation of this post-N400 effect.

Post-N400 slow wave effects have been previously described in studies on joke comprehension (Coulson & Williams, 2005; Coulson & Wu, 2005), as well as language comprehension tasks (Baggio et al., 2008; Baggio et al., 2010; Davenport & Coulson, 2011; Davenport & Coulson, 2013; Pijnacker et al., 2009; Rhodes & Donaldson, 2008). However, such slow wave effects were often observed as sustained negativities (Baggio et al., 2008; Coulson & Williams, 2005; Nieuwland & Van Berkum, 2008; van Berkum, 2009) or as late positivities (Davenport & Coulson, 2011; Davenport & Coulson, 2013) over frontal electrode sites. Studies that report slow wave effects over centro-parietal electrodes sites therefore offer a better comparison to the results found in the present study.

For example, Baggio et al. (2010) reported a similar centro-parietal slow wave effect following the reading of sentences like: “The journalist began the article before his coffee break”. These sentences necessitate the reader to infer that the journalist started to write the article. This “silent semantic element” therefore requires additional cognitive computations, which were reflected in a post-N400 time window (500-1000 ms) in form of a sustained negative shift (Baggio et al., 2010).

In a study by Pijnacker et al. (2010), participants had to decide whether a presented conditional inference was correctly drawn from a given modus ponens which was either preceded by a congruent or a disabling context (Pijnacker et al., 2010). A disabling context led to more rejections of the drawn conclusion and elicited a slow negative wave starting at around 250 ms after onset of the critical word and lasting until 1000 ms over central electrodes. The authors interpreted this slow wave negativity as a correlate of a “complex, inference-driven interpretive process” (Pijnacker et al., 2010).

Both studies thus reported a post-N400 sustained negativity possibly reflecting higher cognitive demands, which is not entirely in line with the present findings as the post-N400 sustained negativity was found for nonsensical uses which were not necessarily more cognitively demanding or involved complex inference processing.

The findings of Rhodes and Donaldson (2008) offer a better fit to the current results regarding the sustained negativity effect for nonsensical trials. In their experiment, unrelated word pairs elicited a comparable sustained negativity in a time window between 500 and 900 ms over left parietal electrode sites compared to word pairs which were either associatively or semantically related (Rhodes & Donaldson, 2008). The more positive amplitudes for related word pairs compared to unrelated word pairs were interpreted as recollection from long-term memory, possibly reflecting the well-known parietal old/new effect (Rugg & Curran, 2007). However, the effect in their study followed a left parietal distribution, whereas the effect in the present study showed a more right-lateralized centro-parietal distribution.

In summary, although there aremany findings regarding post-N400 slow wave effects, it is still difficult to draw clear conclusions about the function of such late ERP components. This is because each of these studies have targeted different cognitive processes with different paradigms, and therefore cannot be readily aligned with one another. While the studies could be partly related to one another with reference to the nonsensical uses condition and the findings of associated sustained negativity, there is little comparability between the paradigms in the context of the creative uses condition and the underlying process of conceptual expansion. So the hypothesis that the post-N400 late ERP component reflects the success associated with the semantic integration process is one that begs further exploration.

3.5.3 Conclusions and Implications

In summary, this study successfully adapted a novel experimental fMRI paradigm within an EEG setting (Kröger et al., 2012) to carry out one of the first ERP experiments to investigate conceptual expansion as one critical aspect of creative thinking. In doing so we have demonstrated that well-established ERP components can be used to investigate the neural correlates of creative thinking when suitable paradigms are developed that focus on specific creative cognitive processes.

The results of the current study, where a modified alternate uses task was used to assess passively induced creative conceptual expansion relative to novelty and appropriateness, found two ERP components to be instrumentally implicated in these operations: the N400 and a post-N400 late component. By relating these findings to those of related fields in the literature, it appears that the N400 acts like a semantic novelty or mismatch indicator whereas the successful integration of relevantly associated concepts within one's conceptual knowledge is reflected within a later post-N400 time window.

With regard to implications of the findings for the field of creative cognition, the N400 was found to reflect the processing of novelty or unusualness as it was insensitive to the distinction between novelty that is contextually inappropriate (nonsensical uses) and novelty that is contextually appropriate (creative uses). The post-N400 late component, in contrast, reflected the process of appropriateness as it was insensitive to the distinction between appropriateness that is contextually familiar (common uses) and appropriateness that is contextually unfamiliar (creative uses). The discovery that the cognitive operations relevant to conceptual expansion are best captured by taking into account the influence of both the N400 time window (novelty or originality) AND the post-N400 late time window (reflecting appropriateness or fit) is a valuable one for the field of creative neurocognition. This is especially significant as originality (novelty/unusualness) and appropriateness (relevance/fit) are the two defining elements of creativity (Stein, 1953).

