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Creativity and the brain: An investigation of the neural correlates of creative thinking

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List of abbreviations

The following list contains frequently used abbreviations and their respective meaning.

ACC	Anterior cingulate cortex
ANOVA	Analysis of variance
AUT	Alternate Uses task
BA	Brodmann area
BOLD	Blood oxygen level dependence
CBF	Cerebral blood flow
EEG	Electroencephalography
ERP	Event-related potential
fMRI	Functional magnetic resonance imaging
FPC	Frontopolar cortex
HUHA	High unusual, high appropriate
HULA	High unusual, low appropriate
IFG	Inferior frontal gyrus
ITG	Inferior temporal gyrus
LUHA	Low unusual, high appropriate
LULA	Low unusual, low appropriate
LPC	Late positive component
MFG	Middle frontal gyrus
PET	Positron emission tomography
ROI	Region of Interest
RT	Reaction time
SFG	Superior frontal gyrus
STG	Superior temporal gyrus

Creativity is a complex construct involving several different mental operations. Neurophysiological studies on creativity have seldom fully considered this fact and have instead approached creativity as a single entity. Furthermore, most neurophysiological studies of creativity face methodological problems. The present studies follow a novel approach to investigate the neural underpinnings of creativity by focusing on one creative mental operation, namely conceptual expansion which refers to the ability to widen the conceptual structures of acquired concepts, a vital process in the formation of new ideas. Avoiding drawbacks from previous neurophysiological studies, the new approach introduced in the present work borrows from psycholinguistic research on novel metaphor processing to generate a passive conceptual expansion task. Two studies using functional magnetic resonance imaging (fMRI) and event related potentials (ERP) were carried out, assessing participants' brain activity while they read novel metaphoric, senseless and literal sentences. Participants' responses regarding the unusualness and appropriateness of the sentences served to categorize each trial into three subject-determined conditions: creative (high unusual and high appropriate), nonsensical (high unusual and low appropriate), and literal (low usual and low appropriate). Sentences regarded as "creative" were of special interest because they are thought to induce conceptual expansion passively in participants.

The results of the fMRI study pointed to the involvement of a fronto-temporal network in the processing of conceptual expansion. Activations in the anterior inferior frontal gyrus and the frontopolar regions in the processing of both novel and appropriate stimuli reflect an increased effort to retrieve semantic information and greater semantic selection and integration demands from temporal lobe areas where semantic information is stored. The findings of the ERP study revealed an N400 modulation with regard to the unusual and appropriate (creative) as well as the unusual and inappropriate stimuli (senseless), again reflecting greater effort for semantic retrieval and integration.

1 Introduction

One of the most fascinating human abilities is certainly the ability to be creative. From stunning masterpieces of art and extraordinary pieces of literature or music to the development of new products for daily use – every one of these innovations requires the ability to create something new. The ability to generate novelty allowed the human race to evolve into the highly developed beings that we are today. Creativity, in interplay with other important tools of evolution like increasing brain size and development of speech, helped humans to adapt to their changing surroundings and gave human beings an advantage in survival (Gabora & Kaufman, 2010).

The investigation of creativity has had a long tradition. Whereas earlier experimental attempts were limited to behavioral assessments of creativity, the rise and technological advancement of neurophysiological techniques opened up a whole new world of possibilities for researchers. Among it was the possibility to investigate creativity at its origin: the brain. However, due to problems associated with the neurophysiological assessment and the general conception of creativity, research in this area has not advanced far.

The present work is primarily focused on uncovering the neural correlates of creativity using a novel approach that renders it possible to overcome some of the pitfalls of most neurophysiological studies on the subject. It is aimed at taking a closer look at the cognitive processes underlying creative thinking using neurophysiological methods, such as functional magnetic resonance imaging (fMRI) and event-related potentials (ERP) in electroencephalograms (EEG).

The following chapters will give a brief overview of the definition of creativity and the prominent theories concerning this cognitive construct. Neurocognitive and neurophysiological research on creativity will be reviewed in detail, prior to the introduction of the new experimental paradigm that was employed in the current studies. The findings of the empirical studies will be critically discussed in terms of their limitations and implications for future creativity research and assessment.

2 Creativity as a cognitive construct

As with many other constructs of higher-order cognition, the study of creativity can be approached in terms of different frameworks and scientific backgrounds which in turn influence theories and definitions of creativity in general. Depending on the theory in question, different aspects of creativity are of special interest. While, for instance, developmental theories will primarily focus on the development of and influencing factors on creativity, economic theories will adopt a more product-oriented perspective that takes market-specific characteristics into account (for an overview, see Kozbelt, Beghetto, & Runco, 2011). Despite differing emphases, most theories and approaches to creativity discuss the role of cognitive processes to some extent.

The following section focuses on the definition of creativity and introduces cognitive theories concerned with creative thought as they build the framework for the present work.

2.1 Definition of creativity

Creativity is a multifaceted and complex construct which makes it challenging to reach a consensus regarding its definition. Creativity can be defined at various levels.

For instance, the focus on what is being judged as creative can vary, and with it vary the different approaches to the investigation of creativity. The most common subject of creative evaluation is the product. Other possible foci on what can be judged as creative and be centered upon are processes or persons (Amabile, 1996). A creative process is one that produces a creative outcome, whereas a definition of creativity in terms of a person centers on personality traits associated with an enhanced ability to create (e.g., Boden, 2003).

Further, in order to properly define creativity and what it entails, a distinction has to be made with respect to its magnitude (Kozbelt et al., 2011).

The magnitude of creativity refers to the subjective (private) or objective (public) impact that a creative outcome has. Creative magnitude covers a wide range of creative experiences, all of which need to be taken into account to arrive at a sensible definition. Whereas most laypersons undoubtedly agree on the creativity of an artist's work, smaller everyday experiences of creative outcomes are often disregarded. The small subjective creative achievements as, for instance, the novel culinary creation made by an amateur cook, might not have an objective public impact but nevertheless need to be considered when defining creativity as it has a subjective impact. This distinction between magnitudes of creative outcomes is also imminent in Boden's differentiation between H-creativity and P–creativity concerning two senses in which's light creativity can be seen (Boden, 2003). H–creativity refers to creativity in a historical sense as, for instance, in situations involving important inventions or scientific discoveries which would be considered to be globally novel. P–creativity, on the other hand, refers to ideas or achievements that are novel to the individual person.

The necessity to come to a consensual and operational definition of creativity that nevertheless can be generalized across the different investigative approaches has been a critically discussed issue since the beginning of creativity research (Runco & Jaeger, 2012). This eventually lead to a relatively stable and agreed upon definition of what creativity entails among researchers. According to this definition, creativity entails two fundamental features: novelty and appropriateness (e.g., Stein, 1953; Sternberg & Lubart, 1999; Runco & Jaeger, 2012; Ward, 2007). For an idea or product to be creative, it must be unusual or novel in its occurrence and at the same time be relevant or appropriate to the task or problem at hand. This operational definition of creativity can be suitably applied to both objective (public) and subjective (private) creative achievements. However, this consensual definition is limited to the product level as it only refers to a creative outcome. The mental operations that lead to these novel and appropriate, and thus creative, outcomes are assessed through the cognitive approach in the investigation of creativity.

2.2 Cognitive theories of creativity

2.2.1 Early theories

This section will highlight the theories that focus on the cognitive basis of creative achievements or the mental operations that are involved in bringing about creative outcomes.

One of the earliest accounts that emphasized cognitive processes in creative thinking was formulated by J.P. Guilford (1950), a pioneer in the field of creativity. Guilford took a person-centered approach to creativity stressing that the creative person possesses a variety of certain traits. In his “structure-of-intellect” model that identifies different factors contributing to human thinking, Guilford introduced two groups of factors as being important for the production of ideas and solutions (Guilford, 1956), convergent thinking factors and divergent thinking factors. Whereas convergent thinking entails that cognitive efforts are geared towards reaching one single correct solution to a given problem, divergent thinking refers to an open-ended, more flexible thinking process that is not directed at leading to one specific solution, but is instead aimed at the production of many possible solutions with differing degrees of relevance to a problem. Within the divergent thinking component which he regarded as vital for creative thinking, Guilford (1968) identified four factors: fluency, referring to the number of produced ideas or solutions; flexibility which concerns the ability to overcome one’s established course of thinking to arrive at an unusual solution; originality, describing the novelty and unusualness of ideas or solutions; and elaboration, referring to the degree of details with which one’s ideas or solutions are provided.

Another early account that focused on individual differences in information processing as pivotal for the ability to be creative was described by S. Mednick (1962). The approach is grounded on the assumption that information within memory is represented through conceptual nodes which, in turn, are organized in semantic networks (Collins & Loftus, 1975). The nodes in the network represent different word meanings that are interconnected through associations of differing strength to form a conceptual network. The strength of the connection and the distance between these nodes depend on their semantic and associative relations. When a conceptual node is activated, activation spreads to other nodes in the network, with more closely associated nodes being more likely reached by the activation than distantly related ones. Based on this semantic network theory, Mednick postulated that the creative process involves combining associative elements, or nodes, to form something new. According to his theory, a creative outcome is most likely achieved when elements that are only distantly associated in the semantic network are combined. A creative outcome was defined by the originality, as determined by the probability of the occurrence in a given population, and its usefulness, a definition that is in accordance with the conceptual definition that researchers follow today. Mednick hypothesized that an individual's associative hierarchies determine the likelihood of producing a creative outcome (Mednick, 1962). Creative individuals are assumed to differ in the style in which their associative networks are organized. Individuals with a lower level of creativity possess a steep associative hierarchy, meaning that their associative network is organized in such a way that a conceptual node has only very few but strongly associated nodes connected to it which leads to the production of associative combinations that lie close together in their associative structure, but seldom generate original combinations. In comparison, the associative hierarchy of creative individuals is organized in a flat manner with nodes in their conceptual networks being strongly connected to both closely and distantly related nodes. Creative individuals initially produce combinations at a lower rate but more often come up with responses to a stimulus that draw from two only distantly related elements. Both non-creative and creative individuals will produce conventional elements that are strongly associated first, creative individuals, however, are able to overcome the conventional answers quickly and produce something more creative.

The Remote Associates Test (RAT; Mednick, 1962), as a measure of individual differences in creativity, utilizes the ability to overcome conventional and dominant answers. Individuals are presented with three words, e.g. "rat", "cottage" and "blue" and asked to find a fourth word acting as an associative link between them. The answer to the given problem being "cheese", it becomes apparent that the words differ in the strength of their associative connection to the target word. Whereas "cottage" and "blue" share a stronger associative connection to the target word, "rat" is only distantly related to "cheese" making it necessary to go beyond conventional answers. In conclusion, within Mednick's theoretical framework, an individual’s ability to be creative is limited by the organization of his associative networks and by his ability to produce a large number of combinations that exceed the dominant stereotypical and closely related responses. Newer research by Benedek and Neubauer (2013) challenged and attempted to empirically test Mednick's theory by mapping associative hierarchies of high and low creative individuals through a continuous free association test. Their results did not support Mednick's notion of differences in associative hierarchies between high and low creative individuals. High creative individuals are rather characterized by higher associative fluency and the emergence of more uncommon and creative responses (Benedek & Neubauer, 2013).

Mendelsohn (1976) took Mednick's theoretical deliberations one step further by demonstrating that the type of attentional focus plays an important role for the production of a creative solution. Focus of attention refers to the subjects or events that one's limited cognitive resources are directed at. Here, again, individual differences are at play, determining the focus of one’s attention. Creative individuals approach a problem with a defocused attention, meaning that they are able to widen their attention and to keep multiple subjects or events in their attentional focus at the same time, whereas people with a narrow attentional focus can attend to only a limited number of subjects or events. As creative ideas emerge from the combination of different elements to form something novel, a widened attentional focus, or defocused attention, makes it possible to attend to more elements simultaneously, thereby increasing the chances to produce a creative combination. Individuals that are less creative, on the other hand, possess a focused attentional capacity that only allows them to concentrate on a few elements at a time, thereby limiting the number of possible combinations resulting from these elements.

Both theories see individual differences in the activation of distantly related elements as responsible for the differing degrees of creativity in people. Whereas Mednick's account highlights individual differences in the architecture of one's associative conceptual networks as determining the likelihood of a creative outcome, Mendelsohn stresses the differences in the manner in which elements can be retrieved from these networks and attended to as important to produce creative responses.

2.2.2 The creative cognition approach

Whereas the above described early accounts on creativity focused on explaining individual differences in creative ability, the creative cognition approach takes a different approach. Instead of confining the focus of interest on individual differences in creativity, the creative cognition approach takes a qualitatively different stand by postulating that creativity is based on a magnitude of cognitive processes that are recruited in a certain manner to work together and produce a creative outcome (Finke, Ward, & Smith, 1992; Ward, Smith, & Finke, 1999). As opposed to the wide-spread belief that creativity is inherent to only a few gifted individuals and cannot be quantified, the creative cognition approach postulates that creativity arises from fundamental cognitive processes shared by most humans and can therefore be investigated. In this manner, the creative cognition approach accounts not only for achievements that are ordinarily viewed as being creative and innovative, such as inventions or different forms of artistic expressions, but also for more commonplace outcomes of generative cognitive processes, such as every-day language use or the ability to construe concepts (Ward et al., 1999). The likelihood of and variability in creative achievement stems from individual variability in how and to what extent these processes are available, recruited and combined (Ward et al., 1999; Ward & Kolomyts, 2010).

The Geneplore model as a framework within the creative cognition approach and described by Finke and colleagues (1992) does not assume the presence of a “creative process” per se, but rather takes a look at the cognitive operations forming the very complex construct that is creativity.

According to the Geneplore model, creativity involves different stages that recruit different processes. The first stage consists of generative processes that lead to a pool of initial ideas and possible solutions or “preinventive structures”, whereas the second phase of creativity is made up of exploratory processes. Preinventive structures can be seen as incomplete ideas, proposals or possible candidates for a solution. Exploratory processes are needed to further explore and evaluate these preinventive structures to determine their usefulness for the problem or task at hand. The stages of creativity do not elapse in a linear manner. Instead, the stages follow a circular course in which the generative stage can follow the exploratory stage to modify and refine the initially generated ideas after their first evaluation deems them to be inappropriate or ill-conceived. This cycle repeats until the final outcome is evaluated as fitting for the task at hand (Ward et al., 1999).

Moreover, Ritter, van Baaren and Dijksterhuis (2012) showed that the processes involved in the evaluation of preinventive structures are not limited to the conscious realm. In this study, participants were better at recognizing their most and least creative ideas after a period of unconscious thought. The generation of ideas, on the contrary, did not profit from unconscious thought, as participants did not produce a greater number of creative ideas after unconscious versus conscious thought. The study thus showed that both conscious and unconscious processes contribute to creative performance.

The stages of creative production postulated in the Geneplore model comply with the common definition of creativity through its two core features. Generative processes lead to preinventive structures that are certainly novel and original and to some extent appropriate (Ward et al., 1999). The model, however, does not only involve feedback loops between the two stages, but also constraining factors that have to be considered as influencing the outcome of creative production. Whereas constraints during exploratory processes are primarily linked to the practicality of the generated ideas and solutions for the task at hand, constraints occurring in the generative phase are of a diverse nature. Most simply, constraints on cognitive capacity can hinder the production of preinventive structures.

Other constraints during generative processes stem from an individual's tendency to take the "path-of-least-resistance" approach to problems and tasks. The path-of-least-resistance refers to an individual's preference for effortless information processing. Within creative thinking, this tendency reveals itself, for example, during retrieval of information from long-term memory. When faced with a task that requires coming up with something novel, individuals often rely on retrieving very specific instances from a certain domain as opposed to more general and abstract ones which would be better suited as a basis for creative outcomes. For example, if asked to create a new type of sitting furniture, people will likely retrieve a very specific exemplar of e.g., a chair instead of coming up with more general or abstract features that make a chair a piece of furniture one can sit on. Retrieval of specific instances limits the possibilities to produce something original due to the constraints of the retrieved specific features that might not be easily modified in a suitable way to fit the given problem. In the case of the chair, people might retrieve an example of a chair that they have previously seen and are thus unable to overcome this chair's specific features and appearance, consisting in e.g., four legs, two armrests and a high back. However, if relying on more abstract instances retrieved from memory, the outcome may be more original but might lack appropriateness (Ward, 2008). This tendency to take the path of least resistance is predominant in people's information processing and requires effort to overcome.

Constraints brought about by recently given examples to a task can also be explained by the path-of-least-resistance approach. When individuals are given examples of instances they are asked to generate, they use many of the previously seen features in their own creations due to the inability to overcome this recently activated knowledge (Abraham & Windmann, 2007; Smith, Ward, &

Schumacher, 1993). A study by Smith and colleagues (1993) investigated how providing participants with examples influenced their generation of ideas for a new toy. Participants that had been shown examples prior to executing the task were found to more likely use features from the previously encountered examples in their own designs than participants that had not seen any examples. However, the restriction posed by the given examples is not entirely disadvantageous for the generation of new ideas. Whereas the produced ideas are generally lacking in originality and novelty due to the transfer of features seen in the examples, reliance on previously seen examples can lead to an increase in practicality of the generated ideas. In a study by Ward (2008) in which participants were instructed to create a new sport, participants' creation that they reported as being based on specific exemplars were rated as more playable than creations from participants that relied on more abstract instances. This indicates that in some cases the reliance on specific instances or recently activated knowledge causes a negative correlation between originality and practicability of the generated outcomes. Whether this inverse relation between innovation and relevance constitutes a disadvantage strongly depends on the task or problem that needs to be solved. For some problems, it might be more suitable to find a solution that focuses on the applicability of a given idea, such as might be the case in optimizing established products or work processes where the task is aimed more strongly towards the practicality of the solution and less on its originality.

Recently activated knowledge does not only assert influence through the difficulty to overcome constraints through encountered examples. On a more subtle level, knowledge structures made easily accessible through priming can restrict people's ability to generate original and novel ideas. In a study conducted by Ward and Wickes (2009), participants that were primed with exemplars of fruit and tools through a pleasantness rating were more likely to use the primed items in a creative generation task. Additionally, the authors compared the use of items with high and low unprimed accessibility, finding a more frequent use of items that were per se highly accessible. These results indicate the equal importance of stored knowledge whose retrieval depends on its associative strength and of knowledge that has been made temporarily more accessible for creative production (Ward & Wickes, 2009).

The creative cognition approach concerns itself with the identification of the fundamental cognitive processes that lie at the heart of creative outcomes. The cognitive processes involved cover a wide spectrum of operations ranging from fundamental processes necessary for almost all acts of creative thinking such as working memory processes, inhibitory executive control processes or long-term memory retrieval, to processes that are specific to the features of the respective creative task, such as semantic information processing when engaging in a task containing semantic relations. The aim of this approach is to investigate these cognitive processes empirically and systematically to gain a better understanding of creative thought. Several cognitive operations have been identified as playing an important role for creative thinking. The following section introduces one of these processes and its importance as a basis for the present work.

2.3 Conceptual expansion - a core process in creative thinking

Apart from more general cognitive processes that are relevant to almost all modes of creative thinking, such as working memory and executive control functions, the creative cognition approach has identified a number of other cognitive operations which play an important role for some forms of creative thinking and are to a greater extent task-specific. These cognitive processes include analogy, creative imagery and conceptual combination (Ward & Kolomyts, 2010).

When discussing cognitive processes that play a role in creative thinking, insight takes a special place and therefore deserves a brief introduction within this context. Insight is not a single cognitive operation but rather one type of problem solving consisting of different underlying processes. Since insight bears the potential to produce original ideas, as can be seen in historical accounts on ground-breaking inventions or discoveries (e.g., Andreasen, 2006; Ward et al., 1999), and is associated with creative thinking (Schooler & Melcher, 1995), it certainly deserves mention among cognitive operations playing a role in creativity. Insight solutions are usually characterized by an impasse in the problem solving process and the sudden experience of the solution to a given problem accompanied by an “Aha” - effect. Solving a problem with insight requires cognitive restructuring and flexibility (e.g., Chein, Weisberg, Streeter, & Kwok, 2010; Weisberg, 1995) making it a possible source for creative thinking.

One of the most important cognitive processes from which creativity arises, however, is conceptual expansion, on which the research at the center of this work focuses. Concepts and hence conceptual expansion are terms that arise from theories on how general knowledge about the world or, in particular, objects, people and word meanings are represented in memory. Concepts are mental representations of ideas, objects, people, and so on that contain structured knowledge and typical exemplars of the represented matter. A myriad of theories exists on how semantic knowledge is organized in the brain. One of the oldest and most influential theories (see also section 2.2.1) proposes that semantic knowledge is organized in the form of associative networks (Collins & Loftus, 1975). Concepts and their properties are represented through conceptual nodes that are connected with each other to form a semantic network. The strength of the connection and the distance between two interconnected nodes depends on the semantic and associative relationship between the respective nodes. The closer two concepts are semantically related, the closer they are in the semantic network. If one concept is activated the activation spreads to neighboring nodes which, in turn, become active, as well. Neighboring conceptual nodes are more likely to be activated if they are semantically closely related to the initially activated concept. For example, when one thinks of a house, features such as windows, doors, walls, or a roof in a certain shape will be activated as well.

Newer theories on how concepts are acquired and represented in the brain are mostly based on research on patients with category-specific deficits and can be broadly categorized as belonging to two different groups (Caramazza, Hillis, Rapp, & Romani, 1990; Mahon & Caramazza, 2009). The first group of theories centers on neural structures as a means to organize conceptual knowledge. These neural structure theories are based on the assumption that conceptual knowledge is organized in modality-specific systems. More specifically, conceptual knowledge can be stored as sensory/perceptual or functional/associative (e.g., Warrington & McCarthy, 1987). The second group of theories focuses on the correlated structure principle and argues that concepts are organized in a way that represents the co-occurrence of certain features in the world (e.g., Caramazza et al., 1990). Features and characteristics that more frequently occur together are stored in the same semantic subsystem (for a more thorough review on the different theories, see Mahon & Caramazza, 2009).

Regardless of the underlying theories on how conceptual knowledge is organized, conceptual expansion refers to one’s ability to widen the limits of an existing conceptual representation to include new features, properties or exemplars in it. The retrieval of existing concepts and the expansion of their representations can build the ground for the generation of novel and original preinventive structures, but can also potentially inhibit creative generation if, for instance, people are unable to overcome fixation on concrete exemplars (Ward et al., 1999). One of the most influential series of studies on conceptual expansion and its implications is the structured imagination task developed by Ward (1994). In the task, participants are asked to imagine a creature from a planet that is very dissimilar to earth. Participants’ drawings of their imagined creatures are rated as novel depending on their similarity to earth creatures with deviations regarding physical symmetry, organs and appendices receiving higher originality ratings. Analyses of the figures drawn by participants revealed that the creatures they generated shared many features such as bilateral symmetry, organs and appendices with typical earth animals.

Similar results were obtained by a second study in which participants were assigned to conditions stating that the creature they were to imagine had either feathers, fur or lived under water (Ward, 1994; experiment 2). In this case, participants were more likely to include attributes associated with feather, fur or under-water living in their designs. For instance, participants that were told the creature they were to imagine had feathers, more likely included wings and beaks in their designs. These findings indicate that participants depend on structured knowledge and concrete concept exemplars when generating new ideas. Ward (1994) interprets his findings in terms of the path-of-least-resistance approach. Participants prefer effortless information processing and rely on features and properties of familiar concept exemplars or instances and transfer them to their new designs, resulting in a lack of originality. Under certain circumstances, however, participants are able to circumvent the notion of relying on specific instances. When forced to access more general and abstract knowledge, as when faced with the task to draw an animal living under conditions that they likely do not have structured knowledge about, participants were able to come up with innovative and original figures (Ward, 1994; experiment 3).

Ward's initial findings on the reliance on concept exemplars not only show possible constraints for creative innovation but also shed light on the conditions under which existing concepts can be expanded to generate novel and innovative ideas. This task created by Ward is only one of many still used to assess conceptual expansion in creativity research. Another task that is applied to measure conceptual expansion and possible constraints on this cognitive process requires participants to create a novel toy out of three elements (Smith et al., 1993). The task and the effects of giving examples prior to the execution of the task have been described in detail earlier (see section 2.2.2).

A third task that requires the expansion of existing concepts and hence is used as a measure of creativity is the Alternate Uses Task (AUT; Wallach & Kogan, 1965). In this task, participants are asked to create as many novel uses as possible for a given object in a fixed timeframe. Participants' responses are rated according to their fluency, or the number of different uses generated for an object, and their originality, or uniqueness of the generated use. This task requires participants to activate existing concepts, such as a shoe, and its accompanying features that dictate its uses. The features of a shoe, for example, are strongly linked to its uses as foot protection or as a means to smash insects on the ground. In order to generate novel uses for an object, participants therefore have to overcome these more obvious uses and expand their existing concept of a shoe. A relatively novel and unique use for a shoe, drawing from its shape that resembles a vessel with a top opening, would be its use as a flower pot.

2.4 Creativity and Neurophysiology

While creativity research was mostly limited to behavioral studies investigating creative idea generation in terms of its constraints, implications and contributing factors, the rise of neuroimaging and neurophysiological techniques opened up opportunities to investigate creativity from a new angle. Event-related potentials and functional magnetic resonance imaging are two methods that can be employed to explore creative cognitive processes and their neural correlates.

