The Role of N400 Component of Event-Related Potentials in Subconscious Syntactic Processing and Conscious Semantic Representation

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A. SPECIFIC AIDS

The syntax of a human language is a set of abstract rules which constitute a computational system that defines the grammatical sentences of a language regardless of their semantic content; these sentences are intuitively well-formed to a native speaker (Chomsky, 1965; Batterink and Neville, 2013). Syntax is the study of linguistic form and grammatical structure, and semantics is the study of meaning and reference in language use (Chomsky, 1975). Electroencephalographic (EEG) studies suggest that syntactical processing may use implicit learning mechanisms and occur below the level of conscious awareness (Batterink and Neville, 2013). The biphasic event-related potential (ERP) associated with syntactical violations consists of an early negativity and a late positivity (Batterink and Neville, 2013). A cross-modal distraction task, during which an auditory tone is paired with a visually presented syntactical violation, revealed that only consciously detected syntactic violations elicit both phases of the ERP; undetected syntactical violations exhibited no late positivity (Batterink and Neville, 2013). On the semantic side, a recent study by Frankland and Greene (2015) claimed to identify subregions of the left mid-superior temporal cortex (ImSTC) that encode distinct abstract semantic variables (e.g., “Who did it?” and “To whom was it done?”) using functional magnetic resonance imaging (fMRI). We are interested in characterizing the relationship between subconscious syntactical processing and semantic processing. Theoretical linguists following Chomsky (1957, 1965, 1975) have argued for a distinction between syntax and semantics on the basis of sentences such as “Colorless green ideas sleep furiously,” which is grammatical but meaningless. Frankland and Greene (2015), however, suggest that meaning is structure-dependent on the basis of such sentences as “The baby was kicked by the grandfather” and “The grandfather was kicked by the baby;” they also cite downstream afferent processing differences associated with differences in semantic variable position. We propose that metaphor is an apt domain for cognitive neuroscience to parse the relation between syntactical and semantic processing.

As a comparison of two semantically distinct domains, nominal metaphors involve the figurative use of a noun, as in “Time is a thief” (Cardillo et al., 2010). Nominal metaphors can be transformed between the active and passive voice, a procedure which conserves its syntactic deep structure (Chomsky, 1965). However, it is unclear whether metaphoric meaning is conserved in the active-passive transformation (e.g. “Time is a thief” vs. “A thief is time”). If sentence meaning is structure dependent, the question of where meaning is derived from (deep or surface structure) is of much interest to theoretical linguists and cognitive neuroscientists. Work in the Chatterjee lab, based on findings by Bowdle and Gentner (2005), has shown that the process by which certain words take on additional and directly-accessible figurative meanings involves a qualitative shift in cognitive processing from comparison to categorization: Novel metaphor comprehension initially involves right-hemisphere semantic processing, but as metaphors become familiar, comprehension seems to be increasingly mediated by the left hemisphere (Cardillo et al., 2012). Based on work by Batterink and Neville (2013), Batterink et al. (2010), Frankland and Greene (2015), and the Chatterjee lab, we hypothesize that the N400 response to unconsciously detected syntactic violations (Batterink and Neville, 2013) and consciously detected semantic violations (Batterink et al., 2010) results from a failure to map semantic knowledge onto unconsciously generated syntactic structures.

Aim 1.1 Determine baseline ERP components of active- and passive-voice sentence structure. The goal of this study is to see if meaningful differences in ERP waveform exist between processing active- and passive-voice sentence structures. Protocol from Experiment 1 of Frankland and Greene, 2015 will be replicated, substituting EEG of the left hemisphere for fMRI. We will use a 64-channel ActiveTwo system for ERP recordings (Batterink and Neville, 2013). This study will set a baseline ERP waveform for comparison in additional studies. Aim 1.2 Determine ERP component changes of symmetric and asymmetric metaphor constituents vs. literal active- and passive-voice sentences. This study will explore how the position of semantic variables in grammatical and ungrammatical metaphors affects ERP waveform, and whether any changes in waveform index the locations of semantic or syntactic constituents. To parse the relation between syntactical structure and semantic constituent position, nominal symmetric metaphors (“The cat is a thief” ⇒ “The thief is a cat”), nominal asymmetric metaphors (“The lawyer is a shark” ⇒ “The shark is a lawyer”), and active- and passive-voice transformed literal sentences will be presented to subjects as EEG is recorded. Aim 2. Track effects of conventionalization of metaphor on semantic and syntactic expectancy. This study will attempt to index changes in ERP waveform to structure-mapping failures. Using protocol developed by Cardillo et al. (2012), participants will be taught nominal metaphors to three levels of conventionalization. Subjects will be presented with the metaphors during EEG recording, with either syntactic subject-verb agreement violations or semantic violations.
B. BACKGROUND AND SIGNIFICANCE