Investigating the information processing of novel yet appropriate conceptual combinations that induce conceptual expansion in real-time within neuroscientific settings provide a unique avenue by which one can not only uncover the dynamics underlying select aspects of creative thinking, but also attain a broader understanding of the neurocognitive mechanisms underlying semantic cognition.

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Author Contributions

SK and AA wrote the paper. AA conceived of the study. SK carried out the study and the analyses. SK, BR and AA developed the final experimental design. SW and HH provided theoretical and methodological expertise at several stages of the project. CH provided methodological expertise and laboratory settings to carry out the study.

3.6 Reference List Study 2

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4 General Discussion

Two neuroscientific studies were carried out to investigate the neuronal correlates of conceptual expansion processing, a core component of creative thinking. An innovative paradigm was successfully implemented in these two studies using a modified alternate uses task. The task was designed to separately asses the effects of the two defining elements of creative products, novelty and appropriateness, as well as their conjunction in the form of passively induced conceptual expansion. The results and conclusions of these studies will be discussed in the following sections.

4.1 fMRI results

The fMRI hypotheses could be confirmed for the most part. In accordance to the introduced expectations, conceptual expansion related activity was found in the inferior frontal gyrus (BA 45, BA 47), the frontopolar cortex (BA 10) and the temporal poles (BA 38), predominantly in the left hemisphere. This hemispheric asymmetry is not surprising given the dominant role for the left hemisphere in language processing (Gernsbacher & Kaschak, 2003). It is also in line with previous observations in other creativity studies that have used verbal material (Carlsson et al., 2000; Fink et al., 2009).

The ecological validity of the employed paradigm could be questioned on the basis of whether the induction of conceptual expansion in the presented study is analogous to the processes that take place when actively engaging in creative thinking. There are two grounds on the basis of which to assert confidence about the findings associated with the paradigm. First, given all that is known about brain structure and function, it is not plausible that the brain regions involved in passive conceptual expansion would be wholly distinct from that of active conceptual expansion given that the conceptual knowledge networks being expanded upon in the brain and one and the same. There would be a differential engagement of brain structures based on volitional aspects of the engagement, but not the semantic elements.

Moreover, the findings associated with passive conceptual expansion using a modified alternate uses task could be corroborated by other studies. These include an fMRI study of passive conceptual expansion using a metaphor task (Rutter et al., 2012b) and an fMRI study of active conceptual expansion using a standard alternate uses task (Abraham et al., 2012b)

Rutter and colleagues conducted a very similar paradigm to the one reported here but used metaphors instead of everyday objects. They reported passive conceptual expansion related activation in predominantly left inferior frontal gyrus (BA 45, BA 47), the middle temporal gyrus (BA 20, BA 21), temporal poles (B 38) and frontopolar cortex (BA 10). A shortcoming common to both the Rutter et al study and the current study was that it could be argued that the results could potentially reflect that conceptual expansion processing is cognitive more demanding than pure novelty or appropriateness processing. However, the fact that similar findings were demonstrated in a fMRI study of Abraham et al. (2012b) in which an active conceptual expansion task was implemented while also controlling for cognitive demand speak against this critique.

In the Abraham et al. study, subjects had to execute four different tasks, two regarding divergent thinking (alternate uses: generate as many uses as you can for a given object; object location task: generate as many objects as you can for a given location) and two n-back tasks (1-back:? and 2-back:?). Conceptual expansion (inclusive mask analysis: contrast of alternate uses > object location task with inclusive mask of alternate uses > 2-back task) related activation was found in left inferior frontal gyrus (BA 45, BA 47), lateral frontopolar cortex (BA 10) and temporal poles (BA 38). Thus, the further interpretations now have a broader empirical basis.

The observed activation in the frontopolar cortex (BA 10) fits well in its mentioned role in processing of tasks in which multiple relations have to be integrated and considered simultaneously (Green et al., 2010; Kroger et al., 2002; Bunge et al., 2005), like, for instance, in the Raven's Progressive Matrices test (Christoff et al., 2001). Badre (2008) suggested a hierarchical organization of the prefrontal cortex, with the frontopolar cortex involved in the highest level of abstract thinking. In terms of conceptual expansion, the activation in the frontopolar cortex is assumed to reflect the cognitive demand to integrate the new related concepts into an expanded concept.