Functional magnetic resonance imaging (fMRI) is based on the association between neural activity and increased cerebral blood flow due to metabolic changes in activated brain areas. fMRI is based on the differing magnetic properties of oxygenated and deoxygenated hemoglobin. When a brain area is activated, more oxygenated blood is transported to this area and leads to a change in the MR signal. More specifically, hydrogen protons, whose endogenous spin gives them magnetic properties are deflected from their naturally occurring randomly distributed orientation by exposing them to a strong external electromagnetic field in the scanner. The protons absorb the energy of a second magnetic field, a B1 or radio frequency pulse, and release it again after its termination causing the protons to return to their original orientation. The thereby emitted electrical field is measured as the MR signal. In the case of functional MRI, the different magnetic properties of oxygenated and deoxygenated hemoglobin are taken advantage of to generate the blood oxygen level dependence (BOLD) signal with an increase in BOLD signal indicating an increase of oxygenated blood flow to the activated area. fMRI captures the time-course of this hemodynamic response (Gazzaniga, Ivry, & Mangun, 2009; Huettel, Song, & McCarthy, 2009). The use of fMRI offers many advantages such as high spatial resolution and the possibility to observe neural activation that is not limited to the cortical areas of the brain. This method, however, also holds an important disadvantage, namely its temporal solution. Due to the physiological processes that lead to the BOLD response, its peak is temporally delayed from the onset of the event that triggered it, therefore making it unsuitable to measure neural activity brought about by events occurring close to each other.

Whereas fMRI only allows for the indirect measurement of neural activity through the BOLD response, electroencephalography (EEG) measures brain activity directly through the recording of postsynaptic electrical potentials through electrodes applied to the scalp. When a group of neurons are active at the same time due to cognitive operations, the electrical potentials become large enough to be measured as voltage changes that directly reflect differences in the potential measured by active electrodes and a predetermined reference electrode. Event-related potentials (ERPs) are changes in the continuous EEG signal that occur as a response to a certain stimulus or event. In relation to the onset of an event, different components can be identified that are characteristic for certain underlying cognitive processes (Luck, 2005). ERPs offer advantages such as a high temporal resolution and the possibility of continuously measuring cognitive processes occurring as a response to an event. The main disadvantage of the method lies in its poor spatial resolution, as the localization of the source of any given ERP pattern is difficult.

The following section will give an overview of previous research on creativity using ERPs and neuroimaging methods and their respective drawbacks and limitations.

2.4.1 Findings from neuroimaging studies

The advances in neuroimaging technology over the last decades made it possible to investigate creativity at its origin by uncovering some of the neural correlates of creative thinking. Even though, the present work focuses on fMRI as one neuroimaging method to measure creativity, the following overview also includes findings from other neuroimaging techniques to draw a more complete picture of the respective findings.

Studies on creativity and its neural basis span a wide range of possible investigative issues. Some studies focus on the connection between cortical thickness and different creative measures (e.g., Jung et al., 2010; Jung, Mead, Carrasco, & Flores, 2013) or the role of white or gray matter for creative achievement (Takeuchi et al., 2010a; Takeuchi et al., 2010b). The majority of studies, however, concentrate primarily on the importance of different brain regions on creative thinking. Unfortunately, the existing studies on creativity have not led to the isolation of a few brain areas involved in creative thinking. Apart from studies on insight (e.g., Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Jung-Beeman et al., 2004; Kounios et al., 2006; Luo, Niki, & Phillips, 2004; Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009) which consistently showed the involvement of bilateral inferior frontal gyrus (IFG; BA 45), anterior cingulate cortex (ACC; BA 9, 24 and 32) and superior temporal gyrus (STG; BA 21 and 22) or temporal pole (BA 38), findings from studies on creativity differ with regard to the brain regions involved.

One of the earliest studies that focused on differences between high and low creative individuals by Carlsson, Wendt and Risberg (2000) showed cerebral blood flow (CBF) differences. The researchers reported an increased activation in anterior and superior prefrontal and fronto-temporal regions when performing a creative task versus a fluency task or automatic speech. Highly creative individuals differed from low creative individuals only in superior frontal regions by showing a left hemispheric asymmetry.

In a similar manner, Chavez-Eakle and colleagues investigated cerebral blood flow differences between high and low creative individuals while they performed two creativity tasks (Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2007). Their results revealed greater CBF for highly creative individuals in a range of prefrontal areas, such as the right precentral gyrus (BA 6), bilateral middle frontal gyrus (BA 6 and BA 10), left inferior frontal gyrus (BA 47), as well as in the right cerebellum and in temporal regions (BA 38).

While the aforementioned studies mainly looked at the individual differences between high and low creative individuals and the arising differences in brain activation, other studies put an emphasis on the common neural correlates of cognitive processes underlying creativity regardless of individual differences in underlying creative ability.

In one of theses studies, Howard-Jones and colleagues (Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005) had participants imagine stories from related or unrelated word sets under the condition to be either creative or uncreative. The results revealed greater activation in the right medial frontal gyrus (BA 9/10), as well as in the left ACC (BA 9/32) when comparing creative versus uncreative story generation. Additionally, the authors reported greater activation in the right medial gyrus (BA 9/10) when the participants used related as opposed to unrelated words when asked to be creative rather than uncreative.

In a positron emission tomography (PET) study by Bechtereva and colleagues (Bechtereva et al., 2000) participants executed four tasks with differing levels of difficulty. Participants were required to generate a story from semantically distant words, create a story from semantically related words, reconstruct a given story or memorize a set of words. When contrasting the distantly and closely related story generation tasks, greater activation could be observed in the right superior frontal gyrus (BA 10), right mediofrontal gyrus (BA 11) and right inferior frontal gyrus (BA 45). Contrasting the distantly related story generation task with the reconstructing task resulted in greater activation in the left superior frontal and mediofrontal (BA 8) gyri, as well as the left cingulate gyrus (BA 32) and cuneus (BA 19) and precuneus (BA 7). Compared to the memorizing task, the distantly related story generation produced greater activation in bilateral IFG (BA 45/47), the left mediofrontal and mediotemporal gyri (BA 9, BA 21 and 39), as well as in the cuneus (BA 19).

Fink and colleagues conducted two studies to investigate possible underlying brain regions for creative tasks (Fink et al., 2009; Fink et al., 2010). In the first of these studies, the researchers compared brain activity during the Alternate Uses task with an Object Characteristics task (in which participants had to think of typical characteristics of common everyday objects, such as "leathery" or "matched" for "shoe") and found stronger activation in the left angular gyrus for the Alternate Uses task (Fink et al., 2009; experiment 2). In a later study, they investigated how brain activity changed when participants received cognitive stimulation in form of exposure to other people’s ideas (Fink et al., 2010). When comparing the Alternate Uses with the Object Characteristics task, greater activation of the left supramarginal gyrus could be observed. When comparing activation for the Alternate Uses task before and after participants received external cognitive stimulation, cognitive stimulation resulted in greater activation in the right posterior cingulate gyrus, bilateral precuneus, right middle temporal gyrus, right angular gyrus, medial orbitofrontal gyrus, as well as medial superior frontal gyrus.

In a more recent study, Benedek and colleagues compared creative idea generation with the mere retrieval of old ideas (Benedek et al., 2013). In the study, participants completed a self-paced Alternate Uses task and indicated afterwards whether their responses represented old or new ideas. The results showed that divergent thinking as measured by the Alternate Uses task led to activation in the left IFG and parts of the superior frontal gyrus (SFG), as well as in areas of the medial temporal lobe and the medial part of the precentral gyrus. When comparing the generation of new ideas to the mere recall of old ideas, new idea generation was associated with activation in the left inferior parietal cortex and the left supramarginal gyrus.

When bringing together the findings from the aforementioned studies on creativity, it is readily apparent that there does not seem to be a consistent pattern of activated brain areas associated with creative cognition. The findings rather reveal a myriad of possible neural correlates for creativity spanning almost the entire prefrontal cortex and other brain regions (Dietrich & Kanso, 2010). This inconsistency in creativity research findings is due to different reasons. Some of the reasons are of methodological nature and stem from drawbacks of imaging techniques for the investigation of creative thinking that will be discussed in the following section.

2.4.2 Limitations of neuroimaging studies

Although the rise of neuroimaging techniques offers the possibility to investigate creativity at its core, there are a number of limitations that need to be taken into consideration (Abraham, 2013).

Due to the high sensitivity of imaging methods to movement artefacts, especially of the head, many of the creativity tasks used under behavioral experimental settings are insufficient for use in neuroimaging studies. Creativity tasks often involve expressing one's generated ideas verbally or through writing or drawing. Some studies avoid the problem of movement artefacts by asking participants to generate ideas during the scanning period and to recall them from memory after the scanning session (e.g., Howard-Jones et al., 2005). This approach, however, poses only a suboptimal alternative to traditional creativity tasks as participants are prone to recall and memory biases limiting the reliability of their accounts. Participants may forget what they generated during the experiment (Wixted, 2004) or add details, thereby falsifying their initially generated ideas.

Additional problems arise from timing issues. The open-ended nature of creativity tasks together with long trial durations used by many researchers makes it almost impossible to time-lock the onset of a creative process to a certain stimulus or response (e.g., Fink et al., 2009; Howard-Jones et al., 2005). In the case of Howard-Jones et al.'s story generation task, one trial lasted 22 s during which a variety of cognitive processes may take place making it impossible to determine their specific onsets. Another drawback lies in the relatively small number of trials that can be applied in a neuroimaging setting, so as not to overstretch time that participants spend in the scanner. For instance, Fink and colleagues (2009) assessed four conditions with only 8 trials per condition in their experiment. Having a relatively small number of trials may lead to a loss of statistical power and increases the chance of possible effects remaining undetected.

Further drawbacks of previous studies that might be responsible for the heterogeneous findings lie in the deficit of sufficient control tasks that the creativity tasks can be contrasted with. Bechtereva and colleagues (2000) contrasted their story generation task with a word memorizing task, which is hardly comparable in difficulty. Moreover, memorizing a word list certainly recruits a whole set of different cognitive processes than are required for the completion of a generative task involving distantly related words. This lack of discriminatory power of the control task makes it impossible to detect neural correlates of creative cognitive processes.

The reason that probably accounts most for the unsatisfactorily inconsistent results of previous neuroimaging studies of creativity is the treatment of creativity as a single unitary construct (e.g., Dietrich, 2004; Dietrich & Kanso, 2010). Even though the creative cognition approach postulates that creativity requires the involvement of many fundamental cognitive processes (e.g., Finke et al., 1992), studies with the objective to investigate creative cognition fail to view creativity as a complex construct. By treating creativity in such a way, researchers do not consider that the experimental creativity tasks they are applying involve not only one but many cognitive processes that only partially overlap between different tasks. This failure to concentrate on the differentiable cognitive processes that lie at the core of creative thinking results in heterogeneous findings that unfortunately only limitedly illuminate the neural underpinnings of creative thinking.

2.4.3 Findings from ERP studies

While electroencephalography (EEG) has been widely used in the investigation of creativity, event-related potentials (ERP) in particular have rarely been employed for the same.

A fair amount of studies using EEG frequency band differences between task types or between participants differing in creativity scores have been conducted (e.g., Fink et al., 2009; Fink, Graif, & Neubauer, 2009; for an overview see Dietrich & Kanso, 2010 and Fink & Benedek, 2013). The study conducted by Fink and colleagues (2009) using a creative idea generation task revealed that the generation of original ideas is associated with heightened alpha synchronization over frontal areas of the brain. When taking individual differences into account, participants that produced highly original ideas showed greater alpha synchronization over parietal areas, as well. Similar results were found in a study by Fink, Graif, & Neubauer (2009) when they compared performances in an imagined improvisation dance and in the Alternate Uses task between professional and novice dancers. Professional dancers showed stronger alpha synchronization in parietal areas of the brain than novices. When imagining an improvised dance, stronger alpha synchronization in the right hemisphere could be observed in professional dancers as compared to the novices.

The field of research on insight in creative thinking has been the subject of a number of EEG and ERP studies. The focus has been limited to frequency band activity and ERP components associated with insight (e.g., Jung-Beeman et al., 2004; Qiu et al., 2008; for an overview see Dietrich & Kanso, 2010). However, there are no studies so far that investigated the association between ERP components and other creative cognitive operations in a creativity task. This is surprising considering the advantages that ERP investigations offer. For one, ERPs allow for a high temporal resolution which makes it possible to time-lock stimulus or response onsets more accurately to underlying brain activity, giving this method an advantage over fMRI which relies on the slow temporal resolution of the BOLD response. Additionally, ERPs are associated with distinct cognitive processes offering the opportunity to investigate their respective onsets and temporal distributions. These advantages make ERPs a suitable instrument for investigating creative thinking.

2.4.4 The present studies: Neural correlates of conceptual expansion

Introducing a new approach to investigate creative thinking

When summing up the existing neuroscientific research on creativity, it becomes apparent that there is abundant room for improvement to arrive at a better understanding of the neural correlates of creative thinking. Whereas findings concerning creative cognitive processes measured by way of ERPs are still missing entirely, results from fMRI and other neuroimaging studies draw a very heterogeneous picture of brain areas possibly involved in creative thinking.

The present work therefore follows three main objectives. The first objective concerns the problem of conceptualizing creativity as a single unitary construct and the thereof resulting inconsistent findings. The present studies are aimed at avoiding these issues by adopting a new perspective on creativity, viewing it as a construct involving different cognitive processes. Tying into this first objective, the second goal of the present work is to improve the many methodological issues arising when applying creativity tasks in a neuroscientific setting. As a last objective, one of the studies presented in this work is aimed at investigating creative thinking through ERPs, an attempt that has not been made so far. To meet these three main goals it is necessary to choose a new approach towards investigating creativity.

The approach adopted in the present work tries to overcome the general notion of creativity studies that views creativity as a unitary construct without disentangling the fundamental cognitive processes it possibly involves. Following the creative cognition approach and its postulations, the presented studies focus on one cognitive process thought to be vital for producing a creative outcome, namely conceptual expansion. Concentrating on one core process allows for a more distinct association between a cognitive process of interest and the respective brain areas and ERP components it recruits and is associated with. Previous studies on creativity used tasks that involved a variety of different cognitive processes, as can be seen, for instance, in the story generation task applied by Howard-Jones and colleagues (2005). When generating a story, participants recruit a number of cognitive operations ranging from working memory and other executive functioning operations to memory retrieval. Next to these cognitive operations that very likely occur for all participants, the recruitment of other cognitive operations to meet the goal of generating a creative story might differ between individual participants. In this manner, a creative story can arise from conceptual combination or conceptual expansion, as well as from analogy. Focusing instead on one individual creative cognitive process, such as conceptual expansion, would enable one to uncover the neural structures underlying this cognitive operation.

The second goal of the presented work is to investigate creativity while avoiding pitfalls of earlier neuroimaging studies on the subject. The greatest methodological issues in creativity research in neuroimaging settings are, as discussed above, long trial durations, relatively small numbers of trials, the lack of knowledge about the onset of a creative process, the difficulties associated with recording vocal or drawn responses, as well as suboptimal control conditions to contrast the experimental task with. These problems often arise when assessing creativity through a task that requires active generation from participants. In the case of conceptual expansion, one example for an active task is the one by Ward (1994) that asks participants to draw animals living on a planet different from earth. The new approach introduced in the present work tries to avoid the common methodological problems by assessing conceptual expansion through a passive task.

Usually, individuals expand their existing concepts actively when faced with a problem or task that requires a creative solution. However, it is also possible to bring about the expansion of existing concepts passively by way of exposing individuals to a novel and unusual idea. While it can be argued that the processes involved when actively broadening the limits of existing concepts differer to a great degree from those involved when conceptual expansion is passively induced, this argument is only partially valid. Clearly, the cognitive operations necessary for an active widening of concepts exceed the operations that are recruited when merely processing and comprehending a creative idea causing conceptual expansion. Active conceptual expansion will likely require additional processes that are unnecessary for passively expanding concepts, such as inhibitory control processes. The concepts that are being expanded, however, are the same in both types of tasks. Changes occurring to these concepts in terms of how they impact the conceptual networks in the brain, are therefore likely to be reflected by the activation of the same brain areas and by the same ERP components regardless of whether the expansion of concepts was self-driven and brought about actively or passively through the exposure to a creative idea.

Investigating conceptual expansion through novel metaphors

This novel approach towards assessing creativity in a passive manner can be suitably operationalized by referring to existing research on semantic language comprehension and processing. In particular, the processing of novel metaphors can be viewed as a passive expansion of concepts. Metaphors unfold their effect through the transfer of a certain feature or characteristic over to an unrelated domain followed by the integration of the new feature into the domain, thereby arriving at a novel meaning that neither one of the single domains conveyed individually. When trying to make sense of novel metaphors, existing conceptual representations have to be widened to include a new and formerly non-associated feature in it. "The clouds are crying over the fields" is an example for a novel metaphor. It can be assumed that the feature "crying" is not normally associated with the concept of a cloud. The concept has to be expanded to include this new feature in order to make sense of the metaphor. In contrast, "Her heart is broken" constitutes an ordinary or conventional metaphor that does not require conceptual expansion. Although a heart can not literally break, the expression is widely used in everyday language and "heart" and "break" are therefore already associated with each other for most people.

Research on novel metaphor processing has advanced quite far using fMRI as well as ERPs. A number of studies used fMRI to investigate which brain areas are activated when metaphors are processed. The studies used a variety of stimulus material, ranging from metaphorical word pairs (e.g., Mashal, Faust, & Hendler, 2005; Mashal, Faust, Hendler, & Jung-Beeman, 2007) to complete phrases (e.g., Hillert & Buracas, 2009; Stringaris et al., 2006; Stringaris, Medford, Giampietro, Brammer, & David, 2007) and phrases including metaphorical comparisons (e.g., Rapp, Leube, Erb, Grodd, & Kircher, 2004; Rapp, Leube, Erb, Grodd, & Kircher, 2007). The tasks that participants were asked to carry out in these fMRI studies on metaphor processing included, for instance, decisions on the meaningfulness of the presented material (e.g., Stringaris et al., 2007) or decisions on the metaphoric content of the material (e.g., Rapp et al., 2007). The results of the studies showed an involvement of inferior frontal gyrus (IFG; BA 44, 45 and 47) in the processing of novel compared to conventional metaphors or literal stimulus material (e.g., Mashal et al., 2005; Stringaris et al., 2007; Yang, Edens, Simpson, & Krawczyk, 2009), as well as activation in frontopolar areas (BA 10; Mashal et al., 2007) and temporal brain regions (BA 19, 20, 37, 38,39 and 42, e.g., Mashal et al., 2005; Rapp et al., 2004; Stringaris et al., 2007). A meta-analysis by Bohrn and colleagues (2012) investigating the neural correlates of figurative language across a number of fMRI studies found greater activation in areas such as the left middle frontal gyrus (MFG; BA 46), the left IFG (BA 44/45/47/9/10), left inferior temporal gyrus (ITG; BA 37/21) and the left fusiform gyrus (BA 20) when comparing novel metaphors and literal expressions (see Bohrn, Altmann, & Jacobs, 2012 for a more comprehensive overview of the included studies and their respective results). These regions constitute part of the semantic cognition network of the brain (Binder, Desai, Graves, & Conant, 2009).

Regarding ERP studies on the subject of metaphor processing, the stimulus material again covered different forms of metaphorical expressions, usually accompanied by the task to judge the meaningfulness (e.g., Arzouan, Goldstein, & Faust, 2007; De Grauwe, Swain, Holcomb, Ditman, & Kuperberg, 2010) and interpretability and familiarity (Lai, Curran, & Menn, 2009) of the presented material. When compared to conventional metaphors or literal stimulus material, novel metaphors were consistently associated with an increased N400 amplitude (e.g., Arzouan et al., 2007; Coulson & Van Petten, 2002; De Grauwe et al., 2010). The N400 has been associated with semantic incongruities (Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b), violations of world knowledge or discourse context (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Hald, Steenbeek-Planting, & Hagoort, 2007; van Berkum, Brown, & Hagoort, 1999) and the difficulty of semantic integration (e.g., Kutas & Van Petten, 1994). Some studies also report a greater late positive component (LPC) for metaphoric as compared to literal material (e.g., Coulson & Van Petten, 2002; De Grauwe et al., 2010). The LPC has been discussed in terms of reanalysis (Friederici, 1995) and additional retrieval of information from semantic memory (e.g., Coulson & Van Petten, 2002; Paller & Kutas, 1992).

Even though psycholinguistic studies on metaphor processing do not have the investigation of creative thinking as an objective, they can be modified to be suitable for examining conceptual expansion more closely. The present studies borrow from theses psycholinguistic studies by choosing novel metaphoric expressions as stimulus material for a passive conceptual expansion task. Since the main objective, however, is to draw a clearer picture of the neural correlates underlying creative cognitive processes, the two main characteristics of creativity, namely novelty and appropriateness, are considered in the task. In this manner, three categories of stimulus phrases were used that correspond to the possible combinations of novelty and appropriateness: high unusual and high appropriate (HUHA, novel metaphoric expressions), high unusual and low appropriate (HULA, nonsense expressions) and low unusual and high appropriate (LUHA, literal expressions). HUHA stimuli are considered to induce conceptual expansion and are therefore relevant to creative thinking. HULA stimuli are senseless as they convey something novel and original but impractical, whereas LUHA stimuli are common and well established in daily language use. The combination of a stimulus being low unusual and low appropriate (LULA) is not possible, as low unusualness implies that the conceptual association is known and well-established and therefore automatically has to be appropriate and practical as well.

Taking the present studies even one step further, the approach adopted here does not rely on these categories as pre-determined by the experimenter. Instead, the participants' task was to judge the presented stimulus material on both of the two defining features of creativity: unusualness (YES if unfamiliar to them, NO if familiar to them) and appropriateness (YES if fitting in the given context, NO if unfitting in the given context), thereby making it possible to group the stimuli into the three categories (HUHA, HULA, LUHA) for each subject individually. Forming these subject-determined conditions allows for controlling individual differences in participants' existing conceptual structures and their abilities to expand them. After all, individuals have varying notions on what they consider to be unusual and appropriate.

Another novelty of the paradigm adopted in the present studies lies in the implementation of a passive rather than an active conceptual expansion task. By choosing to induce conceptual expansion passively in participants, many of the methodological downfalls of previous studies, such as long trial durations during which a myriad of cognitive processes take place, and the difficulties associated with verbal responses to a task can be avoided. As discussed in a previous section, passive conceptual expansion may not recruit the exact same cognitive processes found in an active conceptual expansion task, but the conceptual structures being widened remain the same in both types of tasks and their expansion should therefore lead to the activation of the same brain areas.

fMRI: correlates of conceptual expansion

With regard to possible candidate brain regions involved during conceptual expansion, it was hypothesized that conceptual expansion would result in greater activation in areas in the IFG (BA 45 and 47). These areas have been shown to be involved in the retrieval of semantic information and the resolving of semantic uncertainties (e.g., Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Poldrack et al., 1999; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Additional regions that were expected to be activated during conceptual expansion are regions in the temporal lobe, such as the middle and inferior temporal gyri (MTG and ITG; BA 20 and 21) and the temporal poles (BA 38). These temporal areas play an important role for the storage of semantic information (e.g., Binder et al., 2009; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; Lambon Ralph, Pobric, & Jefferies, 2009; Patterson, Nestor, & Rogers, 2007) and were therefore hypothesized to play a role during conceptual expansion.

Finally, the involvement of the frontopolar cortex (BA 10) was also hypothesized. The frontopolar cortex has been shown to be instrumental for the integration of self-generated or inferred information, as well as for the integration of multiple relations (e.g., Bunge, Wendelken, Badre, & Wagner, 2005; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Kroger et al., 2002). Processing HUHA sentences (novel metaphoric expressions) was assumed to require greater efforts to retrieve stored semantic information about the two concepts conveyed through them. For the existing concept to be expanded, however, it is necessary that the two formerly unrelated concepts and features are integrated and put into relation to one another.

Sentences that are judged as novel (HUHA or novel metaphoric expressions and HULA or nonsense expressions) were also expected to lead to an increased demand in retrieving semantic information and resolving semantic uncertainties resulting in activations in the IFG (BA 45 and 47), as well as the temporal knowledge storage areas (BA 20, 21 and 38). Both types of stimuli convey something novel that has not been encountered before, making it necessary to put forth more effort in retrieving semantic information. Concerning sentences that are judged as appropriate (HUHA or novel metaphoric expressions and LUHA or literal expressions), the investigation was of an explorative nature without any specific expectations regarding possibly activated brain regions.

In sum, phrases involving conceptual expansion were hypothesized to lead to greater activation in the IFG (BA 45 and 47), the frontopolar cortex (BA 10) and the MTG and ITG (BA 20 and 21), as well as the temporal poles (BA 38). Phrases conveying novelty were hypothesized to result in the activation of the IFG (BA 45 and 47) and of temporal areas (BA 20, 21 and 38), whereas the investigation of phrases judged as appropriate was purely explorative.