B.1 Introduction

Cognitive science as a discipline emerged from a storm of scientific advances in the fields of propositional logic (McCulloch and Pitts, 1943), communication theory (Shannon, 1948), computational theory (Turing, 1950), and linguistics (Chomsky, 1957). It generated an inward turn in the nascent disciplines of neuroscience and psychology toward the study of inner mental mechanisms. Outstanding debates in the field of cognitive science include (1) the relation of syntactical processing to semantic knowledge and (2) the causal-functional role of phenomenal consciousness in cognition and computation. Chalmer’s (1996) “hard problem of consciousness” has made the causal-functional role of consciousness in cognition difficult to determine. It is conceivable that a computational system could implement precisely the same computations and behavior as a conscious agent without the accompaniment of phenomenal consciousness—the “what it is like to be it” aspect of certain mental states (Nagel, 1974). For example, a machine vision system could respond to “blue” stimuli as skillfully as a human—perhaps more so—but the machine (as best as we can tell) does not “see” the blue in terms of any first-person experience. There is nothing it is like to be the machine. Why this should be so is deeply mysterious. Concerning the relation of syntax to semantics, Chomsky (1957) developed the transformational generative grammar and defined the study of linguistic form—syntax—as the study of grammatical structure. He argued that the appeal to meaning in the study of grammatical structure is most often confused for the appeal to intuitions about linguistic form (Chomsky, 1975). These “intuitions about linguistic form” are constitutive of a mature speaker-hearer’s knowledge of a language and define the “grammatical” sentences of a language, but they are not intuitions about meaning (Chomsky, 1975). Chomsky appealed to phrases such as “Colorless green ideas sleep furiously,” which have an intuitively well-formed sentence structure but no literal meaning, to indicate that syntactical processing and structure are independent of semantic considerations (Chomsky, 1957). Interestingly, the syntactical system is considered to be the core computational system of human language, and recent work has shown that syntactical processing is largely unconscious (Batterink and Neville, 2013). Conversely, within cognitive neuroscience, semantics can be defined as the study of conscious mental representations. This would be a novel and highly controversial definition, but it is not unprincipled. Could a mental representation which cannot be consciously accessed have meaning? What would we take “meaning” to mean if it did? If consciousness is a core property of semantic representation, there may be hope for understanding the role of consciousness in cognition.

B.2 Metaphor, structure mapping

The study of metaphor provides an ideal domain for parsing the relation between syntactical structure and semantic representation, on the one hand, and the role of consciousness in semantic representation on the other. Metaphors are intrinsically syntactical and semantical. Nominal metaphors, for instance, have a Nominal-Phrase*Verb-Phrase syntactic structure (see Fig. 1) and their comprehension requires extensive semantic knowledge and processing. To what extent does their semantic representation depend upon syntactic structure? A dominant paradigm for metaphor study has come from Dedre Gentner’s “career of metaphor” account, which attempts to explain how meanings arise and how representation and processing change as metaphors metamorphose from novel phrases to conventional components of the mental lexicon (Gentner et al., 2001). The “career of metaphor” account is premised on Gentner’s structure-mapping engine, a theoretical construct that posits the existence of abstract semantic variables and relations that are mapped during metaphoric (or non-metaphoric) thought to produce semantic representations (Gentner et al., 2001). Work in the Chatterjee lab using fMRI showed preliminary neural correlates for the career of metaphor.