This interpretation is supported by recent findings of Green and colleagues (2012), who found frontopolar activation in relation to creative analogical mapping. This study is also remarkable, as it bridged the gap between “normative” cognition (in the form of analogical thinking) and creative thinking. Green (2014) also conducted a recent fMRI study using a “thin-slice creativity verb generation task” (Green et al., 2014; Prabhakaran et al., 2014), a task in which subjects have to name a verb after seeing a prompted noun. Subjects are further supposed to either name any verb (uncued condition) or to “think creatively when generating a verb response” (cued condition). Verbs generated during “creative states” tended to show as expected a greater semantic distance to the prompted noun. Frontopolar cortex was significantly recruited during these creative states, as well as bilateral inferior frontal gyrus and the anterior cingulate cortex. An increase in functional connectivity between frontopolar cortex and ACC could also be observed. The ACC activation was interpreted as the inhibition demand regarding conflicting response possibilities. This finding is in line with the finding of ACC involvement in the reported fMRI study of this doctoral thesis and the aforementioned fMRI study by Abraham and colleagues (2012b).

As stated in the hypotheses (section 1.6.2), activations in inferior frontal gyrus und temporal poles were expected to reflect higher search demands in semantic networks both in creative uses trials as well as nonsensical uses trials. These hypotheses were only confirmed for the creative uses, but not for nonsensical uses. This divergence is interesting because other studies have shown that the left inferior frontal gyrus is more strongly activated during processing of associative weakly related concepts (Bunge et al., 2005). However, the interpretation of the present findings were that as the search process within semantic networks during nonsensical trials could be aborted quickly due to the fundamental inability to integrate the new information to existing conceptual structures, the overall search and selection demand was lower than in the creative uses trials. The observed activations in anterior ventrolateral prefrontal cortex (BA 47) and mid-ventrolateral prefrontal cortex (BA 45) in the present study could be interpreted as reflecting controlled semantic retrieval (BA 47) and post-retrieval selection between competing representations (BA 45) as proposed by Badre et al. (2007).

A candidate brain region for pure novelty processing could be the left supramarginal gyrus (BA 40). The supramarginal gyrus has been reported to be active as a function of creativity in several studies (Bechtereva et al., 2004; Fink et al., 2010). However, these studies did not explicitly account for the appropriateness factor of creative ideas. In a recent fMRI study on the other hand, Benedek and colleagues (2013) reported that this region was found to be activated during generation of novel ideas in contrast to old ideas. Taken together there is some evidence, that certain task constraints (appropriateness required by task or subjective adopted) lead to a stronger recruitment of inferior frontal gyrus during divergent thinking tasks related to controlled semantic search (Abraham et al., 2012b; Benedek et al., 2013). With less demanding constraints (high original and low appropriate), the supramarginal gyrus seems to be activated. This hypothesis should be addressed by future investigations.

Brain activity exclusive to appropriateness was found in the medial frontal gyrus (BA 9), middle temporal gyrus (BA 21) and angular gyrus (BA 39). The middle temporal gyrus was also reported in the study by Rutter et al. (2012b) to be engaged as a function of appropriateness. This region is known to be involved in processing of semantic knowledge (Mahon & Caramazza, 2009). Furthermore, a meta-analysis by Wang and colleagues (2010) revealed that the left inferior frontal gyrus and the left middle temporal gyrus were core structures in the processing of abstract (inferior frontal gyrus) compared to concrete concepts (middle temporal gyrus). Bokde et al. (2001) also reported a functional connectivity between left inferior frontal gyrus and middle temporal gyrus among other occipitotemporal and temporal areas for the access of appropriate semantic representations. In their two-process model, Bader et al. (2005) suggested, that the functions of left inferior frontal gyrus and left middle temporal gyrus could be the bottom-up driven automatic semantic retrieval (middle temporal gyrus) versus a top-down controlled semantic retrieval and selection function (inferior frontal gyrus). The findings of the present fMRI study support this hypothesis.