ERP: correlates of conceptual expansion

For the ERP study, one ERP component was of especial interest for the investigation of conceptual expansion, namely the N400. The N400 component is a negative-going waveform that appears around 300 to 600 ms after stimulus onset. It is known to be modulated by a variety of stimulus features, such as semantic incongruity (e.g., Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b), cloze probability (Kutas & Hillyard, 1984a) or discourse context and world knowledge violations (e.g., Hagoort et al., 2004; Hald et al., 2007; van Berkum et al., 1999; van Berkum, Brown, Hagoort, & Zwitserlood, 2003). Considering that the N400 component is also known for indexing the difficulty of semantic information retrieval from memory storage (e.g., Kutas & Federmeier, 2000; Kutas, Van Petten, & Kluender, 2006), it was expected that HULA sentences (nonsense expressions) result in the greatest N400 amplitude, followed by HUHA sentences (novel metaphoric expressions) and LUHA sentences (literal expressions). HULA sentences (nonsense expressions) are unusual, but at the same time meaningless which should have the greatest effect on the N400 component, as they require more effort to retrieve semantic information about the involved concepts. HUHA phrases (novel metaphoric expressions), in comparison, should require less effort to retrieve semantic information than HULA phrases (nonsense expressions), but still to a greater extent than LUHA phrases (literal expressions). As creative thinking has not been investigated by means of ERPs so far, the possible effect of creative sentences on later ERP components remained unclear at this point.

In sum, the present studies adopt a new approach to investigate one creative cognitive operation, namely conceptual expansion, with fMRI and ERP. To avoid drawbacks and problems of previous studies, this new approach adapts experimental paradigms from metaphor processing studies to incorporate a passive conceptual expansion task fitted to take into account individual variations in the organization of conceptual knowledge by relying on subject-determined conditions.

The following sections describe the fMRI and ERP studies with their respective hypotheses, procedures and results regarding the neural correlates of creative thinking.

3 Study 1

Can clouds dance? Neural correlates of passive conceptual expansion using a metaphor processing task: Implications for creative cognition[1]

[1] Publication: Rutter, B., Kröger, S., Stark, R., Schweckendiek, J., Windmann, S., Hermann, C., & Abraham, A. (2012), *Brain and Cognition*, 78, 114-122.

3.1 Abstract

Creativity has emerged in the focus of neurocognitive research in the past decade. However, a heterogeneous pattern of brain areas has been implicated as underpinning the neural correlates of creativity. One explanation for these divergent findings lies in the fact that creativity is not usually investigated in terms of its many underlying cognitive processes. The present fMRI study focuses on the neural correlates of conceptual expansion, a central component of all creative processes. The study aims to avoid pitfalls of previous fMRI studies on creativity by employing a novel paradigm. Participants were presented with phrases and made judgments regarding both the unusualness and the appropriateness of the stimuli, corresponding to the two defining criteria of creativity. According to their respective evaluation, three subject-determined experimental conditions were obtained. Phrases judged as both unusual and appropriate were classified as indicating conceptual expansion in participants. The findings reveal the involvement of frontal and temporal regions when engaging in passive conceptual expansion as opposed to the information processing of mere unusualness (novelty) or appropriateness (relevance). Taking this new experimental approach to uncover specific processes involved in creative cognition revealed that frontal and temporal regions known to be involved in semantic cognition and relational reasoning play a role in passive conceptual expansion. Adopting a different vantage point on the investigation of creativity would allow for critical advances in future research on this topic.

3.2 Introduction

Creativity is one of the most complex cognitive abilities in human adaptive behaviour. Despite many discrepancies between experts on what makes an idea or product creative and the more naïve concept of creativity prevalent in the general population, a widely accepted working definition of creativity has emerged among researchers (e.g., Amabile, 1990; Boden, 2003; Dietrich, 2004; Finke, Ward, & Smith, 1992; Hennessey & Amabile, 2010; Runco, 2004; Sternberg & Lubart, 1999; Ward, Smith, & Finke, 1999). According to this definition, an idea, concept, or solution needs to meet two important requirements to be classified as creative. The first requirement refers to the originality or uniqueness of the concept, the second one concerns its appropriateness or relevance. An outcome has to be both novel and fitting for the task at hand to be considered creative (e.g., Ward, 2007). Creative processes are thought to involve different stages, each of which requires the recruitment of many cognitive processes to solve any given task (Ward, Smith, & Finke, 1999; Ward, 2007). However, their investigation, especially in the light of possibilities given through the rapid rise of neuroimaging techniques, has not advanced very far. Many reasons account for this impasse in creativity research.

First of all, most creativity tasks require verbal responses from participants, or heavily rely on their self-reports, as is the case for the insight tasks where participants have to report whether or not they found the solution by insight (Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Jung-Beeman et al., 2004). Using functional magnetic resonance imaging (fMRI) as a mode of examination makes it difficult to record participants' verbal responses during scanning due to the susceptibility to movement artefacts. Most studies avoid this pitfall by logging participants' verbal accounts after completion of the scanning session (Howard-Jones et al., 2005). This method, however, is associated with uncontrollable biases in participants' recall or the forgetting of earlier ideas (Healy, Havas, & Parkar, 2000; Wixted, 2004), which can lead one to question the reliability of the findings. Additionally, several neuroimaging designs have long trial durations (e.g., 20 seconds in Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, &

Cruz-Fuentes, 2007), or the processes in question are not time-locked to a defined stimulus or response (e.g., Fink et al., 2009), thereby making it harder to relate brain activations to the actual time point at which a creative process occurred. Furthermore, the conditions with which the creative tasks are contrasted often differ not only with regard to the creative processes involved, but, in various other aspects as well, such as task difficulty or task requirements (e.g., Bechtereva et al., 2000; Bechtereva, Korotkov, Pakhomov, Roudas, & Starchenko, 2004; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005). For instance, Bechtereva and colleagues (2000) had participants create stories from semantically distant words and contrasted them with a word remembering task as a control condition. Not only do the two tasks differ in difficulty, as it is harder to create stories from unrelated words, the modes of the tasks themselves are not comparable as the mere remembering of words recruits a whole host of different processes when compared to the active generation of a novel story. Such circumstances render it challenging to interpret findings as creativity-specific.

Most importantly, however, the investigation of creativity has conceptualized creativity not as a complex construct involving a multitude of cognitive processes, but has rather treated it as a singular entity (for criticism of this view, see Dietrich, 2004; Dietrich & Kanso, 2010). Apart from the cognitive process of insight which is defined by the sudden experience of the right solution during problem solving (e.g., Aziz-Zadeh, Kaplan, & Iacoboni, 2009; Jung-Beeman et al., 2004), no other specific creative operation has been the target of concerted neuroscientific investigation. The common approach to the investigation of creativity is to employ divergent thinking tasks which require the production of multiple solutions for a problem. The specific cognitive processes recruited by these tasks, however, are impossible to determine because of the many differences between tasks and designs. The result is a number of very heterogeneous findings that attempt to pin down the neural correlates of creativity as a whole without specifying the distinct processes involved in any given task. The various brain regions identified across these studies span almost the entire prefrontal cortex with only little overlap between studies (e.g., Bechtereva, Korotkov, Pakhomov, Roudas, & Starchenko, 2004; Chavez-Eakle, Graff-Guerrero, Garcia-Reyna, Vaugier, & Cruz-Fuentes, 2007; Fink et al., 2009; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005; for a detailed review, see Dietrich & Kanso, 2010).

One possibility to avoid many of the drawbacks of previous neuroimaging studies would be to target specific operations of creativity individually. Conceptual expansion is, hereby, of particular interest for the investigation of creative cognition. It describes the extension of existing concepts to include new features and attributes, thereby widening its original definition (Abraham, Windmann, Daum, & Gunturkun, 2005; Abraham, Windmann, Siefen, Daum, & Gunturkun, 2006; Abraham & Windmann, 2007; Ward, Patterson, Sifonis, Dodds, & Saunders, 2002), and thus plays a crucial role in generating new ideas. As the behavioural tasks to assess conceptual expansion involve drawing and have no time constraints (e.g., Ward, 1994), they are not suitable for fMRI designs. An indirect approach would therefore be better suited to examine this process in an fMRI setting. The domain of metaphor processing offers an ideal opportunity for such a venture (e.g., Hillert & Buracas, 2009; Mashal, Faust, Hendler, & Jung-Beeman, 2007; Mashal, Faust, Hendler, & Jung-Beeman, 2009; Rapp, Leube, Erb, Grodd, & Kircher, 2004; Stringaris, Medford, Giampietro, Brammer, & David, 2007). Paradigms that assess novel metaphor processing where different and often semantically distant domains have to be integrated mentally in order to derive meaning are particularly relevant as they can be modified to investigate conceptual expansion in creative cognition. For instance, Mashal and colleagues (2007) used novel metaphoric, conventional metaphoric, literal and unrelated word pairs and asked participants to indicate the nature of relatedness for each pair. The authors were able to show stronger activation in the anterior inferior frontal gyrus (IFG; Brodmann’s areas (BA) 44/45) for novel compared to conventional metaphors, as well as activation in frontopolar areas (BA 10) when contrasting metaphors and literal phrases with senseless phrases. Although these studies can partially contribute to shed light on the neural correlates of creative cognition, there are several factors that limit such generalizations. For instance, previous studies either fall short of ensuring the novelty and appropriateness of the material used or only control one of these features necessary to match the definition of creativity (e.g., Rapp, Leube, Erb, Grodd, & Kircher, 2004; Stringaris, Medford, Giampietro, Brammer, & David, 2007).This criticism does not invalidate the conclusion of the cited studies as in neither case the main goal was to investigate creativity *per se*. Mashal and colleagues (2007), however, did claim in their study that findings associated with novel metaphoric expressions were relevant for understanding creative operations. Their stimulus material, though, was pre-categorized by the experimenter as being novel and appropriate. Considering the high inter-individual variability of the organization of semantic networks, a semantic connection that might be deemed as creative (i.e., both novel and appropriate) by one subject, might not be classified as such by another subject. To warrant the conclusions regarding creative thought, it would be important to optimize the experimental design in a manner that accounts for this inter-individual variability.

The present study introduces a new paradigm to investigate conceptual expansion in creative cognition that is suitable to avoid common problems associated with neuroimaging studies of creativity. The study's aim is to investigate singular processes that are involved when engaging in creative thinking. The experimental approach adopted in this new paradigm is based on the assumption that conceptual expansion can be achieved not only through an active cognitive effort to broaden a concept, but can also be induced passively through the perception and the resulting integration of two semantically distant concepts. The difference between active and passive conceptual expansion would be expected to lie in the volitional or self-driven aspect of expanding concepts. It cannot be assumed that the cognitive processes involved when generating something novel and those involved when understanding something novel are exactly the same. However, a substantial overlap between processes involved in the active and the passive task can be expected due to the fact that the conceptual structures that are being expanded are the very same. Expanding existing concepts would therefore engage similar structures related to semantic cognition regardless of the manner in which the expansion was evoked. Engaging in active conceptual expansion would likely result in greater activation of theses areas and incorporate areas not involved during the passive task, such as structures associated with inhibitory control processes or imagery-related operations. Nonetheless, because passive conceptual expansion partially draws on the same neural structures, it allows one to investigate select aspects of creative thinking while avoiding common problems of fMRI investigations of creativity.

Conceptual expansion will be passively induced in the present study by having participants read three different types of phrases derived from the variation of creativity's two main features, namely novelty (or unusualness) and appropriateness (or relevance). By having subjects process stimuli that are either highly unusual and highly appropriate (HUHA: conceptual expansion), highly unusual but low appropriate (HULA: unusual/novel), or low unusual but highly appropriate (LUHA: common/appropriate), the study aims to take a more specific look on the neural correlates of conceptual expansion, novelty and appropriateness. Conceptual expansion is held to be achieved through phrases represented in the HUHA category given that in this case two formerly unrelated or weakly related concepts are directly linked together in an appropriate but novel manner for the first time. This requires the boundaries of both concepts to be expanded beyond their established limits. By basing the condition-specific categorization of the stimuli phrases entirely on participants' dichotomous ratings of the phrases on the response dimensions of unusualness and appropriateness, inter-individual differences in the organization of their conceptual networks are also accounted for within the experimental design. This approach therefore allows for the nonverbal and time-specific investigation of a creative process determined on a subject-by-subject basis while, at the same time, providing appropriate conditions for comparisons.

It is hypothesized that conceptual expansion (HUHA) will involve areas in the anterior IFG (BA 45 and BA 47) because this area has been linked to semantic retrieval and the resolution of semantic uncertainties (e.g., Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Poldrack et al., 1999; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Additionally, conceptual expansion is expected to lead to activation in the frontopolar region (BA 10) due to greater demands on relational information integration for this condition compared to the other two. The frontopolar region has been shown to be especially involved in the integration of self-generated or inferred information and multiple relations (e.g., Bunge, Wendelken, Badre, & Wagner, 2005; Christoff et al., 2001; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010; Kroger et al., 2002). Conceptual expansion is also expected to lead to activation in the temporal lobe in the middle and inferior temporal gyri (especially, BA 20 and 21), as well as the temporal pole (BA 38), areas known to be involved in semantic processing and storage (e.g., Binder, Desai, Graves, & Conant, 2009; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010; Lambon Ralph, Pobric, & Jefferies, 2009; Patterson, Nestor, & Rogers, 2007).

While the investigation of appropriateness will be explorative in the current study, novelty processing is also expected to lead to greater demands on semantic retrieval and semantic selection which should result in activation in the anterior IFG (BA 45 and BA 47) and activation of temporal areas (BA 20, 21 and 38).

3.3 Materials and Methods

3.3.1 Participants

The original sample included 27 healthy, right-handed students of the University of Giessen that participated in the fMRI study in exchange for course credit or monetary compensation (€ 17.50). All participants were native German speakers. A total of nine participants had to be excluded from data analyses due to excessive movement during scanning (*n* = 2), insufficient number of HUHA judgements (*n* = 3), and too many wrong answers in the control condition (*n* = 4), thereby possibly defeating the purpose of the control condition, namely to control effects of difficulty. All reported analyses and results are based on the final sample of 18 participants (9 females). Mean age was 22.78 years (*SD* = 3.26). The experimental standards of the study were approved by the Ethics Commission of the German Psychological Society (DGPs).

3.3.2 Materials

Fifty-four experimenter-determined stimuli sentence triplets were initially created. Each sentence consisted of subject, verb and object in present perfect tense (for examples, see Tab. 1). Three different verbs were chosen for each triplet that rendered the sentence to be either literal (corresponding to LUHA), senseless (corresponding to HULA) or metaphorical (corresponding to HUHA). It is important to note that a combination where both unusualness and appropriateness are judged as low (LULA) is not possible as the two defining characteristics of creativity, unusualness and appropriateness, are not independent from each other. Something that is judged to be usual or common is by definition appropriate at the same time. Low unusualness or low novelty entails that the object, idea or, in this case, combination of semantic instances is known or has been encountered before and is therefore immediately appropriate as well. An association that is inappropriate or irrelevant would not be established in everyday life to also be common or usual. Behavioural pilot studies were conducted to arrive at the final set of 132 stimuli used in the fMRI study. Inclusion criteria for the metaphorical sentences were determined as follows: More than 60% of participants in the pilot study had to judge the phrase as highly unusual and highly appropriate. Additionally, at least 60% of participants had to agree on the unfamiliarity of the phrase.

Table 1: Examples for stimuli phrases

Example phrases for the three experimental conditions. Critical word is printed in bold.

Condition	Sentence
Highly unusual – highly appropriate (HUHA)	The clouds have **danced** over the city.
Highly unusual – low appropriate (HULA)	The clouds have **read** over the city.
Lowly unusual – highly appropriate (LUHA)	The clouds have **moved** over the city.

A one-way ANOVA showed that the three experimental conditions differed significantly (p = .047) from each other in regard of word length of the verb. Bonferroni-corrected post-hoc tests did reveal, however, that this effect was primarily carried by marginally significant differences in verb word length between the senseless and the literal verbs (m = 8.45 and m = 9.39, respectively, p = .051). Additionally, the verbs were checked for their frequency of occurrence in the German language. Using an online tool (http://wortschatz.uni-leipzig.de/), frequency of occurrence for each verb was computed. A median test comparing the three conditions showed that the conditions did not differ significantly regarding the frequency of occurrence of the verb.

In order to ensure that possible differences in activation between the conditions are not merely an effect of varying reaction times (RTs) associated with the answers given to the conditions (as was indicated by the behavioural pilot studies) a control condition was included in the experiment. To keep the control condition as similar as possible to the experimental conditions and only increase difficulty of the task, control sentences consisted of phrases written backwards. Participants' task was to decide whether or not the phrases contained an animal and whether or not they contained a spelling error. Another pretest confirmed that the control condition was at least as difficult as the most difficult experimental condition as could be seen in reaction times. Forty-four control phrases were included in the experiment, containing either an animal and a spelling error, an animal and no spelling error, no animal and a spelling error, or neither an animal nor a spelling error.

3.3.3 Experimental procedure

After giving their written consent to participate in the study and following some practice trials outside the scanner, participants completed the experimental task during fMRI. Participants were placed on the scanner bed in a supine position. Each trial began with a jittered blank screen (0 – 1500 ms), then the presentation of a fixation cross for 300 ms, followed by a 200 ms blank screen. Subsequently, a stimulus phrase was presented for 3000 ms, followed by the questions “Unusual?” and “Appropriate?” for 1500 ms, respectively, separated by a 500 ms blank screen. Participants pressed a “yes” or a “no” button on a response box with their right index or middle finger, respectively, to indicate their judgements. Participants were instructed that they should respond “yes” to the Unusual-question if the presented information was novel or unfamiliar and “no” if it was known or familiar. They were also instructed that they should respond “yes” to the Appropriateness-question if the presented information was fitting or relevant and “no” if it was unfitting or irrelevant. Following the last question, another jittered blank screen was presented (3000 – 4500 ms), resulting in a total trial time of 12 s (see Fig. 1). The experiment included 17 null trials consisting in the presentation of a blank screen for the length of a regular trial.

The stimuli phrases were presented in a pseudo-randomized order and projected onto a screen at the end of the scanner (visual field = 18°) using an LCD projector (EPSON EMP-7250) and were viewed through a mirror mounted on the head coil. Upon completion of the scanning session, participants rated each stimulus phrase in regard to whether or not they had already known the phrase prior to reading it in the experiment on a 5-point Likert scale[2]. Additionally, participants were asked to complete the vocabulary scale of the Hamburg Wechsler Intelligence Test for Adults (HAWIE, Tewes, 1994)[3]. The HAWIE vocabulary scale is assessed by reading 32 words with increasing difficulty to the participants and asking them to give a brief definition of each word. The resulting number of correctly defined words is transformed into a standardized value, while taking the participants' age into consideration.

	+		The clouds have read over the city		Unusual?		Appropriate?	
0–1500	300	200	3000	500	1500	500	1500	3000-4500

Figure 1 Experimental trial *Example of the experimental trial timeline. Durations are displayed in the bottom line in milliseconds.*

[2] In an initial analysis, only HUHA phrases with a familiarity rating of less than 4 were included for each participant. This, however, resulted in a drastic cut in the number of phrases judged as unusual and appropriate. When taking into consideration that these types of phrases had been selected based on a strict cut-off criterion for familiarity in the behavioural pilot studies, the suspicion arose that participants' familiarity judgments might be biased by the recent encounter of the very same phrases in the experiment. To test this assumption, a group of participants that had not taken part in any of the pilot studies or the main study (n = 20) filled out the familiarity ratings independent from the main study. Results from an independent t-test confirmed the existence of a memory bias that was likely to have been caused by the prior presentation of the stimuli. Participants that saw the stimuli prior to the familiarity rating evaluated them as more familiar than participants that did not see the stimuli prior to the rating (m = 2.60 and m = 2.35, respectively; $t(86) = -2.31$, p = .024). Therefore, the familiarity ratings were dismissed in the analyses of the main study due to unreliability.

[3] Analyses that included HAWIE values as a covariate did not lead to differing results and are therefore not reported.

3.3.4 Data acquisition

Functional and anatomical scans were obtained using a 1.5 Tesla whole-body tomography system (Siemens Symphony) with a standard head coil. Structural image acquisition consisted of 160 T1-weighted sagittal images (MPRage, 1mm slice thickness). A gradient echo field map sequence was acquired before the functional image acquisition to obtain information for unwarping B_0 distortions. For functional imaging, one run with a total of 950 volumes was recorded using a T2*-weighted gradient echo-planar imaging sequence (EPI) with 25 slices covering the whole brain (slice thickness = 5 mm; gap = 1 mm; descending slice order; TA = 100 ms; TE = 55 ms; TR = 2.5 s; flip angle = 90°; field of view = 192 mm x 192 mm; matrix size = 64 x 64). The orientation of the axial slices was tilted to parallel the OFC tissue–bone transition to keep susceptibility artefacts to a minimum.

3.3.5 Data analysis

For each participant, stimulus phrases were grouped into the three experimental conditions based on the participant's responses. This resulted in a differing number of phrases per condition for each subject. To avoid underrepresentation of any one experimental condition, subjects with a disproportionate distribution of stimulus phrases between the three experimental conditions were excluded from data analysis. Cut-off criterion for exclusion of participants was determined at less than 28 instances in any one condition.

Functional data processing and analyses were done using SPM8 package (Wellcome Department of Cognitive Neurology, London, UK; see http://www.fil.ion.ucl.ac.uk/spm). Preprocessing routines included realignment, slice timing, normalization, and smoothing procedures. Each subject's functional images were corrected for motion and unwarped using the first volume as a reference, as well as a voxel displacement map (vdm5), constructed using the fieldmap toolbox of SPM8. Realigned and unwarped images were corrected for time differences in acquisition. T1 anatomical images were coregistered to the mean functional image. Functional images were then normalized with a voxel size of 3 mm to the anatomical image and spatially smoothed using a 9 mm full-width, half-maximum (FWHM) Gaussian filter.

First and second level analyses were computed using a general linear model approach (Friston et al., 1994). For each subject, three experimental conditions, the control condition and the null trials were modelled as regressors and convolved with the standard hemodynamic response function combined with time and dispersion derivatives. Regressor onsets were equal to stimulus onsets and were modelled in an epoch-related design with an epoch duration of 7 s (from the stimulus phrase onset till the end of presentation time for the second question). Additionally, the six movement parameters obtained by the realignment procedure were included into the model to account for possible residual movement artefacts after realignment and a high-pass filter of 1/150s was employed. One-sample t-tests were computed to obtain the relevant contrast images for each single subject. The contrast images were entered into group statistics analyses.

Conjunction analyses were carried out to uncover which brain regions are commonly activated across contrasts as a function of a particular process of interest. Conjunction analyses allow for the investigation of activation that is conjointly present in two contrasts. Contrasts of interest obtained on first level were entered into paired t-tests on second level using the conjunction null hypothesis (Nichols, Brett, Andersson, Wager, & Poline, 2005). Tests using the conjunction null hypothesis are more conservative in that they test for an AND conjunction that only dismisses the null hypothesis if all subjects show activation in the tested voxel in both contrasts. Using conjunction analyses allows for the investigation of activation that is specific to conceptual expansion separated as opposed to activations caused solely by novelty or appropriateness. In order to investigate activity related to the novelty of the stimulus phrase, a conjunction analysis of the contrasts that compared the two highly unusual conditions to the low unusual condition, respectively, (Novelty = **HU**HA > LUHA ∩ **HU**LA > LUHA) was computed. For activity specific to the appropriateness dimension of the stimulus phrases, we looked at the conjunction of contrasts comparing the two highly appropriate conditions with the low appropriate condition, respectively (Appropriateness = HU**HA** > HULA ∩ LU**HA** > HULA). Finally, specific activation caused by conceptual expansion was assessed through a conjunction analysis involving the contrasts between the highly unusual and highly appropriate phrases and the remaining two experimental conditions, respectively (conceptual expansion = **HUHA** > HULA ∩ **HUHA** > LUHA).

Based on the a priori expectations, five Regions-of–Interest (ROI) were designed using the WFU Pick Atlas toolbox available for SPM8 (Maldjian, Laurienti, & Burdette, 2004; Maldjian, Laurienti, Kraft, & Burdette, 2003). ROIs were created for Brodmann's areas 10, 45, 47, 21, 22 and 38[4]. Unless specified otherwise, all reported data have been FWE – corrected for multiple comparisons at $p < .05$. As the cognitive effects under investigation in the present study are complex, clusters consisting of three or more voxels (minimum cluster size: 81

[4] We also conducted whole-brain voxel-wise analyses. Alongside other areas of activation, the whole-brain analyses revealed greater activation in bilateral IFG (BA 45 and BA 47) and left MTG (BA 22) for conceptual expansion, in bilateral SFG and MFG (BA 10/11) and left MTG (BA 21) for appropriateness, as well as in right IFG (BA 45) for novelty. Due to a priori hypotheses about the involvement of these areas and overlapping findings for whole-brain and ROI analyses, only the ROI results are reported. Tables with whole-brain results and a color-coded map depicting overlap between conceptual expansion and novelty in the prefrontal cortex can be found in the supplementary material.

Additional contrasts were computed using the control condition as an inclusive mask. Given that masking the contrasts did not change the results and the fact that RTs as an indicator of task difficulty did not differ significantly between experimental conditions, all analyses reported in the paper disregard the control condition. Results of the direct contrast between the HUHA condition compared to the control condition are included in the supplementary material.

cubic mm) are reported in order to reduce the risk of type II errors (Lieberman & Cunningham, 2009).

