Neurocognitive Evidence on the Impact of Topical Familiarity in Creative Outcomes

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Abstract
Engineering programs, in general, do not explicitly address the need to enhance divergent thinking. To a certain extent this is due to a lack in knowledge on the cognitive and neural mechanisms underlying divergent thinking, and creative ideation more generally. We hypothesize that we can help enhance our students' divergent thinking and creative processing outcomes by investigating the impacts of carefully selected methods and tools enabled by developments in the robust analysis of engineering ideation performance, and neurocognitive responses to creativity.

In this paper, we present an experiment on creative language processing, using the Event-Related brain Potentials (ERP) technique (funded by Core R&D Programs). ERPs are derived from Electroencephalography (EEG) recordings that measure variations in electrical activity produced by large populations of brain cells by electrodes placed in key positions on the scalp. ERPs are derived from the large amplitude EEG through a filtering and averaging process, and reflect regularities in electrical brain activity that are time-locked to an external event (for example, a sound or a word). ERPs provide a millisecond-by millisecond record of the brain's electrical activity during mental processing as it unfolds over time. As will be explained in more detail below, specific ERP components can be identified that index a particular cognitive process associated with the processing of this external event. We collected ERP responses to literal, nonsense, and novel metaphorical sentences that were either referring to engineering knowledge or general knowledge, testing engineering and non-engineering students. Following Rutter et al. [1], sentences differed in verb only and had been classified in prior sentence norming studies as highly unusual and highly appropriate (novel metaphors), low unusual and highly appropriate (literal sentences), and highly unusual and low appropriate (nonsense sentences). Participants read sentences while their EEG was recorded, and after reading the sentence made judgments about its unusualness and appropriateness. The findings indicate that prior knowledge modulates novel metaphor processing at the stage of lexico–semantic access, indexed by the amplitude of N400 component. Specifically, N400 amplitudes to novel metaphorical sentences are significantly reduced and pattern with literal sentences in engineers; in nonengineers, by contrast, we observed increased N400 amplitudes to novel metaphorical sentences that pattern with anomalous sentences. This mirror effect on the N400 corroborates recent findings demonstrating a strong impact of prior experience and expertise on meaning ambiguity resolution, which may in turn have implications for creative cognition.

1. Introduction and Motivation

The impact of traditional engineering education on the divergent thinking and creative potential of future engineers has been a concern for many scholars over the years. Divergent thinking is the creative process involved in exploring many possible solutions, whereas convergent thinking involves using logical validity to find a single, correct answer to a problem. Although divergent and convergent thinking are required for innovative solutions in engineering design, many argue that typical engineering curriculum has significant deficiencies in enhancing divergent thinking capabilities of students. Creative production is often correlated to divergent thinking to produce

many different ideas; hence, for the engineering education domain, design learning presents opportunities to enhance divergent thinking. As Liu and Schonwetter [2] put it: “Since creativity emanates from problems, it seems more natural for engineering students to gain creativity through practice of problem solving.”

Engineering design courses provide a problem solving setting for students to practice divergent thinking. Engineering design learning is thought to have a three-pronged foundation [3]: 1) design process knowledge, 2) design analysis knowledge, and 3) creative processing ability (ideation). Design process knowledge, in general, is taught in freshman design courses at American universities, and then practiced during senior capstone design. During sophomore and junior courses, the engineering curriculum focuses on analytical concepts and techniques ultimately intended to support design analysis ability. During these sophomore and junior level courses, students’ engineering knowledge and vocabulary increase. These courses also allow students to focus on their convergent thinking, which focuses on determining the single best, or correct answer to a well-defined question. Senior capstone experience is seen as a venue to showcase students’ preparedness for problem solving as they tackle problems presented by industrial clients.

Overcrowded and sequential nature of typical engineering curriculum, in general, leaves little to no room beyond design experiences to practice divergent thinking. Divergent thinking is generally associated with ideation, and refers to the process of generating diverse and original ideas with fluency and speed. Even during design experiences, neither the importance of creativity nor various methods to boost it is covered, leaving students mostly on their own for a limited duration for “brainstorming”. However, creativity and originality are among the most significant skills employers want today; and they are also projected to be in demand in years to come (see Figure 1).

Today, 2018	Trending, 2022
Analytical thinking and innovation	Analytical thinking and innovation
Complex problem-solving	Active learning and learning strategies
Critical thinking and analysis	Creativity, originality and initiative
Active learning and learning strategies	Technology design and programming
Creativity, originality and initiative	Critical thinking and analysis
Attention to detail, trustworthiness	Complex problem-solving
Emotional intelligence	Leadership and social influence
Reasoning, problem-solving and ideation	Emotional intelligence
Leadership and social influence	Reasoning, problem-solving and ideation
Coordination and time management	Systems analysis and evaluation

Figure 1. A Comparison on Skills Demand – 2018 vs. 2022 (The Future of Jobs Report, 2018, pp.12 [4])

To a certain extent, this rather ad hoc approach to creativity is due to a lack of knowledge on the cognitive and neural mechanisms underlying divergent thinking, and creative ideation more generally. In their extensive review of the literature on the cognitive neuroscience of creativity,

Fink and Benedek [5] note that "this field is only at the beginning of a long search for potential cognitive and neural mechanisms underlying this multifaceted mental ability domain" (p. 112).

New experimental approaches need to be designed and developed to better understand cognitive and neural mechanisms associated with different aspects of divergent thinking. In this paper we present an experiment using the Event-Related brain Potentials (ERP) technique and creative language use. More specifically, we collected ERP responses to literal, nonsense, and novel metaphorical sentences that were either referring to engineering knowledge or general knowledge, testing engineering and non-engineering students. The presented approach exploits the fine-grained temporal resolution of electroencephalography (EEG) to study brain activity patterns associated with language processing and prior knowledge on creative outcomes.

In the next section we present a brief review of literature on effects of prior knowledge on creativity, cognitive neuroscience to understand creativity, along with associations between language processing and divergent thinking. The experimental design is presented in the next section, followed by data collection, analysis and discussion.

2. Literature Review

2.1 Studies in creativity and topical knowledge

Creativity, in broad sense, has been an important topic of research for many domains. While some strived to define it and recognize individuals with high levels of creativity, some others studied its manifestations across different professions and disciplinary boundaries. In general, however, it is difficult to study outcomes of divergent thinking, or creativity, without considering the prior knowledge and expertise of the person. In fact, tying the knowledge to the act of divergent thinking, Simon argues that: “Creative people have stored in memory a great deal of information about the domain of creativity, assembled through a decade or more of effort, and indexed by patterns that can be recognized in the situations that arise in the creative process.” [6]. In other words, what one knows may impact how one thinks about combining the knowledge for new uses. To a large extent, most studies of divergent thinking with engineering students, either compared effectiveness of different ideation tools, or considered various aspects of the person, problem, process or the context for the implications on behavioral outcomes, but did not compare differences in creative outcomes in significantly different cohorts.

2.2 Cognitive neuroscience techniques to understand creativity

Cognitive neuroscience uses different techniques to study the brain in action, and each technique has specific characteristics that make a technique optimal (or suboptimal) for a given research question. Hemodynamic neuroimaging techniques such as functional magnetic resonance imaging (fMRI) or positron emission tomography (PET) have high spatial resolution, but poor temporal resolution (at best several hundreds of milliseconds), because of the slow nature of the hemodynamic response (e.g., the blood-oxygen-level dependent (BOLD) signal in fMRI). Electrophysiological techniques such as electroencephalography (EEG) provide a direct measure of neural activity and have a high temporal resolution of 1 millisecond precision (but poor spatial resolution). EEG is optimal for the analysis of time-related brain activity and enables fine-grained temporal analyses of brain activation patterns associated with creative cognition and divergent thinking [5].

Two widely used EEG techniques are: (1) the assessment of changes in spectral power in different EEG frequency bands, and (2) the analysis of Event-Related brain Potentials (ERPs). With the first technique, task- or event-related power changes can be quantified by contrasting the power in a given frequency band during a cognitive task with a preceding reference interval; power decreases from a reference to an activation interval are termed event-related desynchronization and power increases are referred to as event-related synchronization. Event-related desynchronization and synchronization of the alpha band frequencies have been found to be especially sensitive to cognitive task performance and higher cognitive abilities such as memory [7], language processing [8, 9], and creative idea generation [10]. Importantly, EEG alpha power has been found to vary as a function of creativity-related task demands and the originality of the idea as well as individuals' creativity level and openness to new ideas. EEG alpha power has also been found to increase after interventions aiming to enhance creativity [5]. The second technique, Event-Related Potentials (ERPs), are derived from the EEG and represent voltage changes in electrical brain activity that are time-locked to an external event like the presentation of a stimulus word [11-13]. ERPs provide a millisecond-by-millisecond record of the brain's electrical activity during mental processing, and can be used to index ongoing cognitive processes as they unfold over time. ERP components are characterized by polarity, latency, amplitude, topographic scalp distribution, and a functional description of the cognitive processes they are assumed to index. The ERP component that is most relevant to the present study on creative language use and the processing of literal, nonsense, and novel metaphorical sentences is the N400. The N400 ERP component is a negative-going waveform beginning about 300 ms post-stimulus and reaching its maximum around 400 ms post-stimulus and has a centro-parietal distribution. The N400 is frequently studied in research on language processing and indexes lexical-semantic integration [14], but modulation of the N400 has also been found in creative thinking tasks, in particular conceptual expansion [15]. In the present project, we use the ERP technique to investigate conceptual expansion by means of novel metaphor comprehension. Specifically, we look at how individuals with and without expertise in engineering process novel metaphorical compared to literal and anomalous expressions that relate to engineering and to general knowledge. This paradigm will enable us to explore the impact of prior knowledge and expertise on creative processes in the context of engineering.

2.3 Language processing and divergent thinking

Recent neurophysiological research has investigated the relationship between language and creativity by looking at individuals' brain signatures when they read or produce novel metaphorical expressions [1, 16-18]. Novel metaphors are believed to be a prime example of creative thinking in language use. This is partly because novel metaphor comprehension and production rely on *conceptual expansion*, i.e., the ability to 'stretch' the limits of one's conceptual space to include new features and exemplars [19], which is argued to be one of the core cognitive operations driving creative thinking, underlying both convergent and divergent thinking. Indeed, to arrive at the metaphorical understanding behind a sentence "the metals were married into a weld," we need to integrate two relatively distant concepts, 'metal' and 'to marry', and make sense out of them.

In one of the earliest electrophysiological studies on novel metaphor comprehension, Arzouan, Goldstein, and Faust [20] asked participants to read two-word expressions that were related in meaning (e.g., burning fire), related in meaning (e.g., indirect blanket), metaphorical in meaning

(e.g., lucid mind), as well as expressions that formed novel metaphors (e.g., ripe dream). The results of the study demonstrated a gradual increase of the N400 amplitude, with smallest N400 for related word–pairs, followed by metaphorical expressions, novel metaphorical expressions, and finally unrelated word–pairs. In a later study, Lai, Curran, and Menn [21] investigated the processing of literal sentences (e.g., "The coffee you drank was warm"), conventional metaphorical sentences (e.g., "The love she gave me was warm"), novel metaphorical sentences (e.g., "The anger he felt was warm"), and anomalous sentences (e.g., "The answer they gave was warm."). Similarly to Arzouan et al. [20], this study reported most negative N400 amplitudes in response to anomalous sentences, novel metaphors, and conventional metaphors compared with literal sentences. These findings were one of the first to contribute to a growing body of evidence suggesting that the retrieval of stored conceptual knowledge about conventional and novel metaphorical expressions involves greater cognitive effort (as reflected by more negative-going N400 amplitudes) compared with literal sentences, yet not as much as compared with anomalous sentences (for similar findings, see [18, 22-24]).

In most psycholinguistic experiments that explore phrase or sentence comprehension, participants are asked to make judgments about whether or not a word–pair or a sentence makes sense. Coming back to our previous example, when presented with a sentence "the metals were married into a weld" a participant would be asked to make a binary, yes/no judgment about the meaning of that sentence. However, when studying creative language comprehension it would be beneficial to tap into individual differences in participants' perception of the creative potential of presented sentences. To this end, Rutter et al. [1] employed a novel experimental design and asked their participants to make yes/no judgments about the originality (unusualness) and appropriateness (sensicality) of literal, novel metaphorical, and anomalous sentences. In this paradigm, literal sentences are categorized as highly usual (unoriginal) and highly appropriate (sensical), novel metaphorical sentences as highly unusual (original) and highly appropriate (sensical), while anomalous sentences as highly unusual (original) and highly inappropriate (nonsensical); see Table 1. Participants' electrophysiological data were thus analyzed according to participants' subjective evaluation of the sentences and focused on the N400 component. The results of the study demonstrated a previously reported gradual modulation of the N400 component, with the least negative N400 amplitudes to literal sentences, followed by novel metaphorical sentences, and anomalous sentences. The reported trend of intermediate N400 amplitudes for novel metaphorical expressions is thought to reflect greater cognitive effort required to map distant concepts conveyed by the metaphors.

Sentence type	**Originality/Usualness**	**Appropriateness/Sensicality**
Literal sentences	unoriginal/highly usual	highly appropriate /sensical
Metaphorical sentences	original/highly unusual	highly appropriate /sensical
Anomalous sentences	original/highly unusual	highly inappropriate/nonsensical

Table 1. Characteristics critical sentences (literal, metaphorical, anomalous) used in the experiment.

The present study builds on Rutter et al.'s [1] study with an aim to extend our current understanding on how the creative potential may be dependent on an individual's prior knowledge, with a specific focus on engineering knowledge. To this end, we asked engineering and nonengineering students to make yes/no judgments about originality and appropriateness of literal, novel metaphorical, and anomalous sentences referring to engineering and

nonengineering concepts while their EEG was recorded. In line with previous studies, we expected to observe a general graded modulation of the N400 to literal, novel metaphorical, and anomalous sentences for both participant groups. We also hypothesized that engineering and nonengineering students may show a different N400 modulation when processing metaphors relating to engineering and nonengineering knowledge, whereby prior knowledge of engineering would lead to decreased N400 amplitudes to novel metaphorical sentences referring to engineering concepts in the engineering students only.

3. Experimental Design and Data Collection

3.1. Participants

43 participants gave informed consent to take part in the study. 22 participants were engineering students of various majors; the remaining 21 participants did not have formal education in engineering. 7 participants were excluded from the analyses due to technical problems during EEG data recording, or excessive noise in the recorded data. In total, 36 participants (19 engineering, 17 nonengineering) were included in the analyses.

3.2. Procedure

Upon arriving to the laboratory participants were introduced to the research team, screened for eligibility criteria and asked to read the consent form and decide whether or not they agreed to participate in the study. Participants were next taken to the experimental booth in which participants were prepared for the EEG recording. Following EEG preparation, participants were familiarized with the task. They were asked to read sentences presented word-by-word on the computer screen and respond whether or not a sentence was usual (novel) in meaning and whether it was appropriate (sensical) by pressing one of two buttons. The experimental session took approximately 2 hours. After the experiment students were debriefed and received course credits.

Behavioral and electrophysiological data were collected in Van Hell's EEG lab located in the Centre for Language Science laboratory at Pennsylvania State University, USA. Stimulus presentation and behavioral response logging were operated by E-Prime 2.0 software (Psychology Software Tools, Inc.). Electrophysiological data were amplified with SynAmps2 amplifier (Compumedics Neuroscan, Inc., El Paso, Texas) and recorded at a rate of 500 Hz from 32 Ag/AgCl active ActiCAP electrodes (for more details on procedures related to EEG preparation and signal acquisition, see, for example, [25, 26]). Electrophysiological data were analyzed using in–house scripts and routines in EEGLAB [27] and ERPLAB [28] toolboxes in Matlab (Mathworks, Inc.). The preprocessing pipeline followed common recommendations for electrophysiological analyses (cf., [29, 30]).

3.2. Stimuli

In this study we investigate how engineering and nonengineering students process sentences that relate to engineering or general knowledge, with a particular emphasis on novel metaphorical sentences that tap into creative cognition. To this aim, a set of sentences, half referring to engineering and half to general knowledge, were included in the study. Sentences referring to general knowledge were taken from Rutter et al.'s [1] study and adapted into English by a highly proficient German–English bilingual. Both engineering and general sentences were further classified into literal (e.g., The wind *moved* the turbine), novel metaphorical (e.g., The wind

tickled the turbine), and nonsensical sentences (e.g., The wind *ate* the turbine) based on prior norming studies. The meaning of the sentence, i.e., whether it is literal, metaphorical, or anomalous, was determined by the verb only so that the sentence context (engineering or general) remained the same across conditions.

4. Data Analysis and Results

Electrophysiological responses were time-locked to the verb (mid-sentence position) and the last word (final sentence position) in a sentence, to obtain brain signatures of sentence processing at the relative early and yet incomplete stage of sentence comprehension (mid–sentence position) and the later stage at which sentences reach a more complete meaning analysis (final–sentence position). The latter stage is particularly important in the analysis of novel metaphorical sentences given that the metaphor is not fully resolved until the presentation of the last word in a sentence.

Our first result taking into account both groups of participants and both types of knowledge demonstrated a graded N400 amplitude with the least negative N400 to literal sentences, followed by novel metaphorical sentences, and literal sentences. Critically, between group comparisons revealed differences in the way engineers and nonengineers processed the sentences. In the engineering students, N400 amplitudes to novel metaphorical sentences patterned with the literal sentences, while in the nonengineering students N400 amplitudes to novel metaphorical sentences patterned with the anomalous sentences. We did not find an interaction between the sentence type and prior knowledge, i.e., no difference was observed in how engineering and nonengineering students processed sentences relating to engineering and nonengineering knowledge.

5. Discussion

This study set out to investigate the electrophysiological correlates of the impact of individual's prior knowledge of engineering on their processing of literal sentences, novel metaphorical sentences, and anomalous sentences referring to engineering and nonengineering. Our particular focus was on the processing of novel metaphorical sentences that are known to provide a window onto creative cognition, and reflect individuals' creative thinking. The result of our study support previous electrophysiological evidence demonstrating a gradual N400 amplitude modulation, with the least negative N400 to literal sentences followed by novel metaphorical sentences, and anomalous sentences (cf., [1, 17, 18, 20, 21]). The N400 component indexes lexical-semantic integration [14], and higher N400 amplitudes signify that participants have a harder time integrating the critical word into the sentence context. Our findings indicate that, for both engineering and non-engineering students, lexical-semantic integration of the critical word in metaphorical sentences is cognitively more effortful than in literal sentences, but easier than in semantically anomalous sentences.

Critically, while we did not find differences in how engineers and nonengineers processed sentences referring to engineering and nonengineering, we observed an inter–group difference in the general pattern of responses to the sentences. Specifically, engineers demonstrated decreased N400 amplitudes to novel metaphorical sentences and literal sentences compared with anomalous sentences. By contrast, nonengineers displayed increased N400 amplitudes to novel metaphorical expressions and anomalous sentences compared with literal sentences. We believe that these differences in the processing of novel metaphorical expressions,

reflecting creative thinking, between the engineering and nonengineering participant groups could be accounted for by differences in participants' prior knowledge and experience. In a series of experiments, Rodd et al. [31] found that recent as well as long-term linguistic experiences have a profound effect on how individuals interpret ambiguity in language. For example, in one of their experiments recreational rowers were statistically more likely to come up with rowing–related associations to words that shared a rowing–related meaning (e.g., 'square' or 'feather') if they had rowed recently and/or if they had long–term rowing experience. In the same vein, in a series of two experiments, Wiley, George, and Rayner [32] demonstrated that prior knowledge can have an influence on meaning ambiguity resolution and delays semantic access of non–dominant meanings when the dominant meaning is biased by the readers' prior knowledge. Relating these findings to our study, engineering students had at their disposal knowledge and experiences related to engineering as well as general knowledge about the world. This–we would argue–resulted in quicker semantic access and resolution of ambiguity created by novel metaphorical experiences relating to both engineering and nonengineering knowledge, hence the observed general decrease in N400 amplitudes to novel metaphorical sentences (signifying creative cognition). By contrast, nonengineering students, with little to no experience in engineering, found it more difficult to resolve the ambiguity of unexpected metaphor endings, which could have also affected the resolution of ambiguities in the case of sentences relating to general knowledge, thus leading to a general increase in N400 amplitudes to novel metaphorical sentences.

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