The posterior cingulate gyrus (BA 31) and parts of the frontomedian wall (BA 9, BA 32) have previously been shown to play a role in declarative memory retrieval (Abraham et al., 2008). The medial PFC was also found to be activated during the retrieval of information congruent to prior knowledge (van Kesteren et al., 2010). These brain regions also belong to the so called “default mode network”, a network of areas known to be activated during self-referential thinking (Abraham & von Cramon, 2009; Abraham, 2013b), which is fitting with the idea that trials subjectively classified as appropriate had more personal relevance than trials rated as nonsensical. The default mode network has also been discussed with regard to creative thinking lately (Beaty et al., 2014b; Jung et al., 2013). A study conducted by Beaty and colleagues (2014b) for example demonstrated an association of increased functional connectivity between left inferior frontal gyrus and the default mode network with higher divergent thinking abilities. However, the dynamics of this relationship needs to be the subject of further empirical investigations.

Taken together, this new fMRI paradigm successfully assessed the brain structures involved in the processing of novelty, appropriateness and passive conceptual expansion (the conjunction of novelty and appropriateness). The findings strongly paralleled those of other fMRI studies that used an alternative passive conceptual paradigm to assess the same components (Rutter et al., 2012b) as well as an active conceptual expansion paradigm . This consistency across studies using different paradigms to assess the process of conceptual expansion speaks for the reliability and validity of the associated findings.

4.2 ERP results

Due to a striking lack of ERP studies on creative thinking, the discussion of the findings from the ERP study, that was conducted within this doctoral project, cannot be as detailed as the discussion of the fMRI findings. The ERP study was therefore far more explorative in nature than the fMRI study.

During the conceptualization of this study it was unclear whether the information processing that accompanied passive conceptual expansion would be reflected in the N400 time window or whether the expansion of a prior concept and the consequent integration of this new conceptual element into the existing semantic network would need a longer processing time. The results demonstrated that there was no significant difference between the neural signature when processing creative uses and nonsense uses in the N400 time window as both were comparably higher than that of common uses. Thus the N400 reflected novelty processing in terms of registering the mismatch between prior knowledge and the presented stimuli. There was a switch in the pattern of results in the post-N400 time window (500 – 900 milliseconds after the presentation of the stimuli), such that the results demonstrated no significant difference between the neural signature when processing creative and common uses as both were comparably lower than that of nonsense uses. Thus the post-N400 component reflected appropriateness processing in terms of the recognition and assimilation of the fit of the presented information with existing knowledge.

This indicates that both the N400 and the post-N400 ERP components have to be jointly considered to account for the information processing involved during passive conceptual expansion as the N400 reflects the registering of originality in the object-use combination while the post-N400 component reflects the registering of relevance in the object-use combination.

These results were partially consistent with another ERP study conducted by Rutter and colleagues (2012a) who also used a passive conceptual expansion paradigm but, as in their fMRI study (Rutter et al., 2012b), used metaphors instead of object uses. They reported significant effects related to passive conceptual expansion in both the N400 as well as the post-N400 period. Rutter et al (2012a) found a graded effect in the N400 time window such that, relative to literal phrases, nonsense metaphors were associated with the highest N400 amplitude and creative metaphors associated with a medium N400 amplitude. This graded effect was not observed in the current ERP study using the modified alternate uses task. Rutter et al. (2012a) also reported a continuation of this graded effect observed in the N400 time window in a post-N400 time window (500 to 900ms). So, while these findings also indicate that both the N400 and the post-N400 ERP components have to be jointly considered to account for the information processing involved during passive conceptual expansion, the pattern of the findings is not entirely comparable to that of the present study.

It is very valuable to have a situation where two different paradigms (metaphor, alternate uses) with the same variables of interest (novelty, appropriateness, creative) were developed to assess information processing related to passive conceptual expansion. Given the overlapping conceptual rationale behind the paradigms, the differences in the findings can be largely attributed to the different stimulus material which may have resulted in differential demands on the cognitive operations that are called upon to meet the different task demands. When viewing the differences from a conceptual standpoint, the metaphor processing task in the

Rutter et al. study (2012a) may have required less inferential reasoning as the manner in which concepts had to be connected to each other was clearly spelt out. This could be one reason why the conceptual expansion processing was faster and, as a consequence, observed earlier than in the present study. Other differences between the studies include differences in aspects of the data analysis (e.g., choice of electrodes) as well as trial events(e.g., timing).