3.4 Results

3.4.1 Behavioral data

Table 2 shows means and standard deviations for the four conditions for each question. A repeated measures 4 x 2 ANOVA with factors condition (HUHA, HULA, LUHA, control) and question type (unusual, appropriate) was conducted to determine possible differences in RTs. The analysis showed significant main effects of condition ($F(3, 51) = 3{,}47$, $p = .023$) and question type ($F(1, 17) = 137{,}47$, $p < .001$), as well as a significant interaction between condition and question type ($F(3, 51) = 15.01$, $p < .001$). Further analyses showed that RTs for the “unusual/animal” question were slower than for the “appropriate/error” question (m = 718.1 ms and m = 567.9 ms for unusual/animal and appropriate/error, respectively; $p = <.001$). Reaction times were also significantly longer for the control condition compared to every experimental condition for the “unusual/animal” question only ($p = .038$, $p = .01$, and $p = .001$ for control vs. HUHA, HULA, and LUHA, respectively; see Table 2 for corresponding means). For the “appropriate/error” question, HUHA showed a slightly longer RT compared to the control condition ($p = .025$). As no behavioural differences were found between the three experimental conditions, the control condition will not be discussed further.

Table 2: Reaction times

Mean reaction times in milliseconds for the four conditions for each question. Standard deviations are given in brackets.

Condition	**Question**	
	Unusual	**Appropriate**
HUHA	701.6 (208.3)	605.0 (200.3)
HULA	692.1 (172.6)	593.3 (140.8)
LUHA	677.8 (175.7)	539.3 (151.0)
Control	801.0 (115.3)	533.9 (151.1)

3.4.2 Neuroimaging data

Table 3 shows the regions of significant activation for all three conjunction analyses in the ROIs BA 10, 20, 21, 38, 45 and 47. For the conjunction analysis aimed at revealing activation associated with conceptual expansion (**HUHA** > HULA ∩ **HUHA** > LUHA) it was hypothesized that there would be significant activation in the anterior IFG (BA 45 and 47), the middle temporal gyrus (BA 20 and 21), as well as the frontopolar cortex (BA 10). The findings partially confirm the hypotheses as a significant increase in BOLD signal was found in the left IFG (BA 45 and BA 47) for HUHA compared to HULA and LUHA: Additionally, there was significant activation in the right IFG (BA 45) and the left temporal pole (BA 38). Activations were also found in the left middle frontal and superior frontal gyri corresponding to the frontopolar cortex (BA 10), albeit only uncorrected at a threshold of $p < .001$.

Table 3: Overview of brain activations

Activation peaks for the different conjunction analyses. Peak coordinates of each cluster are given in standard MNI space. Structure, Brodmann's area (BA), Hemisphere (Hem), cluster size and peak t-value (t) are presented, as well. Significance threshold for the analyses is $p < .05$ (FWE-corrected) and extent threshold is $k \geq 3$ (minimum cluster size: 81 cubic mm). Asterisk marks significance threshold of $p < .001$ (uncorrected). ROIs: bilateral Brodmann's areas 10, 20, 21, 45, 47 and 38; IFG: Inferior frontal gyrus; MFG: Middle frontal gyrus; MTG: Middle temporal gyrus; STG: Superior temporal gyrus.

				MNI peak coordinate			
Area	**BA**	**Hem**	**Cluster size**	**x**	**y**	**z**	**t**
Conceptual expansion (HUHA > HULA ∩ HUHA > LUHA)							
IFG	45	L	16	-48	17	4	5.12
IFG	45	R	5	60	17	4	4.80
IFG	47	L	9	-42	20	1	5.05
IFG/MFG	47/11	L	44	-36	29	-8	8.14
MFG	10	L	3	-33	50	13	4.67*
MFG	10	L	4	-30	53	19	3.77*
STG	38	L	5	-48	20	-14	4.91
Appropriateness (HUHA > HULA ∩ LUHA > HULA)							
MTG	21	L	6	-63	-22	-14	6.22
Novelty (HUHA > LUHA ∩ HULA > LUHA)							
IFG	45	R	4	54	29	7	3.94*

It was expected that the processing of novel or unusual information would lead to activations in the anterior IFG (BA 45 and 47) as well as the middle temporal gyrus and temporal pole (BA 20, 21 and 38). These hypotheses were only partially confirmed as the conjunction analysis which assessed activations associated with novelty processing (**HU**HA > LUHA ∩ **HU**LA > LUHA) only showed activation in the right inferior frontal gyrus (BA 45), also at an uncorrected threshold of $p < .001$.

Finally, an explorative conjunction analysis was carried out to uncover which brain areas are associated with the processing of appropriateness (HU**HA** > HULA ∩ LU**HA** > HULA). The findings revealed the significant involvement of the left middle temporal gyrus (BA 21).

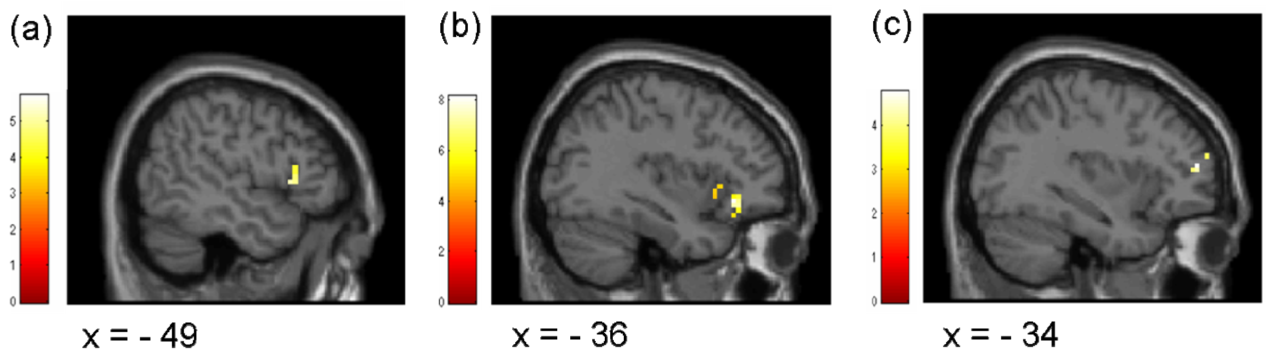

Figure 2 Activations as a function of conceptual expansion *Conceptual expansion: Activations as a function of conceptual expansion in the Regions-of-Interest (a) Left mid-inferior frontal gyrus (IFG: BA 45), (b) Left anterior IFG (BA 47) and (c) Left frontopolar cortex (BA10). Color bars represent Z-value at an FWE-corrected p < .05 for BA 45 and BA 47, at an uncorrected p < .001 for BA 10.*

3.5 Discussion

This study employs a new approach to investigate creative cognition by breaking down the concept of creativity into single processes and focusing on one cognitive operation playing a central role in creative cognition, namely conceptual expansion. Here, passively inducing conceptual expansion in participants and letting them determine the nature of the respective stimulus phrase rendered it possible to obtain a clearer picture on the brain activations that are associated with conceptual expansion, novelty and appropriateness.

3.5.1 Conceptual expansion

The results confirm the hypotheses concerning the aspects of information processing involved in conceptual expansion. As expected, we were able to show bilateral anterior IFG (BA 45/47) involvement in the processing of conceptual expansion. The findings reveal several clusters especially within the left lateral anterior IFG for phrases judged as unusual and appropriate (HUHA). Activations in these areas, albeit to a smaller extent, were also found in analogous regions in the right hemisphere. Recent studies have linked this region to an increased effort to retrieve semantic information and greater semantic selection demands (Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001; Wig, Miller, Kingstone, & Kelley, 2004) as well as increasing semantic distance (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010). In the present study, these regions were more strongly recruited during conceptual expansion, i.e. when a phrase was judged by the participant as being both novel and appropriate in a given context. Deciding on the novelty and appropriateness of the phrases seems to call for an increased demand on controlled retrieval and selection of semantic knowledge that is not as necessary when faced with stimuli that are only novel (HULA) or only appropriate (LUHA). Unusual and appropriate phrases require the recovery of semantic knowledge about the two semantically distant concepts that need to be brought into relation.

While the role of the IFG appears indisputable in semantic processing, there is some debate as to the precise role of this region. Wagner and colleagues (2001), for instance, have claimed that the left anterior IFG is associated with controlled retrieval of semantic knowledge, whereas Thompson-Schill and colleagues (1997) argue for the role of the left anterior IFG in semantic selection rather than retrieval processes. A more recent account by Badre and colleagues (2005) incorporates both possible functions of the anterior IFG, such that the left anterior ventrolateral prefrontal cortex (BA 47) is held to be more strongly recruited when a task necessitates top-down retrieval of semantic knowledge, whereas the left mid-ventrolateral prefrontal cortex (BA 45) is more strongly associated with the mediation of semantic selection. Both of these postulations can be applied to the current results as phrases judged to be both unusual and appropriate require the controlled retrieval of concepts and their distinct features, as well as the selection of an appropriate manner in which the concepts can be linked with each other.

In line with several previous studies that have identified the left middle temporal cortex (BA 21/22) and the temporal poles as areas linked with semantic knowledge (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Bokde, Tagamets, Friedman, & Horwitz, 2001; Lambon Ralph, Cipolotti, Manes, & Patterson, 2010), the present study also found activations along the left temporal pole as a function of conceptual expansion. In an attempt to bring together these two facets of semantic processing, Badre and colleagues (2005) proposed a two-step model of semantic memory in which semantic knowledge is stored within the temporal cortex. Retrieval of information from temporal regions emerges via automatic or controlled processes (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005). Semantic selection processes as subserved by the mid-ventrolateral prefrontal cortex run parallel in both cases whereas controlled retrieval is held to be mediated by the left anterior ventrolateral prefrontal cortex. Results of the present study fit well within this model as both IFG (BA 45/47) as well as temporal pole (BA 38) activations resulted as a function of conceptual expansion (HUHA) implicating semantic selection, controlled semantic retrieval and semantic storage related processes. Automatic semantic retrieval is unlikely to have resulted within HUHA trials due to the uncommonness of the phrase.

The hypothesis concerning greater frontopolar activation (BA 10) when processing conceptual expansion could also be confirmed, albeit only at an uncorrected threshold of $p < .001$. This region has been implicated as playing a role in integrating the output of multiple cognitive operations (Ramnani & Owen, 2004) which was required in the present study due to the processing demands of the HUHA stimuli. Conceptual expansion was expected to result in greater relational information integration efforts in the frontopolar region as the connection of two previously unrelated or weakly related concepts in a novel and appropriate way necessitates the recovery of knowledge about the two distant concepts that need to be brought into relation to one another. Previous studies have shown the recruitment of frontopolar areas when processing highly complex stimuli in a reasoning task (Kroger et al., 2002), as well as when integrating relations across semantic distance in an analogy task (Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010). Some studies have extended the role of the left frontopolar region even further by proposing that relational integration is achieved through the manipulation of self-inferred or self-generated information (Christoff et al., 2001; Christoff, Ream, Geddes, & Gabrieli, 2003). Notably, the involvement of this region as a function of conceptual expansion using the present paradigm could be also seen as an indicator for the suitability of an indirect approach to investigate conceptual expansion. After all, even though participants in the present study did not have to actively or volitionally expand concepts and thereby self-generate the information, the decision as to whether or not a phrase was unusual and appropriate had to be self-inferred by the participants.

In sum, the passive expansion of existing concepts seems to be associated with a network of processes associated with different structures in frontal and temporal areas.

3.5.2 Novelty

In the case of activity caused by the novelty of the phrases, the obtained results partially deviate from what was predicted. Both categories of unusual phrases were expected to elicit activation in the anterior IFG (BA 45/47) due to greater semantic retrieval and selection demands. The results revealed only a small area of IFG activation (BA 45) in the right hemisphere, albeit only at an uncorrected threshold of $p < .001$. One possible explanation for this finding might lie in the nature of the unusual and inappropriate phrases. HULA phrases might have been easily dismissed as senseless. This view is shared by Mashal and colleagues (2009) in their interpretation of the lack of activation for nonsensical sentences compared to literal or metaphorical ones. This would imply that the phrases judged as unusual and senseless by the participants were easily disregarded as such and did not recruit increased retrieval effort to reach a conclusion and to find a link between the two concepts implied through the stimulus. This obvious senselessness seems to, in turn, deem semantic retrieval under the control of the anterior IFG (BA 47) unnecessary. Here, our findings deviate from those of Stringaris and colleagues (2007) who showed anterior IFG activation not only for metaphoric but also for non-meaningful sentences compared to literal ones. However, these differences in the pattern of findings may be due to the different nature of the stimulus phrases used in both studies. While Stringaris and colleagues (2007) presented participants with phrases in the form of “Some X are Y”, our stimulus material was not as abstract and therefore closer to everyday language in content and in structure. This might have made it easier to dismiss senseless phrases as such in our study.

The obvious senselessness of the HULA phrases can also account for the lack of expected activation in the MTG and temporal pole regions (BA 20, 21 and 38) in relation to novelty processing. The senselessness of HULA stimuli might have been too obvious to initiate an extensive search in and retrieval from semantic networks in the temporal lobe. These are only post-hoc theoretical postulations. Yet, this is a previously unconsidered yet fascinating issue in the domain of semantic novelty processing that requires further research in order to comprehend its precise ramifications.

3.5.3 Appropriateness

Due to the explorative nature of the investigation into the neural processing of the appropriateness of the phrases, there were no predictions made in advance. The results nevertheless hold surprising findings that seem counterintuitive at first. Appropriateness in the present study led to activation in the left middle temporal gyrus (BA 21). Initially, greater activation in this area was expected for conceptual expansion as well as for the novelty aspect of the phrases due to greater efforts to retrieve semantic knowledge. For conceptual expansion, these expectations were met, whereas this was not the case for novelty, most likely due to the nature of the HULA phrases. Finding activation in the middle temporal gyrus as a function of appropriateness therefore appears counterintuitive at first. This result can, however, be explained with Badre and colleagues' (2005) proposal on semantic memory retrieval with the temporal areas functioning as knowledge storage that can be drawn upon through automatic or IFG-controlled processes. For phrases rated as LUHA, it can assumed that the retrieval of information about the commonness and appropriateness of the phrases happens through a more shallow processing without the need to elaborate deeper on semantic knowledge due to their literal nature. Common and appropriate phrases occur in everyday language and are therefore likely to be processed highly automatically, whereas the nature of phrases judged to be unusual and appropriate (HUHA) requires prefrontal executive control to retrieve the relevant semantic knowledge.

3.5.4 Limitations of the Study

Even though the results of the present study contribute to the investigation of creative thinking, there are some limitations that have to be kept in mind when interpreting the findings. One of the fortes of the present study is the fact that creativity is not treated as a single entity but rather as a construct involving different cognitive processes. The present study focused on conceptual expansion as one of theses processes involved in creative thinking. However, this approach also brings forth certain limitations to the interpretation of the results. Findings from the present study are related to conceptual expansion as one cognitive operation relevant to creativity, but cannot claim to reflect activation caused by creativity in general. Interpretations of the findings are limited to the process of passively induced conceptual expansion in a verbal task which, nevertheless, plays an important role in creative thought. It must be noted, however, that studies using non-verbal semantic cognition tasks have implicated some of the same regions found in our research (e.g., Lambon Ralph et al., 2010; Thompson-Schill et al., 1997) hinting at the possible involvement of these regions in nonverbal creative tasks, as well. Additionally, the areas found to be associated with conceptual expansion are not exclusive to creative thinking but rather are involved in other cognitive operations, as well. This fact, however, is in line with the creative cognition approach which postulates fundamental cognitive processes that are shared by all humans as forming the core of operations that enable creative thinking (Ward, Smith, & Finke, 1999).

Another limitation of the study stems from the application of a conceptual expansion task that involves semantic relations. The resulting involvement of the IFG and related regions is not surprising when considering that the conceptual expansion task used in the present study is of semantic content. The current findings regarding the IFG are therefore only applicable to creative operations involving semantic relations. Whether or not the IFG would also be activated during creativity tasks that primarily involve other operations such as creative imagery remains an open question.

The most significant limitation of the present study is that creative thinking was not explicitly assessed within the experimental design. Previous functional neuroimaging and electrophysiological studies on creativity have required that subjects attempt to generate original responses while their brain responses are being recorded. The approach adopted in the current study was very different in that (1) only one specific aspect of creative cognition, namely conceptual expansion, was targeted, and (2) conceptual expansion was passively induced (as opposed to actively generated) during the experiment. This raises the critical question of how well the insights gained from the present study can be integrated with the literature on the neurocognition of creativity when the self-generation of creative ideas was not assessed. When considering this question, it is important to keep two critical issues in mind.

First, one of the endemic problems of creativity research is that creative thinking is an inherently unpredictable phenomenon (Dietrich & Kanso, 2011). Despite our best efforts, it is not possible to reliably or predictably prompt creativity within an experimental setting. Previous functional neuroimaging studies on creative thinking have not been immune to this problem because, even if they have assessed the brain's response when participants carry out creative tasks in an fMRI or PET scanner, "trying to be creative" is certainly not equivalent to "being creative". Moreover, it is not possible to guarantee the “creativeness” of the response as participants are likely to also generate uncreative responses despite being told to be creative, and vice versa. These are the limitations of investigating the creative process, as it is, almost by definition, a singular event that is extremely difficult to study in laboratory conditions. Additionally, studying creative thinking within functional neuroimaging settings inherently involves severe methodological problems, such as those that have been outlined in the Introduction that are extremely difficult to overcome in an optimal manner. The field of creativity research has therefore used proxy procedures and measures in order to unravel this fascinating ability and the present study is one such attempt to do so. Even though these proxy procedures to investigate creativity remain imperfect solutions, they can still contribute to enhancing our knowledge of the information processing mechanisms involved in creative thinking.

Secondly, the approach adopted in this study was motivated in part by recent calls in the field for the need to approach the neurocognitive study of creativity in a systematic and creative manner as a necessary next step (Dietrich, 2007). One of the more obvious paths that can be adopted in order to systematically investigate creativity is to assess its component cognitive operations. While the experimental design of the present study is admittedly unconventional, it was tailored to assess conceptual expansion, which is a core facet of creative thinking. We believe that such attempts (also see Kröger et al., in press) will enable us to get closer to the overarching goal of the field which is to understand the neurocognitive mechanisms underlying creative thinking.

3.5.5 Implications for laterality of language processing

Though not specifically planned as a study on the laterality of language processing, the results of the present study can contribute to this discussion. According to the graded salience hypothesis (Giora, 1999) and Jung-Beeman's (Jung-Beeman et al., 2004; Jung-Beeman, 2005) coarse semantic coding theory, novel metaphoric expressions are primarily processed in areas in the right hemisphere, either due to their non-salience (Giora, 1999) or due to a more coarse semantic network that allows for large semantic fields and in turn includes more distant concepts (Jung-Beeman et al., 2004; Jung-Beeman, 2005). The results of our study do not confirm these right hemispheric processing theories. For phrases eliciting conceptual expansion which were non-salient and recruit the activation of semantically distant concepts, we found activations that were more strongly lateralized to the left hemisphere. Such findings also go against the generic idea of a stronger involvement of the right hemisphere during creative processes (Dietrich, 2004; Dietrich & Kanso, 2010).

3.6 Conclusion

In sum, the present study took a step towards untangling the complex concept of creativity. By using a new experimental approach, we were able to show the involvement of frontal and temporal regions known to be associated with semantic cognition and relational reasoning in the processing of novel metaphoric phrases thought to elicit passive conceptual expansion. This was done by assessing the stimuli based on the fundamental features of creativity, i.e., novelty and appropriateness. Our results especially stress the importance of the anterior IFG (BA 45/47), the temporal pole (BA 38) and, to a lesser extent, the lateral frontopolar cortex (BA 10) for conceptual expansion. These regions are known to be involved in semantic selection (IFG: BA 45), controlled semantic retrieval (IFG: BA 47), semantic knowledge storage (temporal poles: BA 38) and relational information integration (frontopolar cortex: BA 10). While the MTG was associated with the factor of appropriateness, only the mid-IFG (BA 45) was associated with the factor of novelty in that it was activated during the processing of novel metaphorical and nonsensical phrases. Even though certain areas of activation can be found for either conceptual expansion, novelty and appropriateness, the fact that the common activation of IFG, frontopolar cortex and temporal pole can only be found in the conceptual expansion conjunction points to the significance of these regions during creative thinking over and above novelty and appropriateness processing. Inducing conceptual expansion through indirect or passive means offers new possibilities that might expedite the research on creative cognition to great heights.

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3.8 Supplementary Material

Table S1 Overview of activations found in whole-brain analyses

Whole-brain activation peaks for the three conjunction analyses. Peak coordinates are given in standard MNI space. Structure, Brodmann's area (BA), Hemisphere (Hem), cluster size and peak t-value (t) are presented, as well. Significance threshold for the analyses is $p < .001$ (uncorrected), extent threshold is $k \geq 10$. IFG: Inferior frontal gyrus; IPL: Inferior parietal lobule; MFG: Middle frontal gyrus; SFG: Superior frontal gyrus; ACC: Anterior cingulate cortex; MTG: Middle temporal gyrus.

				MNI peak coordinate			
Area	**BA**	**Hem**	**Cluster size**	**x**	**y**	**z**	**t**
Conceptual expansion (HUHA > HULA ∩ HUHA > LUHA)							
IFG	45	R	10	60	17	4	3.77
IFG/MFG	45/47	R	73	54	35	13	5.69
IFG/MFG	46/47	L	746	-36	29	-8	8.14
IFG	47	R	14	36	32	-11	4.36
SFG	8/9	L/R	312	-6	26	58	6.13
MFG/cingulate gyrus	8/32	L	45	-27	8	37	5.43
MTG	22	L	32	-57	-52	1	3.94
Thalamus			257	0	-16	7	7.11
Cerebellum		R	221	30	-73	-41	7.50
Cerebellum			17	0	-43	4	3.66
Appropriateness (HUHA > HULA ∩ LUHA > HULA)							
MFG	10	L	44	-21	59	10	5.69
SFG/MFG	10/11	L	101	-33	47	-14	6.15
SFG/MFG	11	L/R	68	3	50	-17	4.82
SFG	8/9	L	135	-15	47	40	6.59
ACC/Caudate	24/32	L	77	-9	14	-2	4.63
Caudate		R	70	9	17	-2	4.69

				MNI peak coordinate			
Area	**BA**	**Hem**	**Cluster size**	**x**	**y**	**z**	**t**
MTG	21	L	43	-63	-22	-14	6.22
IPL/angular gyrus	39/40	L	392	-51	-58	49	7.25
Cerebellum		L	105	-42	-70	-38	4.30
Cerebellum		R	43	42	-76	-44	5.60
Novelty (HUHA > LUHA ∩ HULA > LUHA)							
IFG	45	R	11	51	29	7	3.44
SFG	6	L	42	-6	11	64	4.70

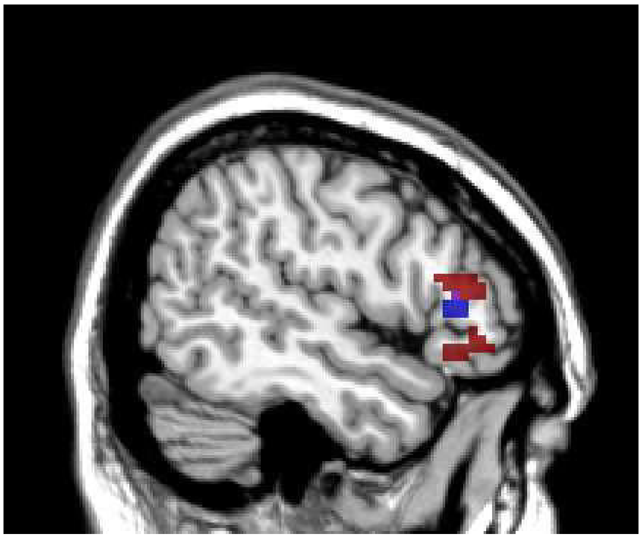
Table S2 Overview of activations found for HUHA > control

Activation peaks for bilateral Region-of-Interests BA 10, BA 20, BA 21, BA 45, BA 47 and BA 38. Peak coordinates of each cluster are given in standard MNI space. Structure, Brodmann's area (BA), Hemisphere (Hem), cluster size and peak t-value (t) are presented, as well. Significance threshold for the analyses is $p < .05$ (FWE-corrected); extent threshold $k \geq 3$. IFG: Inferior frontal gyrus; MFG: Middle frontal gyrus; SFG: Superior frontal gyrus; STG: Superior temporal gyrus.

				MNI peak coordinate			
Area	**BA**	**Hem**	**Cluster size**	**x**	**y**	**z**	**t**
			HUHA > control				
IFG	45	L	6	-48	26	1	5.68
IFG	47	L	48	-42	29	-11	8.57
IFG	47	L	4	-48	35	-5	6.11
SFG	10	L	11	-18	56	28	7.56
MFG	10	L	32	-6	62	22	6.86
STG	38	L	6	-48	20	-14	5.42

Figure S1 Overlapping activation for Conceptual expansion and Novelty

Commonly activated areas across two conjunctions (conceptual expansion and novelty) for whole-brain voxel-wise analysis at $p < .001$ (uncorrected). Red: Conceptual expansion; blue: Novelty; purple: overlapping area of activation. x = 54.



4 Study 2

Can clouds dance? Part 2: An ERP investigation of passive conceptual expansion[5]

[5] Publication: Rutter, B., Kröger, S., Hill, H., Windmann, S., Hermann, C., & Abraham, A. (2012). *Brain and Cognition*, 80, 301-310.

4.1 Abstract

Conceptual expansion, one of the core operations in creative cognition, was investigated in the present ERP study. An experimental paradigm using novel metaphoric, nonsensical and literal phrases was employed where individual differences in conceptual knowledge organization were accounted for by using participants' responses to categorize the stimuli to each condition. The categorization was determined by their judgment of the stimuli on the two defining criteria of creativity: unusualness and appropriateness. Phrases judged as unusual and appropriate were of special interest as they are novel and unfamiliar phrases thought to passively induce conceptual expansion. The results showed a graded N400 modulation for phrases judged to be unusual and inappropriate (nonsense) or unusual and appropriate (conceptual expansion, novel metaphorical) relative to usual and appropriate (literal) phrases. The N400 is interpreted as indexing greater effort to retrieve semantic information and integrate the novel concepts presented through the phrases. Analyses of the later time-window showed an ongoing negativity that was graded in the same manner as the N400. The findings attest to the usefulness of investigating creative cognition using event-related electrophysiology.

4.2 Introduction

Creativity constitutes a fascinating ability in the repertoire of human adaptive behavior. Among the different theoretical frameworks concerning the definition of creativity and its underlying cognitive structures (e.g., Abraham & Windmann, 2007; Boden, 2003; Finke, Ward, & Smith, 1992; Mednick, 1962; Ward, 1994; Ward, 2007; Ward, Smith, & Finke, 1999), a working definition has resulted about what makes an idea or product creative. According to this definition, a creative thought or product is one that is both original and appropriate to the task at hand (e.g., Sternberg & Lubart, 1999).

4.2.1 Creativity as a complex of multiple cognitive processes

Despite the consensus-based definition of what creativity entails, neuroscientific research is far from drawing a coherent picture of creative processes with reference to brain functions. This is due to various problems, including methodological limitations, such as drawing or vocal responses and lengthy trial durations that render standard creativity tasks suboptimal when combined with neuroscientific techniques.

One of the main conceptual problems, however, is the fact that creativity is rarely investigated in terms of the multitude of single cognitive operations that underlie creativity (Dietrich, 2004; Dietrich & Kanso, 2010). This is based in part on a widely held misconception of creativity with regard to the type of thinking that is believed to lead to a creative outcome. Divergent thinking which is evoked when multiple solutions can be generated to solve a problem, is often thought to be the only type of thinking to produce creativity. However, convergent thinking, which is evoked, when a problem has only one correct solution, can also contribute to creative thinking. Convergent processes in creativity are commonly targeted in the field of insight problem solving (Bowden, Jung-Beeman, Fleck, & Kounios, 2005). Conversely, divergent thinking can also occur during tasks that do not call for a creative solution, such as hypothetical or prospective reasoning (e.g., Abraham, Schubotz, & von Cramon, 2008) where the number of potential solutions is open ended. In studying creative cognition, we move beyond this classification of convergent versus divergent thinking and instead focus on the cognitive operations involved in creative thinking (e.g., Finke, Ward & Smith, 1992). Just as in the case of other cognitive processes like working memory or semantic retrieval, creative operations like creative imagery or conceptual expansion could occur under conditions of divergent or convergent thought.

One cognitive process that is of particular interest in the investigation of creativity is “conceptual expansion”. As the term suggests, conceptual expansion describes the ability to broaden one’s existing concepts beyond their conventional limits to include new features or exemplars (Ward, 1994; Ward, Smith & Vaid, 1997) and requires divergent thinking. Widening one’s concepts, especially over greater associative distances, is the basis for arriving at novel and applicable solutions for a problem at hand, thereby fulfilling the two requirements that render an outcome to be creative. In the framework of the creative cognition approach which postulates that creative thinking arises from ordinary fundamental cognitive processes present in all humans, conceptual expansion is discussed as being among the core cognitive operations that are recruited when arriving at a creative solution (Ward, 1994). The original task that assessed conceptual expansion as a creative process asked participants to draw animals from a planet that is different from earth (Ward, 1994; Ward, Patterson, Sifonis, Dodds, & Saunders, 2002). Participants’ ability to expand existing concepts is measured by the degree to which the drawn animals deviate from earth creatures in terms of their basic features. While the original task assessing conceptual expansion cannot be suitably adapted to assess conceptual expansion in neuroscientific settings, the vital role played by conceptual expansion in creative cognition indicates that it is imperative to develop alternative paradigms that allow for a better understanding of the neurophysiological mechanisms underlying this creative cognitive operation.

4.2.2 Creativity and electrophysiological measures

While several studies have investigated creativity using electroencephalograms (EEG), as yet no study has attempted to link any component related to event-related potentials (ERP) with creative thinking (for a thorough review, see Dietrich & Kanso, 2010). One exception to this claim are studies on the phenomenon of insight during problem solving (e.g., Lang et al., 2006; Lavric, Forstmeier, & Rippon, 2000; Qiu et al., 2008). This is unfortunate given that ERPs offer significant advantages when investigating cognitive operations compared to other neurophysiological methods such as functional magnetic resonance imaging (fMRI). Apart from a high temporal resolution, specific ERP components are held to represent distinct cognitive processes so this method allows for the determination of the onset and temporal distribution of the cognitive process of interest.

The N400 ERP component, for instance, is certainly of great relevance with regard to processes involved during conceptual expansion. The N400 is a negative-going waveform with a centro-parietal distribution, typically appearing around 300 ms to 600 ms after onset of its activating event and peaking around 400 ms after stimulus onset. Modulation of the N400 amplitude has been reported for various factors, including semantically incongruous words (Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b), cloze probability of the final word (Kutas & Hillyard, 1984), words violating the preceding discourse context or world knowledge (Hagoort, Hald, Bastiaansen, & Petersson, 2004; Hald, Steenbeek-Planting, & Hagoort, 2007; van Berkum, Brown, & Hagoort, 1999) and the difficulty of semantic integration (e.g., Kutas & Van Petten, 1994). The N400 is considered to be an index of the difficulty to retrieve conceptual knowledge from the memory stores in the brain (e.g., Kutas & Federmeier, 2000; Kutas, Van Petten, & Kluender, 2006). In semantic priming studies, the N400 has also been interpreted as an index for higher-level integrational processes (e.g., Brown & Hagoort, 1993).

As conceptual expansion requires the search for existing concepts and the integration of new semantic associations with these existing concepts, the N400 constitutes the candidate ERP component to indicate the occurrence of those cognitive operations. Moreover, results from fMRI studies investigating creative thinking have demonstrated that the brain structures that are known to be involved in semantic selection, retrieval and integration (e.g., Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010Poldrack et al., 1999; Thompson-Schill, D'Esposito, Aguirre, & Farrah, 1997) are engaged during creative conceptual expansion, as well (Kröger et al., 2012; Rutter et al., 2012). It remains unclear, however, if such parallels can be transferred to ERPs in a similar manner. The present study is the first of its kind to investigate creative cognition using ERPs. The objective is to clarify the manner in which ERP components that index semantic cognitive operations are modulated by creative cognitive processes.

4.2.3 The present study

Conceptual expansion is investigated in the present ERP study with the concurrent aim of overcoming some of the aforementioned shortcomings in neurophysiological research on creativity. A new approach is adopted which is based on the assumption that conceptual expansion cannot only be brought about “actively” such as when one volitionally attempts to expand a concept to include novel and relevant facets relating to other concepts, but also “passively” through the presentation of two distantly associated items that need to be connected through the widening of concepts (Kröger et al., 2012; Rutter et al., 2012). The approach adopted in the current study takes the latter perspective. Participants are not provided with a task that actively requires them to engage in conceptual expansion. Instead, conceptual expansion is passively induced in participants. A suitable way to implement this approach is to draw from experimental paradigms used in metaphor processing studies.

The comprehension of novel metaphors heavily relies on the integration of two distant concepts to provide meaning. Psycholinguistic studies on novel metaphor processing have repeatedly shown an increased N400 amplitude for novel metaphors compared to conventional metaphors and literal expressions (e.g., Arzouan, Goldstein, & Faust, 2007; De Grauwe, Swain, Holcomb, Ditman, & Kuperberg, 2010; Lai, Curran, & Menn, 2009). While the main focus of metaphor studies is to investigate how language is processed under different syntactic or semantic constraints, the objective of the current study is to differentiate how the information processing involved during conceptual expansion differs from the processing of mere unusualness and appropriateness. Although the current study differs from investigations of metaphor processing in terms of the main goals, paradigms from the language comprehension field have been adapted in the current study to suit our ends.

Participants in the current study were presented with novel metaphoric, nonsensical and literal expressions. In order to account for individual differences in participants' conceptual knowledge structures and their abilities to expand existing concepts, the new paradigm does not rely on classic experimenter-determined experimental conditions. Instead, the current approach requires participants to make yes/no judgments on the presented phrases with regard to the originality (unusualness) and relevance (appropriateness). Originality and relevance, as mentioned earlier, are the two defining features of creativity. This procedure results in the subject-determined categorization of the stimuli phrases as belonging to one of the following conditions: highly unusual and highly appropriate (HUHA/novel metaphoric), highly unusual and low appropriate (HULA/nonsense) or low unusual and highly appropriate (LUHA/literal). Examples for each of the conditions can be found in Table 1. Phrases from the HUHA category are those that induce conceptual expansion in participants as it contains instances where previously unrelated or weakly related concepts are associated with one another in a novel yet relevant manner. It has to be noted that a combination of low unusualness and low appropriateness is not possible, as an association which is low in appropriateness is automatically highly unusual.

Employing subject-determined conditions allows one to rule out variability caused by inter-individual differences as what one participant regards as unusual and appropriate might be deemed as not unusual at all by another participant. The subject-determined conditions based on participant's judgments of the unusualness and appropriateness of the phrases also sets the present study apart from conventional metaphor processing studies. The latter employ phrases or word pairs that are predetermined by the experimenter to be novel metaphoric, conventional metaphoric, nonsensical or literal (e.g., Arzouan et al., 2007; Balconi & Amenta, 2010; Coulson & Van Petten, 2002; Lai et al., 2009). Moreover, participants' tasks in metaphor processing studies either involve silently reading the presented material (Balconi & Amenta, 2010) or making a judgment about whether or not the stimuli are meaningful or appropriate (Arzouan et al., 2007; Lai et al., 2009). The present study, in contrast, asks participants for their judgment on both of the essential elements that characterize a creative response, namely unusualness and appropriateness.

In line with findings from studies on metaphor processing (e.g., Coulson & Van Petten, 2002; Lai et al., 2009), HULA (nonsense) and HUHA (novel metaphorical) phrases are expected to result in greater N400 amplitudes than LUHA (literal) phrases as a function of the higher degree of unusualness in case of the former conditions. Previous studies using novel metaphoric expressions and senseless expressions have reported a greater N400 amplitude for senseless expressions (e.g., Arzouan et al., 2007; De Grauwe et al., 2010). HULA (nonsense) phrases in the present experiment are comparable to senseless expressions as they are incoherent and meaningless phrases. HULA (nonsense) phrases are therefore expected to elicit the greatest N400 amplitude of the three conditions. HUHA (novel metaphorical) phrases would in turn be expected to elicit greater N400 amplitudes than LUHA (literal) phrases due to their unusualness, which is likely to lead to greater effort in semantic retrieval (e.g., Kutas & Van Petten, 1994). However, given that the eventual retrieval of the appropriate semantic information leads to novel associations being forged and integrated within the conceptual knowledge stores, it is expected that less semantic integration difficulty should be encountered for HUHA (novel metaphorical) compared to HULA (nonsense) phrases.

Research on semantic processing also focuses on later ERP components, such as the P600, or late positive component, which has been discussed in terms of sentence-level integration (Kaan, Harris, Gibson, & Holcomb, 2000), reanalysis (Friederici, 1995) and additional retrieval from semantic memory (e.g., Coulson & Van Petten, 2002; Paller & Kutas, 1992). The findings for this late component, however, are less consistent than for the N400 (e.g. Pynte, Besson, Robichon, & Poli, 1996). Due to the novelty of the current ERP paradigm as a tool to investigate creative processes, the analysis of later processing stages will be exploratory.

4.3 Materials and methods

4.3.1 Participants

The original sample included 27 healthy right-handed students from the University of Giessen that participated in the study in exchange for course credit or monetary compensation (15 €). All participants were native German-speakers and had normal or corrected-to-normal vision. Handedness was assessed using the German version of the Edinburgh Inventory of Handedness (Oldfield, 1971). Nine participants had to be excluded from data analyses due to excessive drifts in their EEG data (n = 1), admittance to the consumption of an illegal substance that might influence brain activity (n = 1) or an insufficient number of stimuli classified as unusual and appropriate (n = 7). This resulted in a final sample of 18 participants (10 females). Mean age was 23.39 years (SD = 3.66). In order to ensure the homogeneity of the sample in terms of verbal intelligence participants completed the vocabulary subscale of the Hamburg Wechsler Intelligence Test for Adults (HAWIE, Tewes, 1994). Mean standardized HAWIE score was 12.89 (SD = 1.13), with individual scores ranging from 11 to 14. The experimental standards of the study were approved by the Ethics Commission of the German

Psychological Society (DGPs). Written informed consent was obtained from all participants prior to participation.

4.3.2 Materials

The study used a stimuli-set created for a previous fMRI study (Rutter et al., 2012). The stimulus set consisted of 44 experimenter-determined sentence triplets (132 phrases in total) in perfect tense. Each sentence was composed of a noun, verb and object (for examples, see Table 1 and Table S1 in the supplementary material). The three sentences of each triplet only differed with regard to the verb which was chosen to make the meaning of the sentence novel metaphorical, nonsensical or literal corresponding to the three experimental conditions. Each participant was presented with all 132 phrases and the order of presentation of the stimuli was pseudo-randomized to ensure, for instance, that there were at least five trials presented between any two trials of a sentence-triplet.

Table 1: Example phrases for the three experimental conditions

Critical word is printed in bold. The literal English translation of the example phrases is presented in brackets. A complete list of the stimuli is listed in the supplementary material.

Condition	Phrase
Highly unusual – highly appropriate (HUHA)	*Die Wolken haben über der Stadt* ***getanzt****.* (The clouds have **danced** over the city.)
Highly unusual – low appropriate (HULA)	*Die Wolken haben über der Stadt* ***gelesen.*** (The clouds have **read** over the city.)
Low unusual – highly appropriate (LUHA)	*Die Wolken sind über die Stadt* ***gezogen****.* (The clouds have **moved** over the city.)

Verbs were checked for word length and frequency of occurrence in the German language. A one-way ANOVA revealed significant differences in word length between the three experimental conditions ($F(2, 129) = 3.14$; $p = .047$; $\eta^2 = .05$). Bonferroni-corrected pairwise comparisons showed, however, that this effect was primarily driven by a trend in word length differences between the nonsensical verbs (HULA) and the literal verbs (LUHA) ($m = 8.45$, $sd = 1.42$ and $m = 9.39$, $sd = 2.24$, respectively; $p = .051$). 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/). This database classifies words into different frequency classes based on the frequency of their occurrence relative to the German definite article “der” (“the”). As the resulting frequency values are ordinal-scaled, a non-parametric median test was chosen.

The median test comparing the three experimenter-determined conditions confirmed that they did not differ significantly regarding the frequency of occurrence of the verb (*md* = 15 for HUHA and HULA, respectively, *md* = 14 for LUHA; *p* = .1).

4.3.3 Procedure

Participants were tested individually in one session. After applying the electrodes, participants were seated in front of a computer screen and keyboard. Participants completed a few practice trials to become familiar with the task. Stimuli were presented in black print on a grey background using Presentation software (Neurobehavioral Systems, Inc., Albany, CA). Stimuli phrases were presented in the German language where the verb occupies the sentence-final position. Each trial (see Figure 1) began with the presentation of a fixation cross on the left side of the screen. Presentation time of the fixation cross was randomized and ranged from 1400 ms to 1800 ms in 200 ms steps. After a blank screen lasting 200 ms, the stimulus phrase without the last word (being the verb) was presented for 2000 ms, after which the verb appeared at the end of the phrase for another 2000 ms. Following a 500 ms blank screen, the questions “Unusual?” (in German: “Ungewöhnlich?) and “Appropriate?” (in German: ”Sinnvoll?”) appeared for 1500 ms, respectively, separated by another 500 ms blank. During presentation of the respective questions, participants made “yes” or “no” judgments via button press with their right index or middle finger on the keyboard in front of them. To determine their response to the "Unusual"-question, participants were instructed to respond “yes” if the presented information was novel or unfamiliar to them and “no” if it was known or familiar. To determine their response to the "Appropriate"-question, they were also instructed to respond “yes” if the presented information was fitting or sensible and “no” if it was unfitting or nonsensical. After each trial, participants had the opportunity to take a break and start the next trial via button press at their own pace. Stimuli were presented in a pseudo-randomized order.

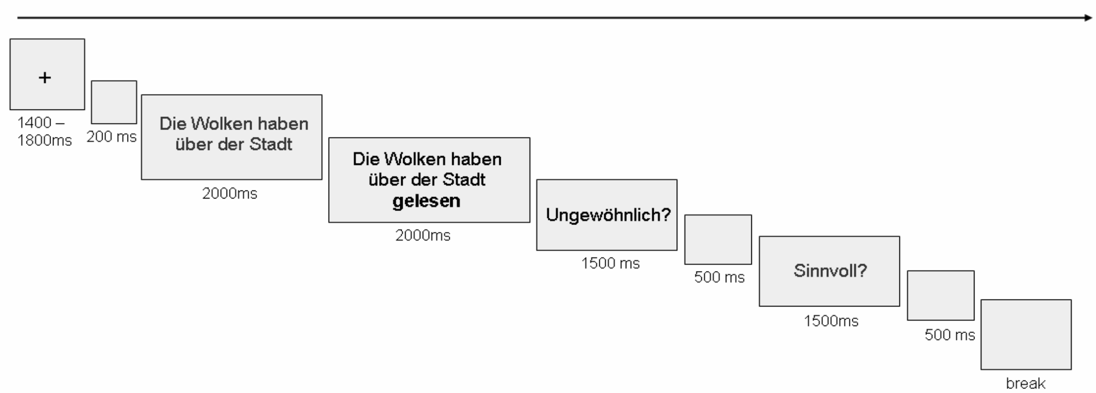


Figure 1

Example of the experimental trial timeline. Total trial length from fixation cross to onset of the break was either 9600 ms, 9800 ms or 10000 ms. Stimuli phrases were presented in German where the critical word (verb) syntactically appears at the end of the phrase.

4.3.4 Electrophysiological recording

The electroencephalogram (EEG) was recorded continuously using the actiCAP system (Brain Products GmbH, Gilching, Germany) with 64 Ag/AgCl electrodes and monitored by the BrainVision recorder software. The EEG signal was amplified by the QuickAmp amplifier (Brain Products GmbH, Gilching, Germany) and digitized at a sampling rate of 500 Hz. Impedances were kept under 5 kΩ. Eye movements were monitored through bipolar electrodes that were placed above and below the right eye, as well as at the left and right canthi. Data was recorded using an average-reference on-line.

4.3.5 Data analysis

For each participant, stimulus phrases were assigned to the three conditions based on their individual evaluations concerning the usualness and appropriateness of the phrase. This resulted in a differing number of cases per condition for each participant. To avoid underrepresentation of any one condition, participants with a disproportionate distribution of stimulus phrases between the three experimental conditions were excluded from data analysis. Cut-off criterion for exclusion of participants was determined at less than 28 instances in any one condition. Paired t-tests were carried out to detect possible differences in reaction times (RTs). As only RT differences between conditions that resulted in the same responses are of interest, RTs to the “unusual”-question were compared for the HUHA (metaphorical) and HULA (nonsense) conditions and RTs to the “appropriate”-question were compared for the HUHA (metaphorical) and LUHA (literal) conditions.

EEG data was analyzed using the Vision Analyzer 2.0 software (Brain Products GmbH, Gilching, Germany). Data was filtered with a 0.01 Hz high-pass and a 40 Hz low-pass filter. Ocular correction to remove eye movement artefacts was computed based on the method described by Gratton, Coles and Donchin (1983). Data was further segmented into epochs of 1150 ms duration, starting at 150 ms before onset of the last word (further referred to as critical word). Segments were baseline-corrected using the 150 ms time window before onset of the critical word. Artefacts with amplitudes exceeding +/-75 µV were removed from the data set. For each participant, ERP averages for each one of the three conditions were computed[6]. Grand Averages for each condition were used to

[6] Information on the mean number of segments per condition per subject that were included in the final analyses can be found in Table S2 in the supplementary material.

derive the temporal intervals for the ERP components. A negative-going wave starting at about 350 ms with a peak at 420 ms was observed, thus the mean amplitude for the time interval 350 ms to 500 ms after onset of the critical word was computed (N400). In order to investigate possible late ERP components, the mean amplitude for the time interval of 500 ms to 900 ms after onset of the critical word was also calculated (late component).

For each of the ERP components of interest (N400; late component), a repeated measures ANOVA was computed with the factors Condition (HUHA, HULA, LUHA), Line (C-line, CP-line, P-line) and Electrode position (3, 1, z, 2, 4). The Greenhouse-Geisser correction (Greenhouse & Geisser, 1959) was applied to all repeated measures with more than one degree of freedom. In these cases, corrected p-values with the original degrees of freedom are reported. In cases where main or interaction effects could be observed, additional planned pair-wise ANOVAs were carried out comparing each phrase category with one another. We focus on the main effects and interaction effects involving the factor Condition.

4.4 Results

4.4.1 Behavioral data

Table 2 shows means and standard deviations across the three conditions for each question. Comparing RTs to the “unusual”-question for HUHA (novel metaphorical) and HULA (nonsense) phrases revealed a significant difference between HUHA (novel metaphorical) and HULA (nonsense) phrases, such that participants responded slower to the “unusual”-question for novel metaphorical phrases relative to nonsensical phrases (t_{17} = 2.25; p = .038). For the “appropriate”-question, the analysis comparing RTs to HUHA (novel metaphorical) and LUHA (literal) phrases revealed that participants took significantly longer to respond when presented with novel metaphorical phrases compared to literal phrases (t_{17} = 4.87; p < .001).

Table 2

Mean reaction times in milliseconds across all three conditions for each question. Standard deviations are given in brackets.

Condition		**Question**
	Unusual	**Appropriate**
HUHA (novel metaphoric)	815.0 (112.8)	666.9 (141.4)
HULA (senseless)	775.6 (92.6)	596.2 (125.7)
LUHA (literal)	785.9(153.4)	550.2 (106.8)

4.4.2 ERP data

Grand averages elicited by the experimental conditions at selected electrode sites are depicted in Figure 2. Figures for all 15 electrodes can be found in the supplementary material. A N100/P200 complex can be observed starting at 100 ms after onset of the critical word. Around 350 ms after onset of the critical word a negative going component can be seen that peaks at around 420 ms and can thus be regarded as the N400 component. After the N400 peak, the waveform shows a late ERP component of sustained negativity, starting at about 500 ms.

N400. The repeated measures ANOVA with factors Condition (HUHA, HULA, LUHA), Line (C, CP, P) and Electrode site (3, 1, z, 2, 4) revealed a significant main effect of Condition ($F(2, 34) = 8.91$; $p = .001$; $\eta^2 = .34$) in the time window between 350 ms and 500 ms after critical word onset as well as a significant linear trend between the three conditions ($F(1, 17) = 15.99$; $p = .001$; $\eta^2 = .49$). The linear trend (Figure 3) indicates that the results can be best understood in terms of a linear function such that the N400 was largest in response HULA (nonsense) phrases, followed by HUHA (novel metaphoric) phrases, both relative to the LUHA (literal) phrases (N400: HULA > HUHA > LUHA).

Three planned pair-wise ANOVAs were carried out to compare each of the conditions individually with one another (HUHA vs. HULA, HUHA vs. LUHA and HULA vs. LUHA). The comparisons revealed that the waveforms elicited by HUHA (novel metaphorical) and HULA (nonsense) phrases for the N400 time-window were not significantly distinguishable from one another[7]. However, the waveforms elicited by both these phrase types were significantly differentiable from that of the LUHA (literal) phrases. HUHA (novel metaphorical) phrases resulted in a more negative N400 than LUHA (literal) phrases, as indicated by a significant main effect Condition ($F(1, 17) = 7.50$; $p = .014$; $\eta^2 = .31$). A significant interaction effect between Condition and Line revealed that the differences in N400 amplitude are limited to central and centroparietal regions ($F(2, 34) = 4.77$; $p = .033$; $\eta^2 = .22$). HULA (nonsense) phrases also produced a more negative N400 than LUHA (literal) phrases, as indicated by a significant main effect Condition ($F(1, 17) = 15.99$; $p = .001$; $\eta^2 = .49$). A significant three-way interaction effect between factors Condition, Line and Electrode position ($F(8, 136) = 2.61$; $p = .037$; $\eta^2 = .13$) showed that HULA phrases produced a more negative amplitude than LUHA phrases on 12 out of 15 electrodes (significant differences on electrodes C3, C1, Cz, C2, C4, CP1, CPz, CP2, CP4, P3, Pz, and P4, all $p < .05$). The lack of two-way interaction effects between the factors Condition and Line or Condition and Electrode position in this analysis indicates that the effects of the experimental conditions found for HULA and LUHA do not appear to be limited to a certain site or hemisphere.