![Figure 1. A nominal metaphor and its phrase structure tree. Nominal metaphors have the form: X is a Y. “Time” is the base (X) and “thief” is the target (Y).](image1)

![Figure 2. Structure-mapping engine and the genesis of abstract concepts via repeated metaphoric mapping. Modified from Gentner et al. (2001) Figure 6.2, this is a representation of how Jamrozik et al. (2016) proposed metaphors construct semantic representations. With repeated metaphoric mapping, only those abstract relations and systems of relations in the target which match the base will be kept; other relations and systems will be pruned.](image2)
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account: As novel metaphors are conventionalized, bilateral inferior prefrontal cortex, left posterior middle temporal gyrus, and right postero-lateral occipital cortex decrease their activity in a predictable manner (Cardillo et al., 2012). Comprehension of novel metaphors initially draws on sensorimotor information about the base, but the semantic representation of the base can be abstracted through repeated metaphor use or conventionalization (Jamrozik et al., 2016). Jamrozik et al. (2016) therefore propose that metaphor may be one cognitive mechanism that guides the development of abstract representations from underspecified placeholders. Jamrozik et al. remain agnostic about the origins of abstract concepts and the nature of the placeholders. Below, we will see that a major goal of this study is to investigate whether these abstract placeholders are subconscious syntactic structures called deep structures, formed by the syntactic component of a transformational generative grammar.

B.3 Transformational generative grammar (TGG)

TGG is a theoretical construct which generates all and only the grammatical sentences (S) of a language. Chomsky (1957, 1965, 1975) held that meaning played no part in the theory of grammatical structure. Grammars have syntactic, semantic, and phonological components, but the latter two are not involved in the generation of sentence structure (Chomsky, 1965) (see Fig. 3A). The syntactic component consists of a base (not to be confused with the metaphoric constituent “base”) and a transformational component. In the Standard Theory (Chomsky, 1965), the base generates deep structures, and the semantic component receives the deep structure generated by the base of the syntactic component to form a semantic representation. Fig. 3B proposes a Phenomenal Semantics Model of generative grammar that considers the role of conscious representations in generating meaning. If this or a similar model is correct, the neurophysiology which realizes the semantic component of the grammar will be distinct from and predictably related to the neurophysiology underlying the syntactic component.

B.4 Unconscious syntactical processing and conscious semantic representation

EEG studies of ERPs have excellent temporal resolution and are thus well-suited to research the time course of syntactic and semantic processing. Consciously detected syntactic violations produce a biphasic response, characterized by (1) an early negativity that appears 100-400 msec after stimulus presentation (known as the Left-Anterior Negativity or N100-N400) and (2) a late positivity that appears 600 msec after stimulus presentation (P600) (Batterink and Neville, 2013). Batterink and Neville (2013) showed that unconsciously detected syntactic violations only elicit the early negativity and no P600, suggesting a subconscious syntactical role for the early negativity and a conscious semantic role for P600. Paradoxically, the N400 component of an ERP is also a known marker of semantic expectancy. An attentional blink study by Batterink et al. (2010) found that semantic errors which reached conscious awareness elicited N400, and that semantic errors which did not reach conscious awareness elicited no such response. Therefore, the N400 is elicited during conscious semantic errors and unconscious syntactic errors.

Figure 3. The standard theory of transformational generative grammar and proposed phenomenal semantics model. A) Adapted from Figure C-1, (Winograd, 1983). The Standard Theory is the model of generative grammar introduced in Chomsky (1965). B) In the proposed Phenomenal Semantics Model, the base rules of the syntactic component generate a deep structure in parallel to a conscious representation which is mapped into the deep structure. Those components of the conscious representation which can map into the deep structure are deemed meaningful and are conserved in the transformation rules. The output is a semantic representation: a syntactically structured conscious representation. The juxtaposition of the surface structure against the initial conscious representation in the semantic representation indicates context-dependence for phenomenal semantics.


C. RESEARCH DESIGN AND METHODS

C.1. Aim 1: Determine baseline ERP components of active and passive sentence structure.

C.1.a. Hypothesis: We hypothesize that active and passive sentence structure will not elicit differences in ERP waveform at N400. Operating on the model that a transformational generative grammar is subconsciously constructing deep structures, and that N400 is elicited during mapping errors of the structure-mapping engine from the conscious representation of the sentence to its deep structure, there is no reason a transformation from active to passive voice should significantly change the ERP waveform.