Some notable caveats in the literature need to be acknowledged here. First, a sustained negativity during novelty processing is not entirely in line with other studies that have reported a sustained negativity in a post-N400 time window reflecting some kind of higher cognitive demand (Baggio et al., 2010; Pijnacker et al., 2010). Rhodes and Donaldson (2008), however, reported a similar post-N400 sustained negativity for unrelated words compared to associatively or semantically related words. Second, unlike the site of focus in the present ERP study, slow-wave positivities after the N400 are often reported over frontal electrode sites (Davenport & Coulson, 2011; Davenport & Coulson, 2013; Thornhill & Van Petten, 2012) and therefore do not share a common interpretation with the present findings. Future research is therefore necessary to further investigate the underlying processes of such slow wave positivities over centro-parietal electrode sites.

In summary, a new approach of investigating passive conceptual expansion with ERP methods was successfully implemented and resulted in findings that conceptually corresponded that of with another ERP study where the same rationale was followed. With this innovative approach, a novel direction in the investigation of creative thinking using traditional electrophysiological methods was made, and these can complement the EEG investigations on synchrony changes in brain activity during creative thinking.

4.3 Future perspectives

The aim of this section is to expand the presented work towards more abstract theoretical considerations which can lead to more informed future perspectives in the area of creativity research. Looking back at both the older and more recent work done in the field of creativity research, it is noteworthy that a great abundance of terms describing similar or the same issues were generated in the past 60 years, as many researchers have described similar processes or combinations of previously described processes with different terminology.

One example is the aforementioned terms “primary and secondary process cognition” used by Kris (1952) versus the terms “deliberate mode” and the “spontaneous mode” used by Dietrich (2004) which essentially refer to the same phenomenon. One possible reason for this is that it is due to the wish of some researchers to have some kind of unique theoretical formulations to be able to identify their views as being separate from others. In this manner though, a substantial amount of redundancy is created which impedes the integration of research findings into a general theoretical framework. It is like a forest of terms in which it is likely not to see the wood for the trees. In the future, further merging of terms belonging to creative cognition or “normative cognition” is likely to occur, which will render the situation even more complicated. One recent example for this trend is the merging of analogical thinking (analogical mapping) and creative associative thinking (e.g., connecting of remote associations) as described in the studies of Green and colleagues (Green et al., 2012). The question is, whether different terms are separable from each other on a neurophysiological basis or whether the differentiation is merely of linguistic nature? The term “conceptual expansion” is no exception of the described tendency of “term abundance”. The fMRI results clearly supported the idea, that conceptual expansion is not a single cognitive process but instead comprises different processes like semantic retrieval, inhibition, mapping (or analogical thinking) etc., as different brain structures reflecting sub-processes of conceptual expansion were found to be activated. An overview of proposed sub-processes that could play a role during passive conceptual expansion based on the found activations in the presented fMRI study is given in Figure 1.

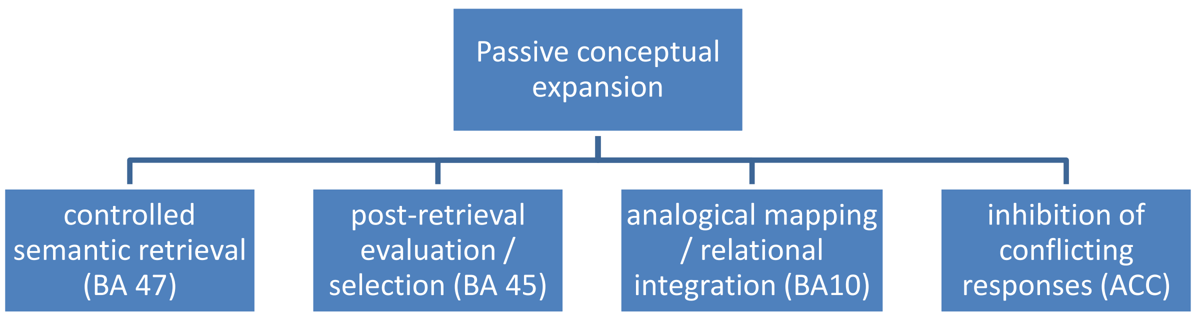

Figure 1. Overview of proposed sub-processes involved during passive conceptual expansion.

In order to attain a better understanding of previous research findings, it would be necessary as a first step to sort the different studies on the basis of the explicitly or implicitly measured sub-processes. Such attempts would certainly necessitate developing some objective methodically consensus about the way to decide how different terms like, for instance “mapping” or “analogy”, relate to each other.

The second step would involve the meta-analytical investigation of common brain areas that underlie the now pre-specified sub-processes from step one. Vartanian and colleagues (2012) undertook an interesting step toward such a project. They argued that the high meta-analytical inconsistency of creativity research results reported by Dietrich & Kanso (2010) as well as Arden et al. (2010) was due to a merging of very different creativity processes. They then tested the hypothesis that a meta-analytic focus on specific processes like analogy and metaphor processing would result in more consistent and dissociable results. Indeed the authors could confirm this assumption by demonstrating that analogy processing consistently recruited brain regions in the rostrolateral prefrontal cortex (BA 10, BA 47) and dorsolateral prefrontal cortex (BA 9, BA 46), whereas metaphor processing activated dorsolateral prefrontal cortex (BA 9, BA 46), temporal pole (BA 38) and cingulate gyrus (BA 24, 32). What the authors did not undertake, however, was to describe how analogy or metaphor processing is related to the more fundamental processes described earlier. Benedek and colleagues, for example, attempted to break creative thinking down into the underlying involvement of executive functions like updating, inhibition and shifting (Benedek et al., 2014). Thus, there is clear trend to further disentangle creative thinking.

A third, and perhaps most important, step which could certainly be facilitated by steps one and two, would be to integrate these findings into a general theoretical framework, as the empirical research on creativity has progressed much faster than the theoretical domain in the last 15 years. So one should take a pause and summarize findings from previous neuroscientific creativity research and most importantly neuroscientific findings from other cognitive areas into a common theoretical framework from which one could guide further empirical research. A general theoretical framework could certainly build up on previous existing theoretical considerations. One such framework could for example be based on the recurrent suggestion of a two-process-model of creative thinking (Kris, 1952; Finke et al., 1992), which has become a modern trend again in the last years (Dietrich, 2004) and especially more recently (Mok, 2014; Beaty et al., 2014a; Mayseless et al., 2014; Sowden et al., 2014). To further demonstrate this recurrence and the aforementioned claim of an abundance of terms, table 1 gives an incomplete overview of some terms and conceptions of different two-process models.

Table 1. Two process models of creative thinking.

Primary process cognition	Secondary process cognition	Kris (1950)
Deliberate mode	Spontaneous mode	Dietrich (2004)
Evaluation	Generation	Smith , Mayseless, Sowden (all 2014)
Focused attention	Defocused attention	Sensu Martindale (1995)
Selective retention	Blind variation	Campbell (1960), Jung (2013)
Controlled processing	Spontaneous processing	Mok (2014)
Executive processes	Associative processes	Beaty (2014)

As can be shown, there is a remarkable intersection suggesting one processing mode characterized by high cognitive control, evaluation and focused attention relative to a second mode comprising, generation, free-association, defocused attention and low cognitive control. Following the logic of this idea, divergent thinking as well as conceptual expansion would result from an interplay or shifting between these two processing modes and thus result in activation of brain areas needed for control, evaluation, and so on (prefrontal areas), as well as widespread search processes, generation, and the like (TOP areas). The idea of two-process models is not specific for creative thinking as it has also been employed in normative cognition for a long time (Sowden et al., 2014)

Taken together, this section provided an outlook on recent and future research and theoretical trends in the neuroscience of creative thinking, and tried to integrate the reported findings of this doctoral thesis from the point of view of such upcoming trends.

5 Conclusion

The reported studies demonstrated a new and promising way to investigate aspects of creative thinking using neuroscientific methods. A new paradigm was developed that focused on conceptual expansion, a critical aspect of creativity. The studies were highly insightful about the brain basis of this mental operation that were in line with *a priori* hypotheses and have proved to be consistent, as they have been affirmed in other studies using alternative paradigms. It also further supported the idea that creative thinking is based on normative cognitive processes.

The sixty-four years of creativity research that have elapsed since Guilford gave his presidential Address to the American Psychological Association have brought many progress and development to our understanding of this complex ability. Today the consensus between creativity experts is that the most urgent next step is to integrate the numerous findings into a coherent theoretical framework.

The fact that creative thinking is based on normative cognitive processes emphasizes the need for a close collaboration between creativity researchers and researchers from other cognitive domains in order to assimilate the myriad findings to build a common neurocognitive framework of creative thinking.

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Ich erkläre: Ich habe die vorgelegte Dissertation selbstständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen, die ich in der Dissertation angegeben habe, angefertigt. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichen Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der "Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ niedergelegt sind, eingehalten.

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