[7] No significant N400 differences were found between HUHA and HULA even in additional analyses where a wider set of electrodes (including frontal electrodes) were analyzed.

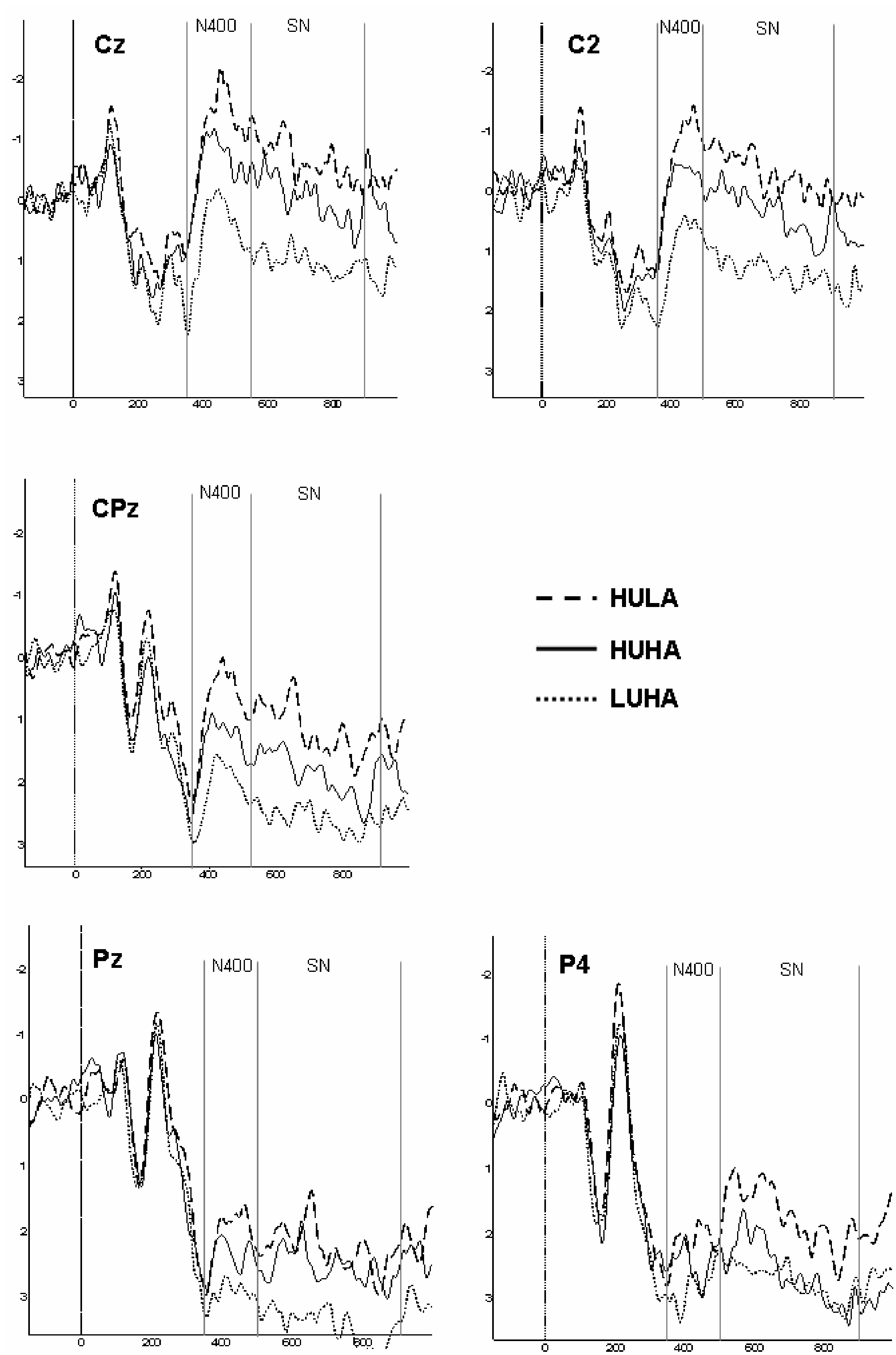

Cz
N400
SN
C2
N400
SN
CPz
N400
SN
HULA
HUHA
LUHA
Pz
N400
SN
P4
N400
SN

Figure 2

Grand Averages on central electrodes Cz, CPz and Pz, as well as on C2 and P4. Vertical line at time point 0 marks onset of the critical word (verb). Gray lines mark onset of N400 and sustained negativity (SN), respectively. Negative values are plotted upwards on y- axis in µV. Time is given in milliseconds. Figures for all 15 electrodes can be found in the Supplementary Material.

Sustained negativity. The findings of the sustained negativity late component closely parallel those of the N400. The repeated measures ANOVA between the factors Condition (HUHA, HULA, LUHA), Line (C, CP, P) and Electrode position (3, 1, z, 2, 4) revealed a significant main effect of Condition ($F(2, 34) = 8.36$; $p = .001$; $\eta^2 = .33$) in the time window between 500 ms and 900 ms after critical word onset, as well as a significant three-way interaction between the factors Condition, Line and Electrode position ($F(16, 272) = 2.12$; $p = .042$; $\eta^2 = .11$). Additionally, the results showed a significant linear trend between the three conditions ($F(1, 17) = 16.37$; $p = .001$; $\eta^2 = .49$). The linear trend (Figure 3) indicates that the results can be best understood in terms of a linear function such that the sustained negativity was largest in response to HULA (nonsense) phrases, followed by HUHA (novel metaphorical) phrases , both relative to the LUHA (literal) phrases (sustained negativity: HULA > HUHA > LUHA). To fully explore the extent of these effects, three planned pair-wise ANOVAs were carried out to compare each of the conditions individually with one another (HUHA vs. HULA; HUHA vs. LUHA; HULA vs. LUHA).

Comparison between HUHA (novel metaphorical) and HULA (nonsense) showed a significant three-way interaction between the factors Condition, Line and Electrode position ($F(8, 136) = 3.04$; $p = .013$; $\eta^2 = .15$). Pairwise comparisons showed that the mean amplitude of HUHA phrases (novel metaphorical) was less negative than the mean amplitude of HULA phrases (nonsense) on 3 out of 15 electrodes (significant differences on electrodes C2, CPz and P4, all $p < .05$). HUHA (novel metaphorical) continued to result in a more negative waveform than LUHA (literal) phrases, as indicated by the significant main effect of Condition ($F(1, 17) = 5.82$; $p = .027$; $\eta^2 = .26$). Just as in the case of HUHA (novel metaphorical) phrases, HULA (nonsense) phrases also continued to remain more negative than LUHA (literal) phrases during this late time-window, as indicated by a significant main effect of Condition ($F(1, 17) = 16.37$; $p = .001$; $\eta^2 = .49$).

The lack of interaction effects between factors Condition and Line or Condition and Electrode position on the sustained negativity indicate that the effects of experimental conditions do not appear to be limited to a certain site or hemisphere.

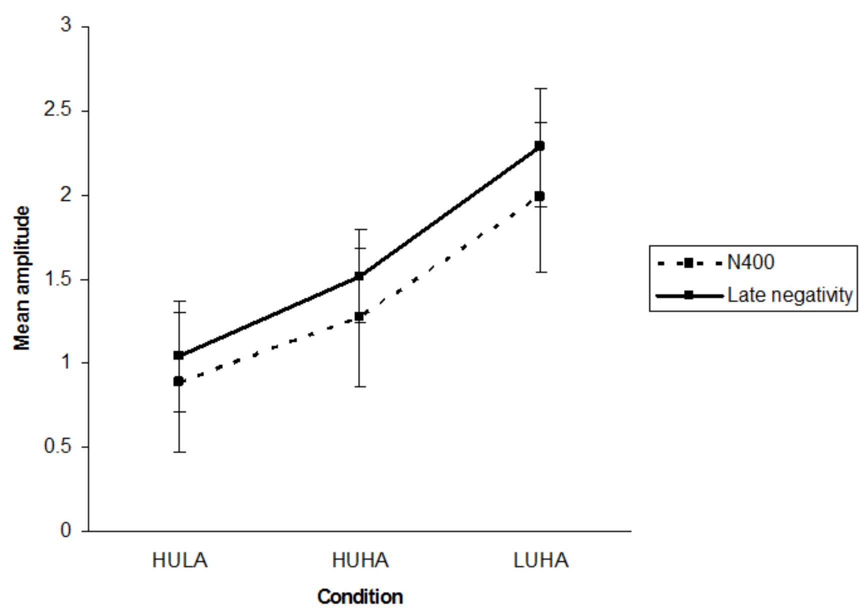


Figure 3

Mean amplitude of the three conditions for the N400 and the sustained negativity. Plots are based on collapsed data over all 15 electrodes. Error bars indicate *standard errors. The linear trend from the repeated measures ANOVAs for both components is significant.*

4.5 Discussion

The main goal of the present study was to use ERPs to draw a clearer picture on how conceptual expansion as a creative cognitive process can be aligned with established aspects of brain function. Together with the advantage of having a high temporal resolution that made it possible to time-lock the creative process, the novel approach allowed for individual differences in the ability to expand existing concepts to be taken into consideration on a trial-by-trial basis. The short trial duration together with an adequate number of trials ensured a sufficient number of instances for each participant and consequently an optimal group average response. Another advantage of the novel approach lies in the possibility of clearly separating instances that are merely original (unusualness: HULA, nonsensical phrases) or relevant (appropriateness: LUHA, literal phrases) from instances that are creative in that they are both original and relevant (conceptual expansion: HUHA, novel metaphoric phrases).

4.5.1 N400

The findings for the early time-window between 350 and 500 ms showed a graded effect of the three experimental conditions on the N400 amplitude with LUHA (literal) phrases resulting in the least negative waveform, followed by HUHA (novel metaphorical) and then the HULA (nonsense) phrases. It is to be noted, however, that HUHA (novel metaphorical) and HULA (nonsense) phrases did not differ significantly in the direct comparisons. Instead, this subtle and graded effect could be gleaned from the linear trend of the main effect within the repeated measures analysis. A similar pattern has been reported in several studies from the field of language comprehension. For instance, Arzouan and colleagues (2007) found such a graded N400 modification when investigating literal, conventional metaphoric, novel metaphoric and unrelated word pairs. More recently, DeGrauwe et al. (2010) found this graded N400 modification for both mid-sentence and sentence-final words, which is in line with other studies on metaphor processing (e.g., Coulson & Van Petten, 2002; Coulson & Van Petten, 2007; Lai et al., 2009; Pynte et al., 1996; Tartter, Gomes, Dubrovsky, Molholm, & Stewart, 2002).

Graded N400 amplitudes for different types of phrases have been interpreted in terms of conceptual blending theory (Fauconnier & Turner, 1998) in language processing. The conceptual blending theory postulates that the construction of multiple cognitive models and mappings between their components are the underlying processes for language comprehension. Greater N400 amplitudes for metaphorical or nonsensical expressions, for instance, are consequently interpreted as reflecting greater effort to construe mappings between distantly related domains and their components as well as the activation of background knowledge regarding the distant domains to derive meaning (Arzouan et al., 2007). The assumptions and interpretations of findings in this field can be extended and applied to the current results.

Taken together with the claim that the N400 component indexes higher-level integrative processes shown in semantic priming studies (e.g., Brown & Hagoort, 1993; Brown, Hagoort, & Chwilla, 2000; Holcomb, 1993), greater N400 amplitudes for HUHA (novel metaphorical) and HULA (nonsense) phrases compared to LUHA (literal) phrases in the current study can be seen as indexing greater efforts to establish a connection between the two semantically distant concepts conveyed through the stimuli. For LUHA (literal) phrases the derivation of meaning appears to be comparatively effortless since the phrases are literal in their nature (e.g., moving clouds) and represent established links between strongly associated concepts. In contrast, HUHA (novel metaphorical) and HULA (nonsense) phrases are both novel (e.g., dancing clouds; reading clouds) and require the integration of two unrelated concepts. The effort associated with this endeavor seems to be greatest for phrases that participants categorized as HULA (nonsense) due to their senselessness (e.g., reading clouds) and the inability to successfully integrate the two concepts to be associated with one another. Although the HUHA (novel metaphorical) phrases were unusual and unfamiliar to the participants, it was possible to successfully integrate the two presented concepts to give rise to a novel conceptual combination (e.g., dancing clouds). Even though the absolute difference in N400 amplitude triggered by HUHA (novel metaphorical) and HULA (nonsense) phrases did not reach significance, the linear trend findings support this interpretation.

Such a rationale is also in line with findings from a study by Rhodes and Donaldson (2008) where an N400 modulation was reported for word pairs with only an associative connection or for word pairs with a semantic and an associative connection, both relative to unrelated word pairs. In the current experiment, HUHA (novel metaphorical) phrases were not previously linked through association. A new semantic connection was established through the expansion of the existing concepts during the course of the experiment. The fact that this connection could be successfully established in the case of the HUHA (novel metaphorical) phrases but not the HULA (nonsense) phrases may account for the partially lower N400 amplitude accompanying the HUHA (novel metaphorical) compared to the HULA (nonsense) phrases. Further research is needed to confirm this interpretation. It is of note that the differing effort for integration observable in the graded N400 modulation is not apparent from the behavioral data. The behavioral data showed that RTs were highest for HUHA (novel metaphorical) phrases, whereas the ERP data revealed that the HULA (nonsense) phrases were accompanied by the most negative N400 amplitude. The N400 findings indicate the greater integrational effort involved in HULA (nonsense) relative to HUHA (novel metaphorical) and LUHA (literal) phrases (N400: HULA> HUHA> LUHA).

An alternative interpretation of the N400 treats this component as an index for the effort to retrieve semantic knowledge from memory stores in the brain (e.g., Kutas & Federmeier, 2000; Kutas, et al., 2006). Both HUHA (novel metaphorical) and HULA (nonsense) phrases entail unusualness and it can be argued that the increased N400 amplitude for these conditions reflects an increased effort to search for semantic information regarding the novel concepts imparted through the phrases. The data provided through the present study does not suffice to fully clarify whether the greater N400 amplitude for HUHA (novel metaphorical) and HULA (nonsense) phrases reflects semantic memory retrieval or higher-order integrative processes. Further research will be needed to decide on the exact nature of the processes indexed by the N400 during a conceptual expansion task.

It could be argued that cloze probability might be a further explanation for greater N400 amplitudes for HUHA (novel metaphorical) and HULA (nonsense) compared to LUHA (literal) phrases as some studies have shown N400 modifications based on degree of expectedness associated with the sentences (Kutas & Hillyard, 1984). While HUHA (novel metaphorical) and HULA (nonsense) phrases are both unusual or novel and are therefore both unexpected in the given context, to solely base the interpretation of the N400 differences on the violation of semantic expectations does not suffice to explain the full extent of possible cognitive processing that can be reflected by this ERP component in the current study. The highly significant linear trend suggests the presence of processes exceeding merely expectation violations and it therefore appears to be more fitting to view these violations of semantic expectations as a catalyst that activates the enhanced retrieval and integration efforts discussed above.

4.5.2 Sustained negativity

The analysis of the later time-window in the current study was exploratory and the results from the late component were found to closely correspond to the N400 findings. ERP studies on language comprehension have lead to heterogeneous findings concerning the late time-window. Some studies report the emergence of a P600 component after the N400 when processing ambiguous sentences (Friederici, 1995) and metaphors (Coulson & Van Petten, 2002; De Grauwe et al., 2010) whereas Pynte et al. (1996) did not find a P600 component for metaphors compared to literal sentences.

HUHA (novel metaphorical) and HULA (nonsense) phrases in the present study did not elicit greater P600 components compared to literal phrases, but instead showed an ongoing negativity in the later time-window. Sustained negativities have been conceived as indexing different cognitive processes. Ruchkin and colleagues (Ruchkin, Johnson, Mahaffey, & Sutton, 1988) have linked slow negative waves to stimuli that are conceptually difficult to process, an interpretation that would be fitting for the stimuli at hand as well. However, the waveform described in their study differed in onset and latency from the waveform found in the present study.

Rhodes and Donaldson (2008) found a similar more negative going wave in a later time-window for unrelated word pairs relative to semantically or associatively connected pairs as in the current study. This was interpreted as recollection from long-term memory for the semantically and associatively linked pairs. This is in reference to old/new memory effects and episodic retrieval operations as described by Greve, van Rossum and Donaldson (2007) and Donaldson and Rugg (1998) among others. However, the effect described in their work is limited to the left parietal areas and may therefore not suffice to be applicable to the interpretation of the effect found in the present study given that the discussed effect was not limited to a certain location.

The effect observable in the later time-window manifested itself as a continuation of the effects observed for the earlier time-window, namely a more negative-going waveform for both HUHA (novel metaphorical) and HULA (nonsense) phrases relative to LUHA (literal) phrases. In the case of the sustained negativity however, both the direct comparisons as well as the linear trend of the condition main effect demonstrated a graded effect of the three experimental conditions with LUHA (literal) phrases resulting in most pronounced negative waveform, followed by HUHA (novel metaphorical) and then the HULA (nonsense) phrases.

Recent ideas by Jiang, Than and Zhou (2009) on sustained negativity might be applicable to the current results in this light. In a series of studies on how violations of universal quantifiers in sentences are processed (e.g., the universal quantifier "all" was mismatched with a noun in singular object, as in "He threw away all that apple"), the authors found a sustained negativity, but no N400, on verb onset for violations of the quantifier (Jiang, Tan, & Zhou, 2009). The sustained negativity was conceived of as a reinterpretation of the verb after a mismatch between the phrase and the quantifier. The negativity was therefore proposed to index a reinterpretation process after an initial failure to reach meaning.

A similar underlying process is conceivable to explain the late negativity in the present study. Continuing the process indexed by the N400 associated with the establishment of a connection between two semantically distant concepts, the late negativity may mark the ongoing difficulty of integrating the two concepts. In the case of HUHA (novel metaphorical) phrases, the integration is eventually successful which could account for why the waveform becomes more positive in the later time-window and converges to the level of the LUHA (literal) phrases. The continued inability to bring together the concepts from the HULA (nonsense) phrases though is likely to have contributed to the continued negativity associated with this condition. It must be noted, however, that unlike in the present study, Jiang and colleagues (2009) did not report a preceding N400 for the sustained negativity and their primary focus lay on the processing of language comprehension.

Given the similarity of the N400 effects and the effects observed in the later time-window, it could be argued that the two components can be seen as one single sustained effect. When taking the linear trend and the direct comparisons into consideration which show a graded effect for the three conditions, it also seems plausible that two separate effects can be observed. Especially, the finding that waveform associated with the HUHA (metaphorical) phrases becomes significantly different from the waveform elicited by HULA (nonsense) phrases supports the existence of two distinguishable effects. However, the postulations on the significance behind the condition-based negativity and the question of whether or not the observed effects are indeed one single sustained effect in the present study on creative cognition are post-hoc and therefore require further research to be fully clarified. Follow-up studies are necessary to fully understand the implications of this late ERP component together with the N400 in the context of creative cognition.

Taken together, the findings from the present study provide a first insight into which ERP components are important in indexing the operation of passive conceptual expansion as a creative cognitive process. As the paradigm of the present study used a passive conceptual expansion task, interpretation of the findings is certainly limited to this field and cannot be generalized to other creative processes, such as creative imagery. Conceptual expansion is only one among many cognitive operations that form the complex construct of creativity and cannot alone be held responsible for creative achievements. An important next step in the investigation of creative cognition will be to replicate the present findings in an active conceptual expansion task, as well as carrying out ERP investigations of other creative cognitive processes.

4.5.3 Conclusion

The present study was aimed at assessing conceptual expansion as a vital process of creative cognition using ERPs. The novelty of the employed paradigm was twofold. Unlike previous studies on metaphor processing for instance, participants were asked to judge not only the appropriateness but also the unusualness of the stimuli. The participants' judgments on these two defining aspects of creativity were then used to classify the stimuli into different conditions. This rendered it possible to incorporate individual differences in the organization and reorganization of existing conceptual knowledge within the paradigm. The results showed not only a clear difference within the N400 and the late sustained negativity components between nonsensical and creative phrases relative to literal phrases, but also a graded N400 and sustained negativity modulation for nonsensical, creative and literal phrases (in that order).

The N400 component was interpreted as reflecting the effort necessary to establish a connection between two unrelated concepts. The late negative component is postulated to be an indicator of a reanalysis process and ongoing effort. More research is needed, however, to clarify the cognitive operations underlying this late ERP component.

Taken together, the results support the notion of conceptual expansion as a continuous process involving different cognitive operations, such as semantic information retrieval, the formation of new associations between concepts and semantic integration processes. The current findings suggest that these different operations are not exclusively indexed by one specific ERP component, but are rather jointly represented by different ERP components. The results from the present study contribute greatly to the understanding of verbal creativity and parallel findings from fMRI investigations on verbal creativity that have demonstrated the involvement of similar brain regions during creative cognition as commonly found in semantic cognition such as the inferior frontal gyrus and the orbitofrontal cortex (e.g., Fink et al., 2009; Howard-Jones, Blakemore, Samuel, Summers, & Claxton, 2005; Kröger et al., 2012; Rutter et al., 2012). The current findings show that ERP components known to index semantic operations can be explored further to understand the dynamics underlying creative cognitive processes as well.

The experimental paradigm employed in the current study is the first systematic investigation of creative cognition using ERPs. The findings of the present study attest to the fact that using an event-related electrophysiological approach provides a rich and novel avenue to explore further relevant questions that can provide genuine insights into the neurocognitive mechanisms underlying creative thinking.

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4.7 Supplementary Material

Table S1 Complete list of stimuli phrases used in the experiment and the corresponding classification proportions (in %) by the participants of each stimulus within each category. Stimuli phrases were presented in German. Critical word is printed in bold.

HUHA (highly unusual – highly appropriate)	HUHA	HULA	LUHA	Error
Der Wind hat die Bäume **gekitzelt**.	61.1	0	33.3	5.6
Das Wasser hat den Schwimmer **umarmt**.	94.4	0	5.6	0
Der Forscher hat eine Theorie **geboren**.	77.8	0	22.2	0
Das Riff hat die Fische **verschluckt.**	77.8	22.2	0	0
Die Wolken haben über der Stadt **getanzt**.	72.2	5.6	22.2	0
Der Mond hat die Welt **getröstet**.	55.6	33.3	0	11.1
Die Frau hat ihm Worte ins Ohr **geträufelt**.	83.3	16.7	0	0
Die Sternschnuppen haben den Himmel **zerschnitten**.	61.1	27.8	11.1	0
Der Garten ist im Winter **gestorben**.	77.8	11.1	11.1	0
Der Regen hat die Lippen **geküsst**.	77.8	11.1	0	11.1
Die Biene hat die Blüte **bezirzt**.	61.1	11.1	27.8	0
Die Wolkendecke hat das Land **erstickt**.	66.7	16.7	16.7	0
Die Früchte haben den Kuchen **vergoldet**.	61.1	11.1	27.8	0
Die Melodie ist durch die Luft **geflattert**.	83.3	5.6	11.1	0
Der Sturm hat die Düne **verscheucht**.	83.3	11.1	0	5.6
Der Surfer hat mit den Wellen **gerangelt**.	66.7	16.7	11.1	5.6
Der Wurm hat sich durch den Apfel **geschraubt**.	83.3	0	16.7	0
Die Gestirne haben über dem Meer **geschwiegen**.	27.8	72.2	0	0
Die Hitze hat den Boden **vernarbt**.	66.7	22.2	5.6	5.6
Die Sonne hat auf die Erde **eingehämmert**.	55.6	33.1	0	11.1

Die Fahne hat sich im Wind **geräkelt**.	77.8	16.7	5.6	0
Das Erdbeben hat die Stadt **aufgefressen**.	83.3	11.1	5.6	0
Das Laub ist von den Bäumen **getaumelt**.	72.2	16.7	11.1	0
Der Efeu hat den Baum **erstickt**.	61.1	22.2	16.7	0
Die Sonne hat den Tau **getrunken**.	83.3	16.7	0	0
Die Schwerkraft hat den Mond **gefesselt**.	61.1	33.3	5.6	0
Der Poet hat seine Gedanken **eingefroren**.	50.0	38.9	11.1	0
Der Vulkan hat die Lava **herausgewürgt**.	77.8	5.6	11.1	5.6
Der Traum hat die Richtung **geleuchtet**.	66.7	22.2	5.6	5.6
Das Bächlein ist durch den Wald **gehuscht**.	61.1	38.9	0	0
Das Gewitter hat Blitze **gehustet**.	72.2	27.8	0	0
Die Sterne haben über der Wüste **gelauert**.	55.6	33.3	5.6	5.6
Die Nacht hat die Sterne **entzündet**.	83.3	5.6	0	11.1
Die Sirene hat über der Stadt **gesungen**.	72.2	5.6	16.6	5.6
Das Echo ist durch die Höhle **gezittert**.	55.6	38.9	0	5.6
Die Wellen haben den Strand **ertränkt**.	83.3	11.1	5.6	0
Das Lied ist ihr ins Ohr **gehüpft**.	77.8	16.7	0	5.6
Der Morgentau hat auf der Wiese **geschlafen.**	83.3	16.6	0	0
Der Schnee hat den Boden **verschlungen**.	66.7	11.1	22.2	0
Die Gewitterwolken sind über die Felder **galoppiert**.	66.7	22.2	5.6	5.6
Der Musiker hat die Geige **geneckt**.	50.0	44.4	5.6	0
Das Gelächter ist aus den Fenstern **getropft**.	55.6	44.4	0	0
Die Sonne hat hinter den Wolken **geschmollt**.	77.8	11.1	5.6	5.6
Die Liebe ist mit der Zeit **versunken**.	61.1	22.2	11.1	5.6
HULA (highly unusual – low appropriate)				
Der Wind hat die Bäume **angezündet**.	0	94.4	5.6	0
Das Wasser hat den Schwimmer **vergessen**.	5.6	83.3	11.1	0
Der Forscher hat eine Theorie **geteert**.	5.6	88.9	0	5.6

Das Riff hat die Fische **verboten.**	0	100	0	0
Die Wolken haben über der Stadt **gelesen**.	11.1	83.3	0	5.6
Der Mond hat die Welt **gegessen**.	5.6	94.4	0	0
Die Frau hat ihm Worte ans Ohr **genäht.**	27.8	72.2	0	0
Die Sternschnuppen haben den Himmel **umgetauscht**.	5.6	88.9	0	5.6
Der Garten ist im Winter **kondensiert**.	0	88.9	5.6	5.6
Der Regen hat die Lippen **geflochten**.	0	100	0	0
Die Biene hat die Blüte **getöpfert**.	5.6	94.4	0	0
Die Wolkendecke hat das Land **gebraten**.	0	100	0	0
Die Früchte haben den Kuchen **gesehen**.	22.2	72.2	0	5.6
Die Melodie ist durch die Luft **gebohrt**.	38.9	55.6	0	5.6
Der Sturm hat die Düne **gebraten**.	16.7	77.8	0	5.6
Der Surfer hat mit den Wellen **telefoniert**.	0	94.4	0	5.6
Der Wurm hat sich durch den Apfel **geschnarcht**.	5.6	94.4	0	0
Die Gestirne haben über dem Meer **gekeimt**.	16.7	83.3	0	0
Die Hitze hat den Boden **gewischt**.	0	100	0	0
Die Sonne hat auf die Erde **geregnet**.	22.2	66.7	5.6	5.6
Die Fahne hat sich im Wind **geduscht**.	5.6	94.4	0	0
Das Erdbeben hat die Stadt **aufgetaut**.	0	83.3	5.6	11.1
Das Laub ist von den Bäumen **geronnen**.	27.8	66.8	5.6	0
Der Efeu hat den Baum **verglast**.	5.6	83.3	5.6	5.6
Die Sonne hat den Tau **geleimt**.	5.6	94.4	0	0
Die Schwerkraft hat den Mond **getauft**.	0	94.4	5.6	0
Der Poet hat seine Gedanken **gedünstet**.	0	100	0	0
Der Vulkan hat die Lava **gehämmert**.	22.2	72.2	0	5.6
Der Traum hat die Richtung **rasiert**.	0	100	0	0
Das Bächlein ist durch den Wald **geradelt**.	11.1	77.8	0	11.1
Das Gewitter hat Blitze **getrocknet**.	0	94.4	0	5.6

Die Sterne haben über der Wüste **gemäht**.	0	88.9	5.6	5.6
Die Nacht hat die Sterne **gebrochen**.	5.6	83.3	0	11.1
Die Sirene hat über der Stadt **gebügelt**.	0	94.4	0	5.6
Das Echo ist durch die Höhle **gepinselt**.	11.1	88.9	0	0
Die Wellen haben den Strand **ausgewildert**.	11.1	83.3	5.6	0
Das Lied ist ihr ins Ohr **gerudert**.	11.1	88.9	0	0
Der Morgentau hat auf der Wiese **debattiert**.	0	88.9	5.6	5.6
Der Schnee hat den Boden **poliert**.	22.2	72.2	0	5.6
Die Gewitterwolken sind über die Felder **gezuckelt**.	77.8	5.6	5.6	11.1
Der Musiker hat die Geige **gebacken**.	5.6	83.3	5.6	5.6
Das Gelächter ist aus den Fenstern **geschehen**.	11.1	77.8	11.1	0
Die Sonne hat hinter den Wolken **gestrickt**.	0	94.4	5.6	0
Die Liebe ist mit der Zeit **vermalt**.	22.2	72.2	0	5.6
LUHA (low unusual – highly appropriate)				
Der Wind hat die Bäume **umgeweht.**	5.6	0	94.4	0
Das Wasser hat den Schwimmer **durchnässt**.	27.8	11.1	61.1	0
Der Forscher hat eine Theorie **entwickelt**.	5.6	5.6	83.3	5.6
Das Riff hat die Fische **beheimatet**.	16.7	5.6	72.2	5.6
Die Wolken sind über die Stadt **gezogen**.	0	0	100	0
Der Mond hat die Welt **erhellt**.	11.1	0	88.9	0
Die Frau hat ihm Worte ins Ohr **geflüstert**.	0	0	94.4	5.6
Die Sternschnuppen haben den Himmel **erleuchtet**.	5.6	5.6	83.3	5.6
Der Garten ist im Winter **erfroren**.	16.7	11.1	61.1	11.1
Der Regen hat die Lippen **benetzt**.	27.8	5.6	66.7	0
Die Biene hat die Blüte **verlassen.**	5.6	5.6	83.3	5.6
Die Wolkendecke hat das Land **verdunkelt**.	5.6	0	88.9	5.6
Die Früchte haben den Kuchen **umgeben**.	22.2	27.8	33.3	16.7
Die Melodie ist durch die Luft **gezogen**.	50	0	50	0

Der Sturm hat die Düne **verweht**.	0	0	100	0
Der Surfer ist mit den Wellen **geschwommen**.	11.1	5.6	83.3	0
Der Wurm hat sich durch den Apfel **gefressen**.	5.6	0	94.4	0
Die Gestirne haben über dem Meer **gestrahlt**.	5.6	11.1	83.3	0
Die Hitze hat den Boden **ausgetrocknet**.	0	0	100	0
Die Sonne hat auf die Erde **geschienen**.	11.1	0	88.9	0
Die Fahne hat sich im Wind **gedreht**.	0	5.6	94.4	0
Das Erdbeben hat die Stadt **verwüstet**.	0	0	100	0
Das Laub ist von den Bäumen **gefallen**.	0	0	94.4	5.6
Der Efeu hat den Baum **überwuchert**.	5.6	0	94.4	0
Die Sonne hat den Tau **verdunstet**.	11.1	5.6	77.8	5.6
Die Schwerkraft hat den Mond **beeinflusst**.	11.1	0	66.7	22.2
Der Poet hat seine Gedanken **aufgeschrieben**.	5.6	0	88.9	5.6
Der Vulkan hat die Lava **herausgeschossen**.	5.6	0	94.4	0
Der Traum hat die Richtung **gewiesen**.	22.2	0	77.8	0
Das Bächlein ist durch den Wald **geflossen**.	5.6	0	94.4	0
Das Gewitter hat Blitze **hervorgebracht**.	11.1	0	88.9	0
Die Sterne haben über der Wüste **geschienen**.	5.6	5.6	83.3	5.6
Die Nacht hat die Sterne **sichtbar gemacht.**	16.7	5.6	72.2	5.6
Die Sirene hat über der Stadt **geheult**.	11.1	0	83.3	5.6
Das Echo hat durch die Höhle **geschallt**.	0	0	94.4	5.6
Die Wellen haben den Strand **überflutet**.	0	5.6	83.3	11.1
Das Lied ist ihr ins Ohr **gedrungen**.	11.1	5.6	83.3	0
Der Morgentau hat auf der Wiese **gelegen**.	5.6	0	88.9	5.6
Der Schnee hat den Boden **bedeckt**.	5.6	0	83.3	11.1
Die Gewitterwolken sind über die Felder **gezogen**.	5.6	0	94.4	0
Der Musiker hat die Geige **gespielt**.	0	0	94.4	5.6
Das Gelächter ist aus den Fenstern **gedrungen**.	0	0	100	0

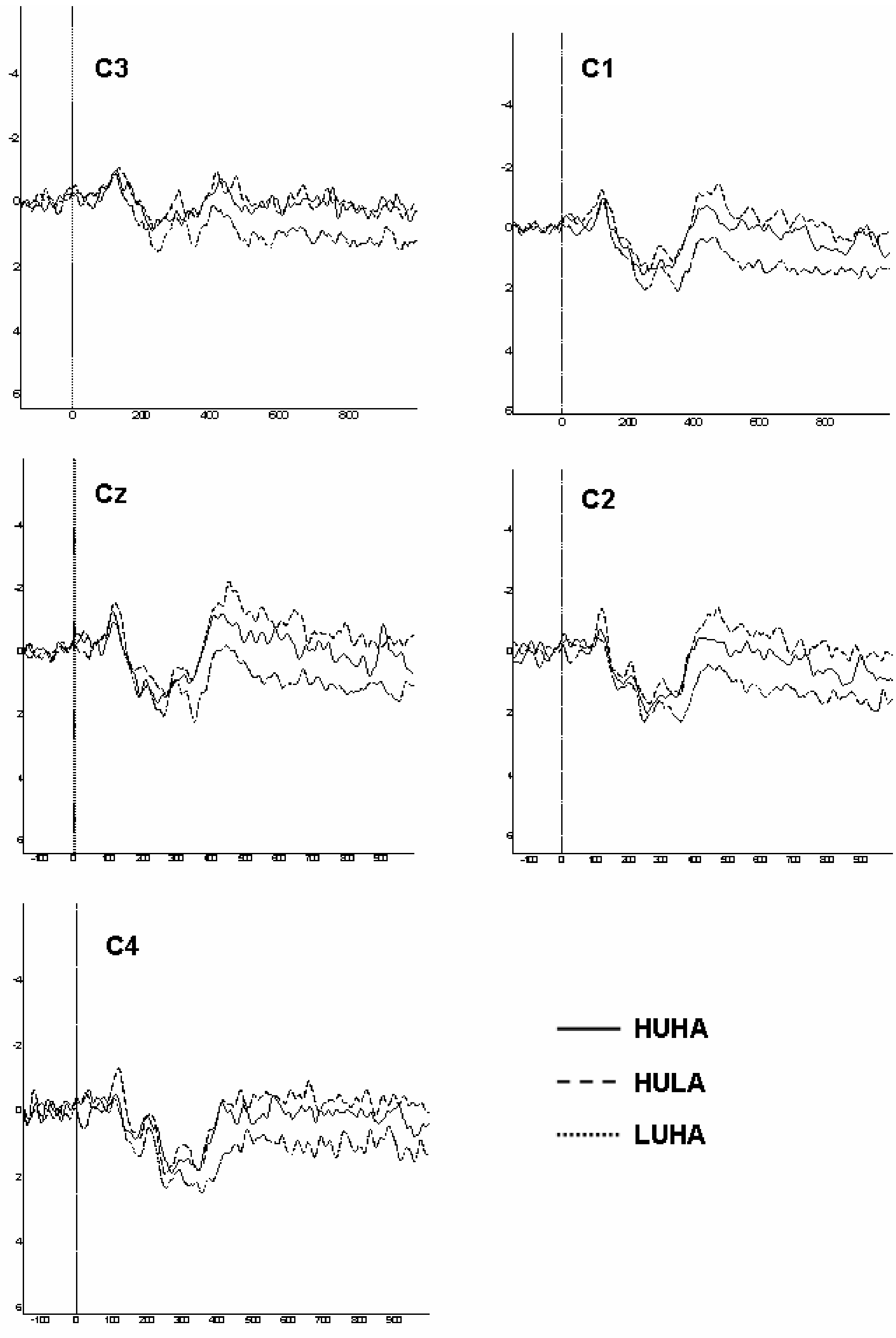
Die Sonne hat hinter den Wolken **geschienen**.	5.6	0	88.9	5.6
Die Liebe ist mit der Zeit **vergangen**.	0	0	94.4	5.6

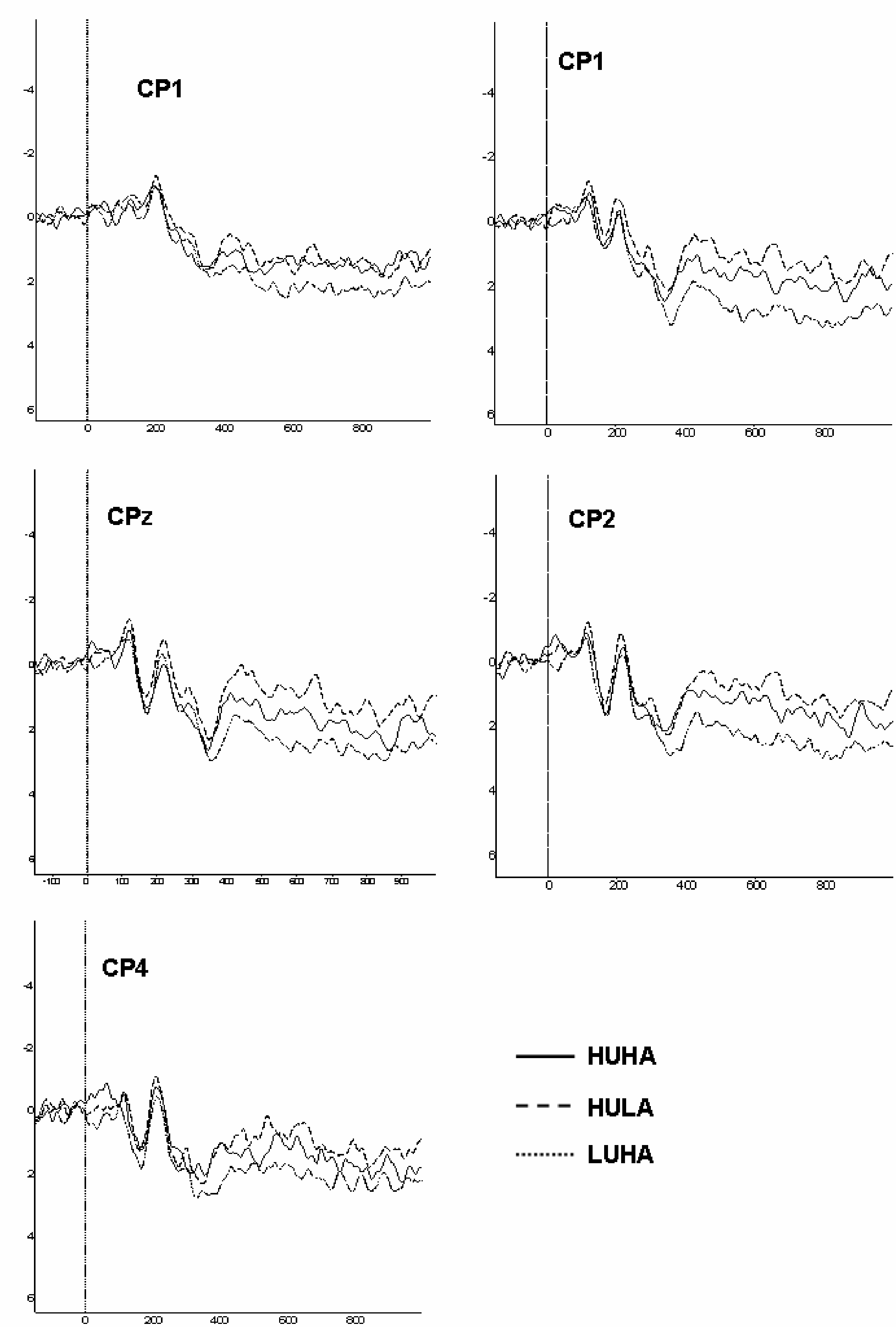
Table S2 Mean number of segments per condition per subject included in the final ERP analyses.

Subject	HUHA	HULA	LUHA
1	41	50.7	37
2	38	44	43
3	40.9	47	43
4	45	44	43
5	35	53	43
6	41	45	43
7	41	45.9	44
8	43.8	40.4	44.1
9	41	45	31
10	38	51	41
11	32.4	43.8	45.8
12	35.8	41.3	43.3
13	29.8	52.7	39.2
14	28	57.2	39.9
15	52	40.9	37
16	28	47	40
17	30	61	41
18	50	31	47.9

Figure S3

Grand averages for all 15 electrodes included in the analyses.


C3
C1
Cz
C2
C4
HUHA
HULA
LUHA


CP1
CP1
CPz
CP2
CP4
HUHA
HULA
LUHA

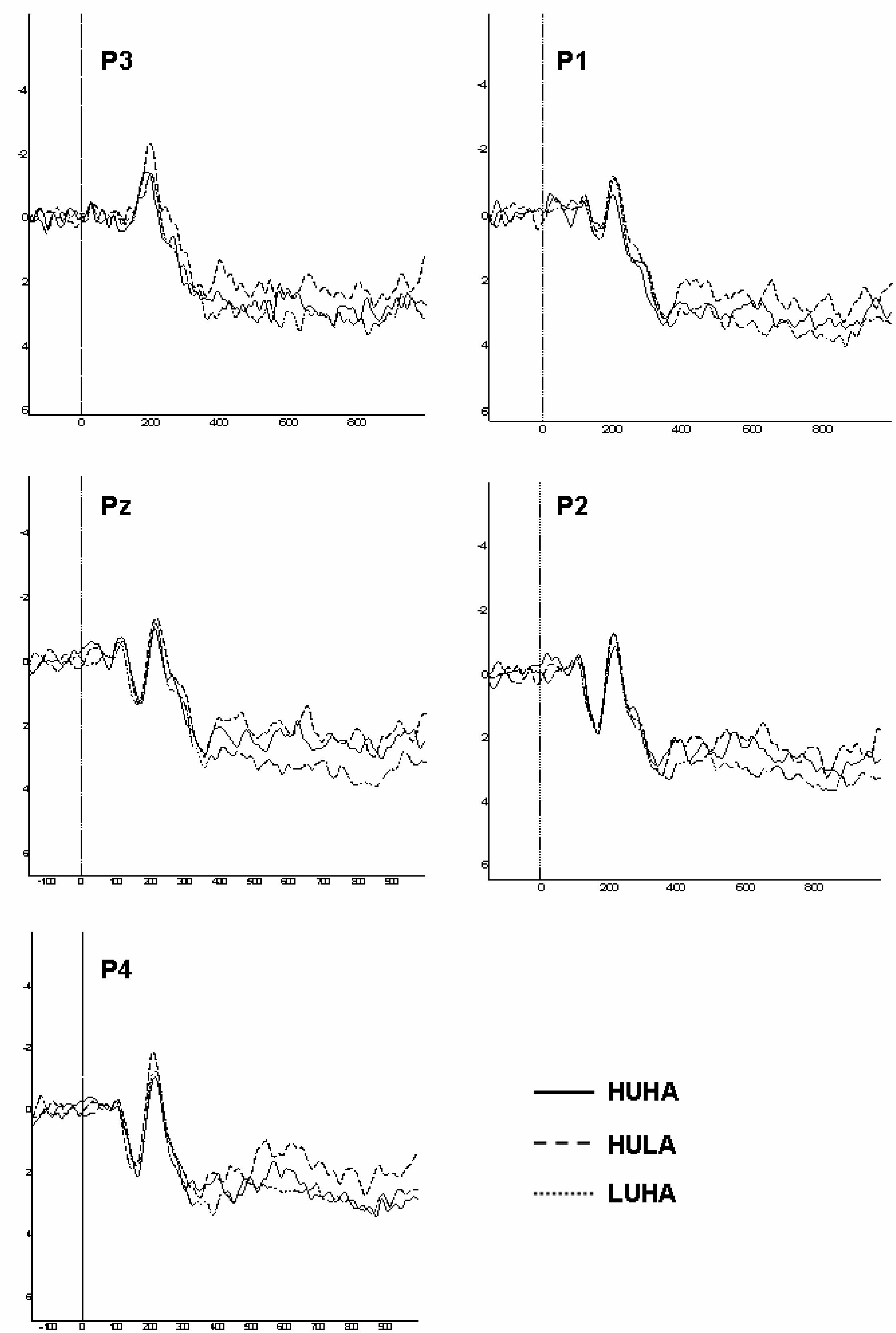
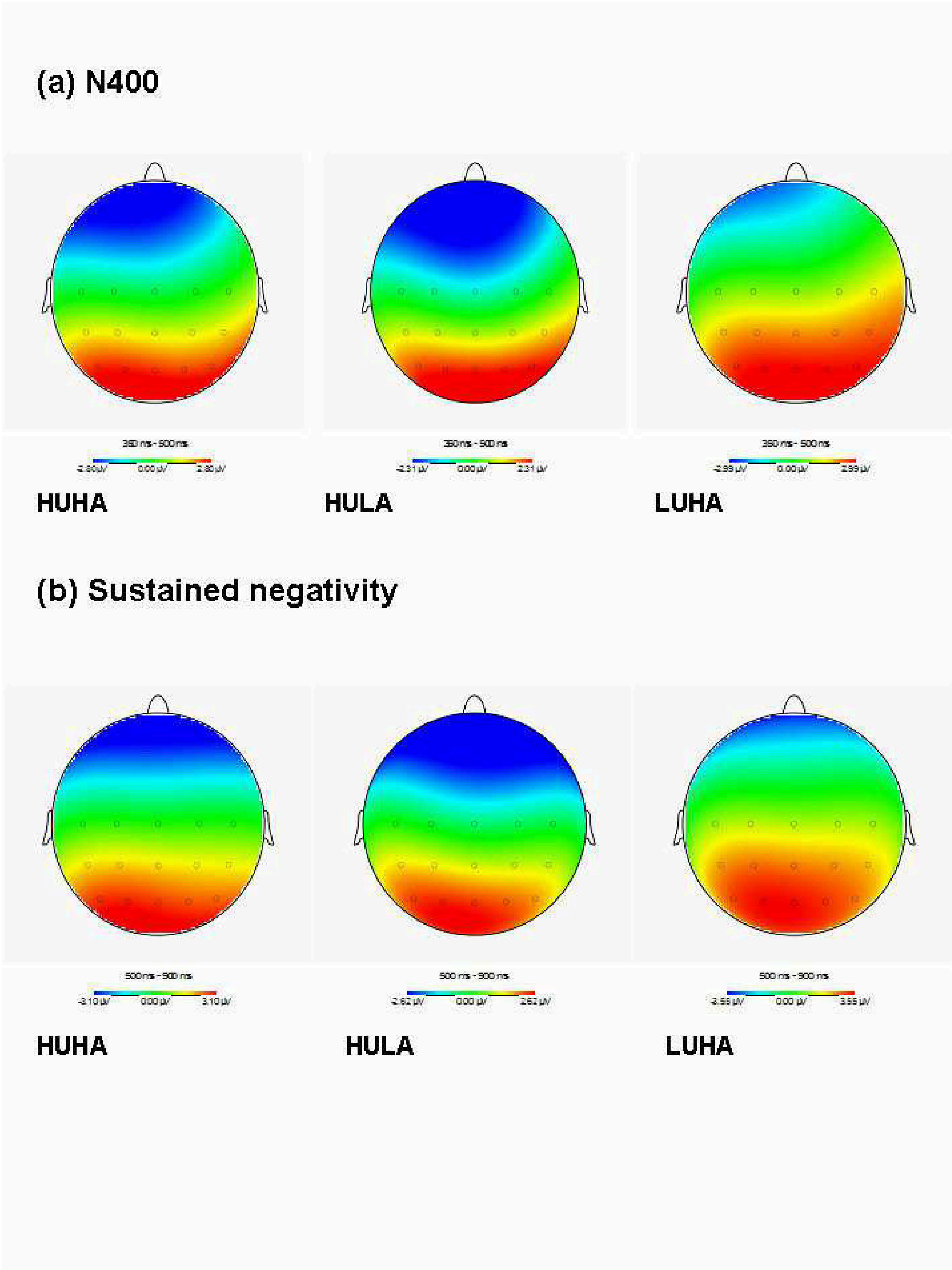

P3
P1
Pz
P2
P4
HUHA
HULA
LUHA

Figure S4

(a) Topographical distribution of the N400 effect for each of the three conditions.

(b) Topographical distribution of the effect in the later time-window for each of the three conditions.



(a) N400
350 ms - 500 ms
-2.80 µV
0.00 µV
2.80 µV
HUHA
350 ms - 500 ms
-2.31 µV
0.00 µV
2.31 µV
HULA
350 ms - 500 ms
-2.99 µV
0.00 µV
2.99 µV
LUHA
(b) Sustained negativity
500 ms - 900 ms
-3.10 µV
0.00 µV
3.10 µV
HUHA
500 ms - 900 ms
-2.62 µV
0.00 µV
2.62 µV
HULA
500 ms - 900 ms
-3.55 µV
0.00 µV
3.55 µV
LUHA

5 General discussion and implications

The above reported studies used two different methods to investigate the neural correlates of one creative cognitive process, namely conceptual expansion. The studies applied a novel paradigm which passively induced conceptual expansion within participants. Whereas the hypotheses for the fMRI study could only be partially confirmed, the results regarding the earlier ERP component conformed to *a priori* predictions. Nevertheless, the two studies and their respective findings are subject to certain limitations. The findings of the studies as well as their respective limitations and implications will be discussed in the following sections.

5.1 Discussion of fMRI results

One of the studies used fMRI to assess participant's brain activity while they read and judged sentences on their unusualness and appropriateness. By choosing the statistical method of conjunction analysis, it was possible to differentiate brain activities caused by the novelty or the appropriateness of the sentences from brain activity that was caused by conceptual expansion as a creative cognitive operation.

Conceptual expansion was hypothesized to result in greater brain activations in the anterior inferior frontal gyrus (IFG; BA 45/47), the middle temporal gyrus (MTG; BA 20 and BA 21), and the frontopolar cortex (FPC; BA 10). The results obtained by this study were fully in line with the predictions of brain activity in the anterior IFG and the frontopolar cortex, but were not supported in the case of the MTG.

The present findings confirmed the involvement of the anterior IFG when participants judged a phrase as unusual and appropriate, thereby conveying conceptual expansion. This finding is in line with several other studies that have linked this particular region to an increased effort when retrieving semantic information and with greater demands on semantic selection (e.g., Thompson-

Schill et al., 1997; Wagner, Pare-Blagoev, Clark, & Poldrack, 2001; Wig, Miller, Kingstone, & Kelley, 2004), as well as to greater semantic distance in analogical mapping (Green et al., 2010). Greater activation in the anterior IFG when processing novel metaphoric phrases that were deemed to be both highly unusual and highly appropriate in the present study indicates that these phrases require greater effort to retrieve and select semantic information about the two semantically distant concepts conveyed through the phrases.

The role of the anterior IFG in semantic processing is unquestionable. However, its precise role is still under debate, as is discussed in more detail in section 3.5.1. While Wagner and colleagues (2001) see the area's role in the controlled retrieval of semantic knowledge, Thompson-Schill and colleagues (1997) argue for its importance in semantic selection. Badre and colleagues (2005) integrate both roles of the anterior IFG, assigning retrieval and selection of semantic information to different subregions. The present study and its results cannot clarify the specific role of the anterior IFG in semantic processing. Phrases conveying conceptual expansion rather seem to require both the retrieval and the selection of appropriate semantic knowledge to a greater extent than literal phrases in order to make sense of the novel combination of concepts encountered in unusual and appropriate phrases.

Hypotheses about the involvement of the middle temporal gyrus (MTG; BA 20 and BA 21) in the process of conceptual expansion could not be fully confirmed in the present study. However, the results showed greater activation in the temporal pole (BA 38) when processing unusual and appropriate phrases. This finding is in line with an account by Badre and colleagues (2005) postulating a two-step model of semantic memory. According to this account, semantic memory is stored in the temporal poles and its retrieval is controlled by the left anterior ventrolateral inferior frontal cortex. Results of the present study are in line with this proposed model of semantic memory as both IFG (BA45/47) and temporal pole (BA 38) were activated when participants processed phrases that were judged by them to be unusual and appropriate. This implicates that semantic selection, controlled semantic retrieval and semantic storage related processes are recruited during conceptual expansion.

Results of the present study also indicate the involvement of the frontopolar cortex (FPC; BA 10) when processing phrases that require conceptual expansion. This region has previously been discussed in terms of integrating the outcome of multiple cognitive operations (Ramnani & Owen, 2004), processing highly complex stimuli in a reasoning task (Kroger et al., 2002), as well as integrating semantically distant relations in analogical reasoning (Green et al., 2010; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012). All of these discussed functions of the region apply to the results obtained in the present study. Phrases that induce conceptual expansion recruit multiple cognitive processes, such as the retrieval and selection of semantic information, whose outcomes have to be integrated to connect two formerly unconnected or only weakly connected concepts in a novel and meaningful manner. In a recent study, Green and colleagues (2012) showed that frontopolar activation increased as a function of semantic distance between two stimuli in an analogical reasoning task. The authors interpret these results in terms of the role of the frontopolar cortex as an integration mechanism. Furthermore, semantically more distant analogies were rated as more creative. The results and respective interpretation of this study furthermore support the found activation of the frontopolar cortex in the present work as phrases conveying conceptual expansion require the integration of semantically very distant concepts.

Some studies suggest that relational integration within the frontopolar cortex is achieved through the manipulation of self-generated or self-inferred information (Christoff et al., 2001; Christoff, Ream, Geddes, & Gabrieli, 2003). This idea strongly supports the notion that a passive and indirect approach is suitable to investigate conceptual expansion. Even though participants did not have to volitionally and actively expand existing concepts, deriving a judgment about the unusualness and appropriateness of the encountered stimuli was still self-inferred by participants.

The neural correlates common to novelty processing (novel metaphoric and nonsense expressions) and appropriateness processing (novel metaphoric and literal expressions) were also analyzed in the study. Although the processing of novelty was expected to lead to greater activation in the anterior IFG (BA 45/47), the results revealed only a small area of activation within the mid-IFG (BA 45). This more circumscribed degree of brain activation is likely to be due to the nature of the nonsense (or unusual but inappropriate) stimuli. It can be postulated that the obvious senselessness of the phrases made the recruitment of brain areas responsible for semantic retrieval and an increased effort to reach a conclusion about the two concepts obsolete. This would have resulted in the observed lack of activation in these brain regions when assessing novelty processing. This interpretation is backed by findings of a study by Mashal and colleagues (2009) who attribute the lack of activation found for their nonsensical sentences to their obvious senselessness, which, in turn, rendered the controlled semantic retrieval via the anterior IFG (BA 47) unnecessary. The obvious senselessness of the phrases used in the present study might also account for the lack of activation in other areas, such as MTG (BA 20 and BA 21) and temporal pole (BA 38) in relation to novelty processing. As such phrases are easily dismissed as senseless, further extensive search and retrieval from semantic storage areas in the temporal lobe would be unnecessary.

The appropriateness aspect of the phrases in the present study was investigated in an explorative manner and showed surprising and, at first glance, counterintuitive findings. Appropriateness led to greater activation in the left middle temporal gyrus (BA 21), an area that was expected to be activated as a function of greater effort to retrieve semantic knowledge during the processing of novelty and conceptual expansion. Again, Badre and colleagues' (2005) account on semantic memory retrieval is suitable to explain these findings. Semantic knowledge stored in temporal areas can be accessed through either automatic or IFG-controlled processes. Literal phrases used in the present study are commonly encountered in everyday language and are likely accessed through automatic processes from temporal areas without the involvement of the IFG, explaining the activation found in the left middle temporal gyrus (BA 21) and the lack of activation in the IFG.

In summary, core aspects of the semantic network in the brain, such as the IFG and the temporal poles were recruited during passively induced conceptual expansion alongside the frontopolar cortex which is involved in conceptual relational reasoning and integration.

5.2 Implications of the fMRI study

The findings of the present fMRI study on creative cognition carry interesting implications and open new directions for the investigation of creativity and semantic processing.

Most notably, the present fMRI study applied a novel paradigm which made it possible to overcome many of the shortcomings and limitations of previous studies on creativity. By focusing on one creative process of interest, it was possible to relate specific brain areas to conceptual expansion and contrast it with brain activity caused by mere novelty and appropriateness. Previous studies on creativity often implemented tasks that require a myriad of different cognitive processes, resulting in the activation of different brain areas with little overlap between studies. By extending this new paradigm to other creative cognitive processes, it will be possible to achieve a clearer and more distinctive picture of the underlying neural networks involved in creativity. Furthermore, the present study showed that a passive approach to assessing conceptual expansion provides a viable alternative to investigate neural correlates of creativity.

It is undisputable that an active conceptual expansion task will recruit other cognitive processes in addition to the ones found in the present study. However, the broadening or expansion of the conceptual structures that is necessary to arrive either at a novel and appropriate solution or to judge the novelty and appropriateness of a solution are one and the same. The findings support this notion. Using passive approaches for the fMRI investigation of other creative cognitive processes can be advantageous, as it allows researchers to avoid many technical problems associated with using neuroimaging-based technology and active creative performance tasks, such as long trial durations and movements associated with oral or written answers. The passive approach allowed for short trial durations and therefore a greater number of trials, leading to greater statistical power.

As the present study was the first to use a novel approach for the investigation of creative cognition, the results are in need of further support through replication and more detailed investigation. In particular, the results obtained for the processing of novelty are worth exploring further. Future studies could, for instance, use unusual and senseless phrases that distinguish between obviously senseless stimuli and stimuli that do not appear senseless on first sight but rather require further processing in order to judge them as such. Such a distinction will make it possible to shed further light on how novelty is processed at the neural level.

5.3 Discussion of ERP results

Using the novel approach introduced in this work made it possible to link established aspects of brain functions to conceptual expansion as a creative cognitive process.

The N400 ERP component was of especial interest as it has been previously implicated as an implicator for semantically incongruous words (Kutas & Hillyard, 1980a; Kutas & Hillyard, 1980b), violations of discourse contexts or world knowledge (Hagoort et al., 2004; Hald et al., 2007; van Berkum et al., 2003) and the difficulty of semantic integration (Kutas & Van Petten, 1994) among others. It was therefore hypothesized that phrases judged as unusual and senseless (nonsense expressions) would show the greatest N400 modification, followed by unusual and appropriate (novel metaphoric expressions) and usual and appropriate phrases (literal expressions).

The results obtained in the present study were in line with these predictions. Although direct comparisons revealed no significant differences in the N400 waveform elicited by nonsense phrases (HULA) compared to the novel metaphoric phrases (HUHA), the graded effect in the N400 for all three stimuli (nonsense > novel metaphoric > literal) was revealed as a significant linear trend of the main effect in the statistical analysis. This pattern of results corresponds with other findings in the field of language comprehension and metaphor processing (e.g., Arzouan et al., 2007; Coulson & Van Petten, 2002; Coulson & Van Petten, 2007; De Grauwe et al., 2010; Lai et al., 2009; Pynte, Besson, Robichon, & Poli, 1996; Tartter, Gomes, Dubrovsky, Molholm, & Stewart, 2002).

The conceptual blending theory (Fauconnier & Turner, 1998) offers one way to interpret the graded N400 amplitude for the different types of phrases. This theory postulates that language comprehension is based on the construction of cognitive models and mapping between its components. Components from existing concepts and structures are transferred into a new space and blended. In line with this theory, greater N400 amplitudes for senseless or metaphorical expressions therefore indicate an increased effort to establish connections between distantly related domains and their components. Additionally, background knowledge about the distant domains is activated to derive meaning (Arzouan et al., 2007).

The findings in this field and their interpretations can be extended and applied to explain the graded N400 effect found the current study. When taking findings from semantic priming studies into consideration that interpret the N400 component as an indicator for higher-level integrative processes (e.g., Brown & Hagoort, 1993; Brown, Hagoort, & Chwilla, 2000; Holcomb, 1993), greater N400 amplitudes for phrases judged as novel metaphorical and senseless can be seen as an increased effort to construe a connection between the two distantly related concepts conveyed through the stimuli. Literal phrases do not require this increased effort, as they are common phrases containing two concepts that are already strongly associated with one another. The derivation of meaning from literal phrases is therefore comparatively effortless. In contrast, senseless and novel metaphorical phrases require the integration of two unrelated concepts as they are both novel and have likely not been encountered previously. The integrational effort seems to be greatest for phrases judged as unusual but inappropriate by participants. This is due to their senselessness and the failure to successfully integrate and build an association between the two concepts conveyed through the phrases. In the case of phrases that participants judged to be unusual and appropriate, the increased effort to build a connection between the two novel concepts is eventually successful, resulting in a novel conceptual combination. Even though direct comparisons between novel metaphorical and senseless phrases do not show a significant difference in N400 amplitudes between the two types of phrases, the significant linear trend of the main effect supports this interpretation.

Further support for this interpretation can be taken from findings reported by Rhodes and Donaldson (2008) where an N400 modulation was found for word pairs with only an associative connection and for word pairs with both a semantic and an associative connection as compared to unrelated word pairs. The authors found that the N400 was greatest for unrelated word pairs. In the case of novel metaphorical phrases in the current study, novel semantic associations were established during the experiment by expanding an existing concept to include a new feature. The fact that such a novel association could be successfully construed for novel metaphorical but not for senseless phrases, similar to unrelated word pairs in the Rhodes and Donaldson study, can possibly account for the partially lower N400 amplitude for phrases conveying conceptual expansion.

Other studies have interpreted the N400 as indexing the effort to retrieve semantic knowledge from memory stores in the brain (e.g., Kutas & Federmeier, 2000; Kutas et al., 2006). This interpretation can also be applied to the current findings. Both novel metaphorical and senseless phrases are unusual and require a greater effort to search for semantic information about the novel concepts conveyed through them. However, as the experimental paradigm was not designed to test between competing semantic theories, the findings from this study cannot ultimately ascertain whether the greater N400 amplitude for theses two types of phrases is due to an increased effort to retrieve semantic knowledge or to an increased effort to integrate two distant domains and thereby derive meaning. This question certainly requires further research.

Another explanation for the greater N400 amplitudes observed for novel metaphorical and senseless phrases could be cloze probability. Cloze probability refers to the probability with which or expectancy that a certain word completes a sentence. As an example, "green" is more likely than "red" to conclude the sentence "The grass is ..." and therefore has a higher cloze probability. Some studies have found N400 modulations based on the violation of semantic expectations (Kutas & Hillyard, 1984). Indeed, both novel metaphorical and senseless phrases convey unexpected semantic information in the given context. However, the highly significant linear trend suggests that other cognitive processes exceeding mere expectation violations are at play. It may be more fitting to view these violations of semantic expectations as a catalyst for the increased effort to retrieve and integrate semantic information in order to derive meaning from these two types of phrases.

The investigation of ERP components occurring in the later time-window (500 - 900ms after onset of the critical word) was conducted on an exploratory basis. Since this study was the first of its kind to investigate ERP components in the light of creative cognition, no predictions for the later time-window were formulated. The results showed that the later ERP component followed a pattern similar to the N400 findings. HULA phrases (nonsense expressions) and HUHA phrases (novel metaphorical expressions) elicited a more negative-going waveform than LUHA phrases (literal expressions). In contrast to the N400 findings, however, both direct comparisons and the linear trend revealed that the waveforms associated with all three types of phrases differed significantly from each other, with HULA phrases (senseless expressions) showing the most negative going waveform, followed by HUHA (novel metaphoric expressions) and LUHA phrases (literal expressions).

When looking at ERP studies on language processing, heterogeneous findings concerning the later time-window become apparent. In some cases, a P600 component after N400 can be observed when processing ambiguous sentences (Friederici, 1995) and metaphors (Coulson & Van Petten, 2002; De Grauwe et al., 2010) in which case this late positive component is often interpreted as an indicator for the retrieval and integration of additional information to establish a link between formerly unassociated or weakly associated concepts. At least one study, however, did not find a P600 component when processing metaphors as compared to literal sentences (Pynte et al., 1996).

In the present study, both types of phrases that were judged as unusual or novel by participants did not elicit a P600. Instead, an ongoing negativity could be observed in the later time-window. This sustained negativity has been described in other studies as an indicator for different cognitive processes. Ruchkin and colleagues (Ruchkin, Johnson, Mahaffey, & Sutton, 1988) interpreted slow negative waves in terms of conceptually difficult to process stimuli. Taking into consideration that the concepts contained in phrases that were judged as unusual in the present study are, per definition, conceptually difficult to process stimuli compared to the literal phrases, this interpretation would fit the results at hand. However, the slow negative waves described in Ruchkin and colleagues' study differ in onset and latency from the waveform found in the present study.

Another possible interpretation for the ongoing negativity for unusual or novel phrases stems from Rhodes and Donaldson (2008) who found a more negative waveform in the later time-window similar to the one found in the present study when comparing unrelated word pairs to word pairs that are semantically or associatively connected. In their study, this was interpreted as recollection from long-term memory for the word pairs with a semantic or associative connection, referencing old/new memory effects and episodic retrieval processes as described by Greve, van Rossum and Donaldson (2007) and Donaldson and Rugg (1998) among others. This interpretation fits the pattern of results found in the present study given that the literal phrases are already semantically or associatively linked, whereas phrases judged as unusual are presumed to be previously unrelated and therefore require further processing. However, the waveform found in Rhodes and Donaldson's study was limited to the left parietal areas and the interpretation of their results may therefore not be fully applicable to the effect found in the present study, as the effect was more widespread, spanning central, centro-parietal and parietal areas.

In particular, the effect observed in the later time-window presents itself as a continuation of the effects found in the earlier time-window. Phrases categorized as novel metaphorical and senseless elicited a more negative-going waveform than phrases judged as literal. In contrast to what was found within the earlier time-window, however, in the case of the sustained negativity both direct comparisons and the linear trend of the condition main effect revealed that the waveforms elicited by the three conditions differed significantly from each other.

A series of studies were conducted by Jiang, Tan, and Zhou (2009) on how violations of universal quantifiers in sentences are processed. As an example, the universal quantifier "all" was mismatched with a noun in singular object, as in the phrase "He threw away all that apple." The authors reported that violations of the universal quantifier did not elicit a N400, but a sustained negativity at verb onset instead (Jiang, Tan, & Zhou, 2009). This sustained negativity was described as a reinterpretation of the verb after a mismatch between the verb and the universal quantifier was detected. The researchers interpreted this negative waveform as an indicator for a semantic reinterpretation process after the initial attempt to reach meaning has failed.

Although these results differ from the findings of the present study with regard to the fact that the former did not find a N400 component preceding the sustained negativity, a similar underlying process could be assumed to explain the sustained negativity found in this study. As a continuation of the N400 component which is associated with the effort to establish a connection between two semantically distant concepts, the late negativity in the later time-window might index the ongoing difficulty to (a) derive meaning from, and (b) establish a connection between the two distant concepts. Only in the case of novel metaphorical phrases this integrative effort eventually is successful which can account for the fact that the waveform becomes more positive in the later time-window, converging towards the level of the literal phrases. In the case of phrases that are judged as nonsensical, this effort to derive meaning and integrate the two concepts continues to fail, possibly reflecting the continued inability to establish a connection as the two concepts cannot be semantically related to one another. Hence, the waveform associated with these senseless phrases continues to stay more negative than the waveforms elicited by the two other types of phrases. It is important to note, however, that this is an ad hoc interpretation that requires further investigation to be confirmed.

When considering the similarity of effects observed in both the early and the later time-window, it could be argued that the two components may be indexing one single continuous effect. However, the findings from the direct comparisons between the conditions, as well as the significant linear trend implicate that there are two distinguishable effects present, each of them indexing a distinct cognitive operation. The linear trends for both ERP components suggested a graded effect such that the highest activity was elicited by nonsense phrases followed by novel metaphoric expressions, both relative to literal phrases. Direct comparisons between the nonsense and novel metaphoric expressions, however, indicated that while the N400 elicited by nonsense phrases (HULA) was not significantly differentiable from that of the novel metaphoric expressions (HUHA), the sustained negativity elicited by novel metaphorical phrases (HUHA) diverged significantly from the waveform associated with nonsensical phrases (HULA). This suggests the existence of two effects. However, the question of whether the observed findings demonstrate one singular effect or two distinct effects cannot be fully clarified and requires further, more specific investigation.

Nonetheless, the present study on creative cognition lent valuable insights on how and which ERP components can be utilized to index passively induced conceptual expansion.

5.4 Implications of the ERP study

The present ERP study on passive conceptual expansion played an important role in the investigation of creative cognition, as it was the first study to associate ERP components with creative cognitive processes. The study hence is a valuable first step towards a more comprehensive understanding of the neural correlates of creativity. The findings implicate that the N400 serves as an indicator of conceptual expansion. However, further detailed research is necessary to clarify the exact role of the N400 in conceptual expansion. Follow-up studies are needed to determine whether the N400 in connection with a passive conceptual expansion task indicates processes associated with information retrieval from semantic memory or higher-level integrative processes instead.

Regarding the effect found in the later time-window, follow-up studies need to be conducted to fully clarify its precise role. Refining the stimulus material and conducting a study geared towards investigating the effects in the later time-window can provide an important step towards a better understanding of the observed effects.

The novel paradigm used in the present study proved to be suitable to investigate passive conceptual expansion in creative cognition. Using this paradigm as a starting point and modifying it to assess other creative cognitive processes can pave the way towards painting a clearer, more comprehensive picture of the many facets of creative cognition.

5.5 Limitations of the fMRI and ERP studies

Both studies conducted within the framework of this project obtained interesting results and led to valuable insights into the neural correlates of creative cognition. Nevertheless, the paradigm used in both studies carries specific limitations that must be kept in mind when interpreting the associated findings.

One of the main goals of this project lay in the emphasis on singling out one distinct creative process, namely conceptual expansion, rather than treating creativity as a single entity. Even though this approach avoided many downfalls of previous studies of creativity, it has to be clearly noted that the results obtained by both studies are limited to conceptual expansion. The findings cannot be blindly expanded to other creative cognitive processes.

Another important limitation to be considered is the fact that the brain regions and ERP components implicated to be involved in creative cognition are not exclusive to conceptual expansion. Other cognitive operations may recruit the same or similar brain areas or may be indexed by the same components used in the present study. This is in line with the theoretical framework adopted in the present project, namely the creative cognition approach. This approach (see section 2.2.2) postulates that fundamental cognitive processes that are present in all humans are recruited to form the core of operations that lead to creative thinking (Ward et al., 1999).

Additionally, the task used in the present studies applied a verbal conceptual expansion task relying on semantic relations. Therefore, it is unsurprising that brain regions and ERP indices corresponding to the semantic network of the brain were found to be of significance in the current studies. The findings of the study concerning conceptual expansion are hence limited and only applicable to creative operations involving verbal semantic relations. Whether or not the same brain regions and ERP components would play a role in non-verbal and non-semantic creative operations, such as creative imagery, remains an open question and cannot be answered through the present work.

The most important limitation, however, is that conceptual expansion was not explicitly assessed with the present paradigm. Previous neuroimaging and electrophysiological studies required participants to actively generate an original and appropriate response. The paradigm used in the present work differed from these suboptimal designs in that it used an approach that passively induced conceptual expansion. This raises the important question of how well the obtained findings can be integrated into existing literature on the neurocognition of creativity when the self-generation of ideas is lacking. Even though, this is a valid argument, the following arguments that lead to the adoption of a passive conceptual expansion task have to be considered. First, one of the problems when investigating creativity stems from the fact that creativity is inherently unpredictable (Dietrich & Kanso, 2010). It is extremely difficult to reliably prompt a creative outcome in an experimental setting. In addition, the outcome of participants' creative generations is not always guaranteed to be creative. Taken together with the many severe methodological problems inherent in the neurophysiological investigation of creativity (see section 2.4.2), choosing an active task to investigate creativity renders a paradigm to be suboptimal at many other levels. In addition, the present work was partly motivated by recent calls in the field of creativity to approach the subject in a more innovative and systematic manner (Dietrich, 2007). The present work followed this call and focused on avoiding many methodological and conceptual difficulties previously associated with the investigation of creative thinking by adopting an approach that broke down the concept of creativity into its many components and focused on assessing the neurocognitive correlates of one operation of importance, conceptual expansion.

As outlined in a previous section, although it is unconventional to assess conceptual expansion through a passive task, it can safely be assumed that inducing conceptual expansion passively recruits the same core processes that can be observed through brain activations and ERP components, as the voluntary and active expansion of concepts. It is undeniable that the active expansion of concepts surely requires additional cognitive processes not found in a passive task. The conceptual structures that are expanded within the semantic network in the brain, however, remain the same in both kind of tasks. The findings presented within this report have been corroborated and extended using alternative passive and active conceptual expansion paradigms (Abraham et al., 2012; Kröger et al., 2012; Kröger et al., 2013).

6 Conclusion

The present work served an important purpose as a first stepping stone towards a novel approach in the investigation of creative thinking. Following recent calls to adopt a more systematic approach in the study of creativity, a novel experimental paradigm to assess metaphor processing was developed in the present studies that integrated the two defining aspects of creativity, namely novelty and appropriateness. By disentangling the very complex concept of creativity and considering it as a construct containing many cognitive operations, rather than as a single entity, it was possible to investigate the neural correlates of one creative cognitive operation, namely conceptual expansion. Utilizing a passive approach to induce conceptual expansion made it possible to account for individual differences in the organization and reorganization of conceptual knowledge and to avoid the many conceptual and methodological problems associated with investigating the complex phenomenon of creativity. The fMRI study revealed the involvement of brain networks for semantic processing and relational reasoning during conceptual expansion compared to the processing of mere novelty or appropriateness. The ERP study showed the relevance of the N400 and the late sustained negativity in indexing differential processing corresponding to semantic novelty and appropriateness. Both studies rendered it possible to gain valuable insights into the underlying neural mechanisms of creative thinking. Furthermore, the ERP study on creative conceptual expansion was the first of its kind and revealed new opportunities for investigation in this field.

Taken together, the novel approach adopted in the present work, as well as the findings of the respective studies, will serve as a vital aid in further investigations of creativity and constitutes an important stepping stone towards a better understanding of the neurocognitive correlates of this fascinating aspect of human thought and behavior.

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