C.1.b. Background and rationale: Recently, Frankland and Greene (2015) claimed to identify two distinct subregions of the left mid-superior temporal cortex (lmSTC) that represent distinct abstract semantic variables. Subjects undergoing fMRI were asked to read sentences describing simple events, conveyed in either the active or passive voice (Frankland and Greene, 2015). The reciprocal of each active-voice sentence was a passive-voice “mirror image proposition” with the same syntactic deep structure but different surface structure (Chomsky, 1965) and sentence-level meaning (Frankland and Greene, 2015). The goal of this experiment is to test a key assumption of Frankland and Greene (2015)—that active and passive sentence forms are equivalent in terms of processing. The N400 is elicited in response to syntactic and semantic expectancy violations (Batterink and Neville, 2013). Thus, we do not expect to see it elicited here, where there are no such violations.

C.1.c. Methods:

C.1.c.i. Participants: Total of 24 right-handed native English speakers without history of neurological or psychiatric symptoms (evenly split between M and F, ranging between 18 and 30 years of age) will be recruited for this study from the Philadelphia community. Participants will give written consent and complete demographic surveys in accordance with the Institutional Review Board of the University of Pennsylvania.

C.1.c.ii. Experimental tasks and stimuli: Using stimuli and protocol developed by Frankland and Greene (2015), we will visually present sentences from Table S1 (Frankland and Greene, 2015) using E-Prime 2.0 for 2.5s followed by 7.5s of fixation. Each sentence will be presented twice within a given block with the following constraints: Each sentence will appear 26 times over the course of a trial block, and no sentence will ever successively follow its mirror image proposition pair or itself (Frankland and Greene, 2015). Four mirror image proposition pairs will have low negative emotional valence and will be morally unobjectionable, according to a norming procedure conducted on Amazon Mechanical Turk, where two mirror image proposition pairs were judged to be asymmetrically morally wrong, depending on the agent of the sentence (Frankland and Greene, 2015). Whether a proposition is presented in active or passive voice will be random for a given trial (Frankland and Greene, 2015). Nonword strings matched to stimuli in terms of letter frequency and length will occur in a third of trials as a control for baseline levels of activation related to stimulus presentation.

C.1.c.iii. ERP recording and analysis: We will record EEG data during the reading task, at a sampling rate of 1024 Hz from 32 Ag/AgCl electrodes attached to an electrode cap (Batterink and Neville, 2011). Electrodes will be positioned according to the 10/20 system, with placement of adjacent electrodes at fixed distances from four anatomical landmarks (nasion, inion, and preauricular points) in steps of 10 or 20% to account for differences in head size (Herwig et al., 2003). Recordings will be performed with the 64-channel ActiveTwo system (Batterink and Neville, 2013). ERP analyses will be conducted using EEGLAB. Trials containing large artifacts will be identified and removed from further analysis (Batterink and Neville, 2013). ERP amplitudes will be averaged across adjacent electrodes to form multiple channel groups. Visual inspection of the data will determine N400 time windows (early and late) for statistical analysis (Batterink and Neville, 2013). Repeated measures ANOVA will be used to determine if ERP waveform is statistically different between the active and passive conditions, when the position of semantic variables is altered, and when sentence meaning is morally unobjectionable.

C.1.d. Expected results and pitfalls: If a single deep structure is successfully being transformed to yield both active and passive sentence structures, then there should be no significant difference between them. There may be differences, however, between the negative-valence/morally-wrong sentences vs. neutral-valence/morally-unobjectionable sentences of the same type (active or passive). It would be surprising if those differences were N400 or P600 related, as there are no syntactic or semantic violations occurring in this study. Pitfalls may include the appearance of unexpected N400 or P600 or artifacts from equipment failure. For this reason, the stimuli will be normed according to protocol in Cardillo et al. (2010), so matching stimuli can be developed and the experiment repeated.

C.1.e. Future directions: Studies of metaphor comprehension by patients with focal lesions have shown that left-lateralized lesions more strongly impair metaphoric than literal sentence comprehension (Cardillo et al., 2014). This would corroborate the claim that the neural architecture described by Frankland and Greene (2015) tracks structure-dependent semantic variables because more semantic knowledge is required for metaphoric compared to literal
sentence comprehension. This task can be modified to function as a behavioral study, testing whether patients with lesions in leftSTC can track abstract semantic variables.

C.1.2. Aim 1.2 Determine ERP component changes of symmetric and asymmetric metaphor constituents vs. literal active- and passive-voice sentences.

C.1.2.a. Hypothesis: N400 will only be elicited by inverted asymmetric metaphors. Based on the model in Fig. 3B, we propose that N400 indexes failures of the structure-mapping engine. Symmetric metaphors generate distinct but meaningful semantic representations. Active- and passive-voice literal sentences have meanings. All these sentences are grammatical. Asymmetric metaphors which are inverted (the target is mapped to the base) have no discernible meaning because of the position of semantic variables within the syntax. Therefore, a failure of meaning in an asymmetric inverted metaphor is a failure of structure-mapping.

C.1.2.b. Background and rationale: Nominal metaphors are composed of a base and target, two semantic variables which change the meaning of the metaphor based on their position. Symmetric metaphors are meaningful and grammatical when the two semantic variables are switched. Asymmetric metaphors are grammatical but not meaningful if the target and base are switched ("The lawyer is a shark" vs. "The shark is a lawyer"). Active and passive voice is a grammatical transformation which conserves syntactic structure (Frankland and Greene, 2015). If N400 is elicited due to failure in structure-mapping (see Fig. 3), then it should be elicited when meaning fails to map onto syntactic structure ("The shark is a lawyer"), compared with a meaningful metaphor with the same semantic variables ("The lawyer is a shark") and a matched literal sentence ("The shark ate a lawyer") or its active/passive transformation ("The lawyer was eaten by a shark").

C.1.2.c. Methods:

C.1.2.i Participants: Subjects recruited for Aim 1.1 will participate in this study (see C.1.c.i above).

C.1.2.c.ii Experimental tasks and stimuli: Asymmetric and symmetric nominal metaphors will be selected from the stimulus set in Cardillo et al., 2010 or generated and normed using their protocol. The metaphors will be paired with a literal sentence based on a battery of semantic and structural variables. All literal sentences will be normed on the same dimensions as the metaphors used in this study; in this way, literal sentences will serve as robust controls (Cardillo et al., 2010). The metaphors will be presented visually in pseudo-random order using E-Prime 2.0 for 2.5s followed by 7.5s of fixation. The pseudo-random order will be constrained such that no metaphor immediately follows its symmetric or asymmetric partner, and such that no sentence follows a metaphor to which it is paired. Each sentence will be presented once.

C.1.2.c.iii ERP recording and analysis: We will record EEG data and analyze ERP data as above (see C.1.c.iii). Repeated measures ANOVA will be used to determine if ERP waveform is statistically different across symmetric and asymmetric metaphors, target-base inverted symmetric and asymmetric metaphors, and literal active- and passive-voice sentences.

C.1.2.d. Expected results and pitfalls: We expect to see the N400 ERP response in base-target inverted asymmetric metaphors relative to all other conditions. We do not expect an effect from active/passive voice. One pitfall could be content-based; without proper care in stimulus selection, some active/passive literal sentences may be morally objectionable or semantically memorable in a way the metaphors are not (e.g., "The lawyer was eaten by the shark").

C.1.2.e. Future directions: One of the primary areas of study for the Chatterjee lab is the neurophysiology of event and spatial representation. Behavioral studies of asymmetric metaphors which can only describe an event in one direction may shed light on the relation of syntax to other domains of thought.

C.2. Aim 2. Track effects of conventionalization of metaphor on semantic and syntactic expectancy.

C.2.a. Hypothesis: The N400 ERP component will be elicited more strongly by syntactic violations of conventionalized metaphors than by semantic violations; and the N400 ERP component will be elicited more strongly for semantic violations of novel metaphors than syntactic violations.

C.2.b. Background and rationale: Novel metaphoric mappings initially draw on sensorimotor systems for comprehension (Jamrozik et al., 2016). As metaphors become familiar, comprehension seems to be increasingly mediated by the left hemisphere (Cardillo et al., 2012). Jamrozik et al. (2016) proposed that metaphor guides the development of abstract concepts by repeated mappings of various bases to target. Nominal metaphors have a NP^VP syntax (see Fig. 1). Deep structures may be the "underspecified placeholders" which Jamrozik et al. (2016) proposed as the source of new concepts. The N400 ERP component has been shown by Batterink and Neville (2013) to be associated with unconscious syntactic error processing and by Batterink et al. (2010) to be involved with conscious semantic error processing. This could mean the N400 is an electroencephalographic marker of errors in the structure-mapping process by which repeated metaphoric mapping builds semantic representations. If this were so, novel metaphors whose deep structures are not strongly mapped to meanings would be more likely to elicit N400 during semantic error processing.
Conventionalized metaphors, on the other hand, would elicit the N400 more strongly when a syntactical failure is detected, as the meaning of the known metaphor fails to map at the syntactic level.

C.2.c. Methods:

C.2.c.i Participants: Total of 24 right-handed native English speakers without history of neurological or psychiatric symptoms (evenly split between M and F, ranging between 18 and 30 years of age) will be recruited for this study from the University of Pennsylvania community. Participants will give written consent and complete demographic surveys in accordance with the Institutional Review Board of the University of Pennsylvania.

C.2.c.ii Experimental tasks and stimuli: Stimuli will be chosen from the set of nominal metaphoric sentences generated and normed by Cardillo et al. (2010) and modified so the target is no longer in subject-verb agreement. Using protocol from Cardillo et al. (2012) participants will randomly be sorted into three conditions: novel, familiar, and conventional; they will not learn ungrammatical metaphors. Participants will be asked to make various semantic judgements before testing to ensure semantic processing (Cardillo et al., 2012). Participants will receive several practice trials of the reading task, which will consist of reading the complete set of metaphors and answering comprehension questions following some percentage of items (to ensure attention and reading for content) (Cardillo et al., 2012). The metaphors will be presented visually in pseudo-random order using E-Prime 2.0 for 2.5s followed by 7.5s of fixation. The metaphors will also be paired with a base from a distinct semantic domain, which will be interchanged on a fourth of trials. The pseudo-random order will be constrained such that no metaphor immediately follows its syntactically modified partner, or its base-substituted partner.

To control for increases in reading speed unrelated to metaphor familiarization (a potential confound), we will ask a control group of participants to press any key on the keyboard when finished reading the metaphor (Cardillo et al., 2012). This way, we will be able to calculate the average reading rate for each metaphoric statement at all levels of familiarity (Cardillo et al., 2012). We expect that familiar and conventional metaphors will be read significantly faster than novel ones.

C.2.c.iii ERP recording and analysis: We will record EEG data during the reading task via the 64-channel Active Two system, at a sampling rate of 1024 Hz from 32 Ag/AgCl electrodes attached to an electrode cap (Batterink and Neville, 2011). Electrodes will be positioned according to the 10/20 system. ERP analyses will be conducted using EEGLAB. Repeated measures ANOVA will be used to determine if ERP waveform is statistically different across the three familiarity conditions for violations of syntactic and semantic expectancy (base-substitution).

C.2.d Expected results and pitfalls: To account for empirical results regarding response time during early stages of metaphor comprehension, Gentner et al. (2001) highlight a model for metaphor comprehension where alignment of abstract relations and systems of relations occurred prior to an emergent abstracted representation. This motivates the career of metaphor account (Bowdle and Gentner, 2005), where metaphors are slowly bleached of their sensorimotor content as repeated mappings are made between its target and various bases. Thus, we expect that if the structure-mapping engine is mapping conscious representations to deep structures, then syntactical violations of metaphors whose meaning is more conventionalized--more abstract, and thus more tied to deep structure--will be more likely to elicit the N400. In contrast, novel metaphors will be more likely to elicit the N400 in response to semantic errors, as Cardillo et al. (2012) found that right hemisphere semantic processing areas are initially recruited during metaphor comprehension and are slowly tuned as the metaphors become conventionalized. One pitfall may concern failure to successfully conventionalize subjects with the provided metaphors, as a result of which observed N400 differences may not be genuine. Should this be the case, we will revise our metaphor conventionalization protocol, which currently relies on the manipulation of participant familiarity with new metaphors (Cardillo et al., 2012).

C.2.e. Future directions: Lesion studies are an important complement to EEG and fMRI work and form part of the backbone of the Chatterjee lab’s work. It would make sense to find left temporal cortex and right postero-lateral occipital cortex lesioned patients and perform this same task with the lab. Will novel metaphors be mapped properly if the neural architecture underlying syntactic structure generation is intact but the initial semantic processing is damaged?
References:


