

**Event-Related Potential Additivity as an Index of Overlap in
Neurocognitive Resources**

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Abstract

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Scalp-recorded event-related potentials (ERPs) are poorly suited for source analysis. Consequently, it is difficult to assess the relative neural independence of two ERP waveforms using such methods. We report here an alternative method grounded in Helmholtz's Rule of Superposition, which stipulates that electrical fields summate where they intersect in time and space. Subjects read sentences that contained a word with one or two unexpected features. The similarity of the two features was systematically manipulated. We then compared ERPs elicited by the doubly anomalous words to composite waveforms formed by mathematically summing the ERP response to singly anomalous words. We quantified the independence of the neural response to the two stimulus features by applying a novel Additivity Index (ranging from -1 to 1). The computed Additivity Index value varied with presumed feature similarity, indicating that the index provides a valid and general method for quantifying the neural independence of scalp-recorded brain potentials.

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DEDICATION

To Charles Darwin and Hermon Von Helmholtz

CHAPTER 1: BACKGROUND

Introduction

This dissertation will describe and apply a novel method for examining neurocognitive modularity through the use of event-related potentials (ERPs), which we will refer to as the Additivity Index (AI). The AI reflects the relative independence of the neural sources underlying the processing of individual stimulus features, and ranges from -1 to 1. The range from 0-1 captures the independence of processing, 0 reflecting a perfectly non-additive function and complete overlap of the neural processors, and 1 reflecting perfect additivity and complete independence of processing. Additionally, the range from -1 to 0 reflects perfect dependence (overlap in processors) and describes the relative inhibition of the processing of one feature by the processing of a second feature.

Although the Additivity Index is novel in its application of quantified differences in additivity to electrophysiological measures, in this case ERPs, additivity has been used as a tool for assessment of cognition for over a century and a half, and was initially described in publication by Donders (1868). This dissertation will describe the uses for and issues associated with additivity in the electrophysiological domain.

In order to demonstrate the validity of the Additivity Index, three experiments will be reported that were conducted to test a putative continuum of similarity of stimulus features with respect to their independence. The AI values obtained from these three comparisons were .20, .42, and .85, which represent the most similar, semi-similar, and most dissimilar stimulus feature pairs, respectively.

These values strongly suggest that the AI is indeed a valid measure of independence in neural processing, and does, in fact, reflect the degree to which two stimulus features engage overlapping neurocognitive resources, thus validating the AI as a powerful tool for exploring neural modularity.

We also carried out two experiments in which we applied the Additivity Index to the processing of linguistic (morpho-syntactic) features in Italian, in native speakers of Italian. We will use the results to illustrate the limitations of the AI, as well as the interpretation of negative values. Finally, we will discuss possible future avenues of research that would be aided by the application of the Additivity Index, as well as ways the AI can be modified in order to make it more appropriate for investigations within other domains.

Scalp-recorded event-related potentials (ERPs) are poorly suited for source analysis (Luck, 2005). Consequently, it is difficult to assess the relative neural independence of two ERP waveforms using such methods. We report here an alternative method grounded in Helmholtz's Rule of Superposition (Kahl, 1971), which stipulates that electrical fields summate where they intersect in time and space. Subjects read sentences that contained a word with one or two unexpected features. The similarity of the two features was systematically manipulated. We then compared ERPs elicited by the doubly anomalous words to composite waveforms formed by mathematically summing the ERP response to the two singly anomalous words. We quantified the independence of the neural response to the two stimulus features by applying a novel Additivity Index (ranging from -1 to 1). The computed Additivity Index value varied with presumed feature similarity,

indicating that the index provides a valid and general method for quantifying the neural independence of scalp-recorded brain potentials.

General Background

One approach to determining the cognitive architecture of a given response to a stimulus is to examine how changes to specific aspects of the stimulus or the required response affect the response time. It is assumed that all high-level cognition involves a series of discreet, or semi-discreet, sub-processes; cognitive architecture simply refers to the nature and relationship of the stages of processing underlying stimulus input and the cognitive chain of events it evokes—whether the processes are serial, parallel, or some combination of the two; whether they interact; and what factors influence stages of processing.

One method that has been used to examine the neuro-cognitive architecture underlying a given cognitive process is the additive factors method (Sternberg, 1969; Schweickert, 2001). In order to avoid confusion due to the contradictory uses of terms in Schweickert (2001), the following terms will be defined for use in this dissertation: the term ‘behavioral task’ will be used to refer to the total response demands placed upon a subject during an individual trial although it does not necessarily include an overt action. For instance, a behavioral task could be to passively sit and listen when there was no stimulus presented. The term ‘cognitive task’ refers specifically to the sum of all of the processing that occurs in response to a specific behavior. The term ‘factor’ refers to a specific change in some variable that is thought to have an impact on a cognitive task. A ‘cognitive event’ or ‘stage’ of

processing is any portion of processing involved in a cognitive task; it does not imply that it is necessarily discreet, nor does it indicate its relationship to other stages of processing. Furthermore, a stage of processing will itself be made up of multiple sub-stages of processing, which, for simplicity's sake, will simply be referred to as 'stages,' as one can get endlessly reductionist in the description of stages. Indeed, even the firing of a single cell necessary for the processing of a cognitive event can be reduced further to the various stages of the electro-chemical changes necessary to produce an action potential, which is well beyond the scope of what additive factors methodology seeks to address.

The main goal of the additive factors method is to determine the nature of the relationships between various stages of processing. It allows the examination of cognitive processes and attempts to describe, at varying levels of complexity, the relationship between the sub-stages of which they are comprised, as well as the factors that variously influence them. These relationships describe the cognitive architecture of the process.

Consider a certain variable that selectively influences¹ (cf. Schweickert 2001) a certain stage of a cognitive process (e.g., the amount of time necessary for its processing) and a second variable that selectively influences a second stage in processing. If both variables are modified and the effects of the two variables sum, then it can be inferred that these two stages are discreet and serial. A simple example of this is proposed by Dehane (1996) in a reaction time (RT) study in which subjects were asked to compare the relative value (larger or smaller) of a target

¹ i.e., influences only that stage and not others in the cognitive process

number to the number to 5, and respond as quickly as possible. A three-stage model for the cognitive processing necessary for this behavioral task was proposed: 1) stimulus evaluation, 2) magnitude comparison, and 3) response. Three factors were thought to selectively influence these three stages of processing respectively: ease of target recognizeability, numerical distance of the target from 5, and whether the subjects were responding with their dominant or non-dominant hand. It was found that each of these factors increased the RT of the subjects; furthermore, it was found that these increases in RTs mathematically summed when multiple factors were applied to the same iteration of the task. This was taken as evidence that these stages were both discrete and serial. One cannot, however, purely by using RT measures, assess which stage of processing specific factors are influencing².

Although it would seem implausible, one cannot rule out that, in the given example, ease of target discriminability was being affected by numerical distance from target rather than target recognizeability. One of the major shortcomings of the additive factors paradigm, as applied to reaction time studies, is that it cannot discriminate between the orders of serial processes, nor indicate which factor is selectively influencing which process.

Other relationships between stages of processing will yield different effects on reaction times. A truly parallel processing stream would, as in a serial architecture, yield

² This, as well as the following critiques, assumes that the various stages of an experimental procedure cannot be decomposed experimentally (i.e., certain stages cannot be left out of the procedure). In cases where stages can be omitted, then it is possible for the stages omitted to assign a specific factor to a specific processing stage. However, since it is often not possible to do so, and even when it is, it is rarely possible to do with all stages, the following critiques are made under the assumption that decomposition is not an option

increases in RTs for single factor effects only if the sum of the factor and the duration of the process it affects is larger than the duration of the process with the longest duration. Consistent with this reasoning, and as noted by Schweickert (2001), in parallel systems in which there are multiple factors simultaneously and selectively influencing stages of processing, only the stage whose duration becomes largest after factor influences will be reflected in changes in RT. Again, this leads to an inability to assign a factor to a specific stage of processing through any empirical measure, as well as an inability to evaluate the relative durations of either the processing stages without the effect of the factors, or the effect on the duration of the stages the various factors have. The one exception is the increase in duration of the stage with the longest duration before factor effects by its selectively influencing factor. Although its identity of the stage or processing remains unknown, the identity of the factor is known (see figure 1).

Also, a parallel processing architecture can lead to an inability to determine if factors are indeed having effects or whether they are having null effects. To illustrate by example: Consider stages A, B and C with relative durations of 20, 40, and 60ms, and factors 1, 2 and 3. If the increase of the duration of stage A as a result of any factor is ≤ 40 ms, or stage B is ≤ 20 ms, it cannot be determined whether it has an effect. This is true whether the factors are presented one at a time or simultaneously. There is one situation in which two factors can be determined to have an effect given the above stages and factors. If the effect of a factor on stage A is > 40 , or B > 20 ms, and the duration of factor C after the selective influence of a factor is greater than the duration of Stage A or B after its factor influence, then one can be sure of two factors causing genuine effects (see figure 1).

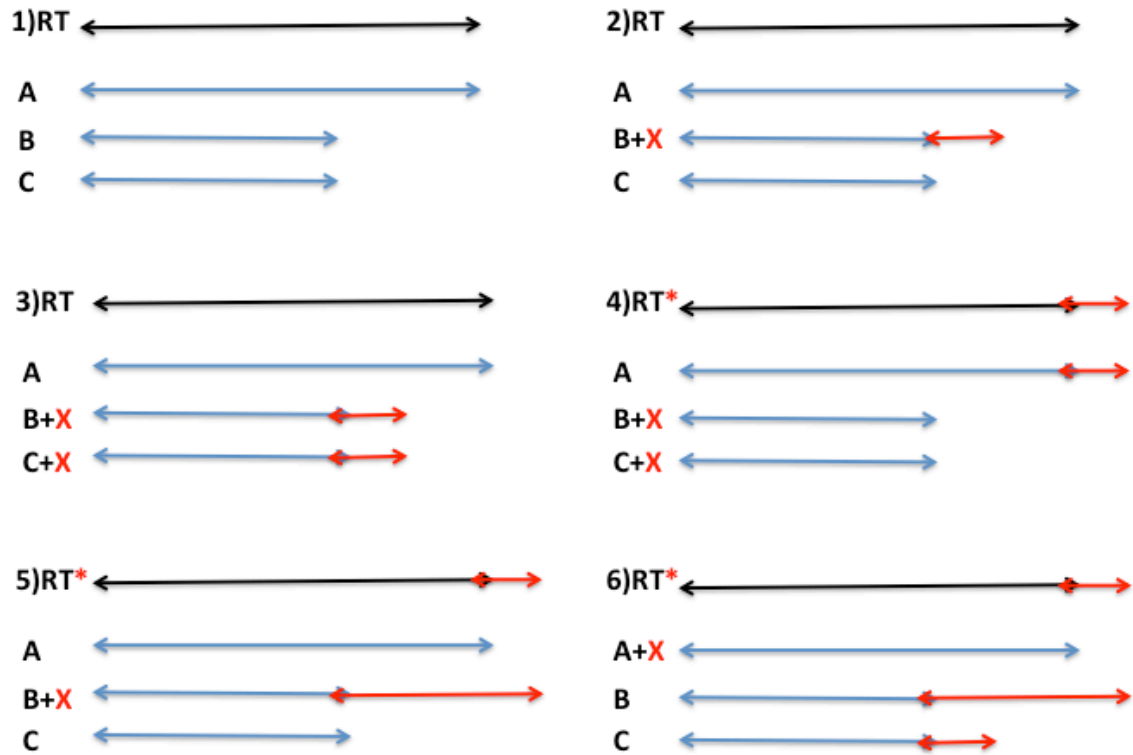


Figure 1. Hypothetical arrangement of stages of processing. Given three parallel stages of processing: A, B and C, conditions, in which the addition of factor X to one or more stages has no measurable effect on the overall time of the processes, RT (1, 2 and 3) and conditions where it does have a measurable effect (4, 5 and 6). As RT is the only measurement available, it is impossible to differentiate between configurations that result in the same RT.

All of the above issues arise out of a theoretically 'ideal' additive factors model in which the nature of the processing is either purely serial or purely parallel, and all stages of processing had a single selectively influencing factor. Such a straightforward system seems biologically improbable, as single factors have been shown to influence multiple stages of electrophysiological processing (cf. Deheane, 1996; Smulders et al., 1995), and multiple factors often affect the same stages of processing (cf. Polich, 2007; Covington and Polich, 1996). Even with reaction time measures, it should not be possible (under the assumptions of footnote 1) to disentangle non-selectively influencing factors as long as their additivity remains. If factor 1 added to the duration of both stages A and B and factor 2 added to the duration of stage B and the influence of factor 1 and 2 on stage B summed, it would not be possible to disentangle this non-selective influence from a selective influence. It has been assumed that two factors that influence the same processing stage would interact, but this is not necessarily the case (McClelland 1979 demonstrated this mathematically, although his cascade model differs from the strictly serial model presented here).

It is also worth noting that reaction time is not the only behavioral measurement that is sensitive to additivity effects. Response accuracy has also been demonstrated to reflect additivity. Fedorenko et al., (2009) combined linguistic complexity with musical complexity, and assessed the relative rates of comprehension for musically complex, linguistically complex, and doubly complex sung sentences. They found a 'super-additive' effect in that the subjects'

interpretations of the sentences was incorrect more often for musically complex vs. musically simple, as well as for linguistically complex vs. linguistically simple. Interestingly, their explanation was based on overlap of neurocognitive resources, rather than separation of stages of processing; if musical and linguistic processing share neural processors, then taxing either of them individually should reduce performance on a linguistic task, and taxing them simultaneously should additively reduce performance.

Recently, investigators have been applying additive factors theory to measurements of neural activity, specifically through the use of event-related potentials (ERPs). ERPs are summed electroencephalograms time-locked to the onset of a particular stimulus and reflect the summed activity of populations of cortical pyramidal neurons. Both the amplitude and latency of many ERP components³ are mediated by many different stimulus parameters, and latency effects in particular offer a strong parallel to reaction time work. Also, because ERP components allow latency measurement from either the onset of a stimulus or the onset of a response, they are able—under certain conditions—to provide a measure of the order of serial processing events, one of the features that RT additive factors measures lacks.

³ Amplitude comparisons of ERPs are typically done by computing the mean amplitude across a particular temporal range for each condition (eg 500-800ms). If an experimental condition is being compared to a control condition, then the two mean amplitudes are simply compared. If two experimental conditions are being compared, however, it is typical to compare the difference waves, (the mean amplitude for an experimental condition minus the mean amplitude for the control condition) rather than the raw ERP values.

The basic theory behind additive factors theory as applied to ERP research is two-fold. The first is the same as that of reaction-time work: presuming a serial stage model of processing which is necessary before an ERP component is evoked, factors that impact the processing speed of the different stages will have a summed effect on the latency of the production of that particular component. Furthermore, since many stimuli evoke multiple components, examining the relative timing of various components as various factors are applied can provide a framework for the order at which various processes occur. The second, and it seems more likely to be reflected in systematic measurable way, relates to amplitude rather than latency. Rather than assuming a serial stage model (although the two are not mutually exclusive) it assumes that there are multiple factors that affect the amplitude of a single component, or that what is commonly referred to as a component is actually multiple sub-components which are differentially affected by various factors. When there is a change in multiple factors (i.e., discrete aspects of a stimulus), the effects they have on the component of interest sum. This produces a deflection that is equivalent to the difference in amplitude from baseline to deflection from factor one, plus the difference from baseline of all additional factors.

One approach to applying additive factors logic to electrophysiological measures, which is especially prevalent in the literature, is a combination of the measurement of ERPs and reaction times in response to multiple factors. If a factor, A, affects a component of the ERP waveform but not the RT, while another factor, B, affects both, then factor A necessarily influences a process that occurs before factor B, given a strictly serial processing stream. The assumption of seriality does not

necessarily hold up in the context of neural processing, as factors that have additive effects on the amplitude of the waveform at the same latency suggest parallel processing. If the change in the scalp measured ERPs occur at the same point relative to stimulus presentation, it can be inferred that the processes are occurring simultaneously rather than serially. However, the existence of multiple components across differing time windows that are affected by differing factors implies that there is some degree of seriality in neural processing that is reflected in the serial (i.e., non-simultaneous) changes in the ERPs.

In one of the earliest examples of the ERP/RT additive factors paradigm, McCarthy and Donchin (1980) compared the effects of stimulus discrimination and response complexity on the P300 component as well as on overall reaction times. P300 in this context will refer to the component that is also often referred to as the 'P3b' or 'canonical P300'; the other components that are often considered to be part of the P300 complex, the 'P3a' and the 'slow wave' component will not be addressed here. The P300 is a positive deflection in the ERP waveform typically peaking between 200 and 800ms after stimulus onset and has been demonstrated to be modulated by stimulus frequency and stimulus meaning (Polich, 2007). Johnson (1993) has further proposed that stimulus meaning can be further deconstructed into task complexity, stimulus complexity and stimulus meaning, basing his argument partially on an additive argument. McCarthy and Donchin (1980) found that the increases in the difficulty of "stimulus discrimination" increased the latency of both the P300 and RT, whereas changes in "response difficulty" had an effect only on RT. Additionally, increasing the difficulty of both "processing" and "stimulus

discrimination” had additive effects on reaction time, but not on P300 latency. The McCarthy and Donchin (1980) study was a useful demonstration of how additive factors logic could be applied to ERPs, it did not directly apply the logic of the additive factors paradigm to the electrophysiological signal itself.

Following on this work, Smulders et al. (1995) examined RTs as well as two ERP components: the P300 and the lateralized readiness potential (LRP), a component that responds to the preparation for motor activity whether or not the movement is actually made (Rugg and Coles 1995). The factors varied were ‘stimulus degradation’ (affecting stimulus discrimination) and the complexity of the required response. Presuming that these aspects of processing were independent, the authors hypothesized that they would find additivity in latency of the LRP as well as the RT for a condition in which both factors were made more difficult than in control conditions. Additivity, however, was only found for the RT. This is probably due to the fact that the LRP is not an index of motor performance, but simply a reflection of pre-motor preparatory mechanisms, a finding that had not been reported at the time of publication (Rugg and Coles, 1995). So, as in McCarthy and Donchin (1980), no additivity in ERP effects was reported.

The N400 component is a negative-going component of the ERP waveform seen in response to the presentation of words in most conditions. It’s amplitude is mediated by semantic congruence with the context in which the word is presented. Semantically incongruous word pairs or words embedded in a sentence with infrequent lexico-semantic properties increase the amplitude of this component--the N400 effect (Rugg and Coles, 1995; McPherson and Holcomb, 1999). It has also

been shown that non-linguistic stimuli such as incongruous pictures and videos containing incongruous imagery produce a larger negativity peaking roughly 400ms after the onset of the target, which has been reported as an N400 effect as well (Sitnikova et al., 2003). Kounios and Holcomb (1992) compared two factors that increased N400 amplitude: whether the critical word in a sentence containing a category exemplar relationship (e.g. “All horses are animals.”) was a category or an exemplar of a category (a noun which is an exemplar causes a larger N400 than a noun which is a category), and whether the critical word was congruous or incongruous within the context of the sentence (e.g., “All horses are animals.” vs. “All horses are cars⁴”). A graded effect was found in which, relative to the category/related condition, the N400 became progressively larger for the exemplar/related, the category/unrelated, and the exemplar/unrelated, respectively. Unfortunately, the authors did not make the necessary statistical transformations, i.e., summing the two single effect groups and comparing them to the double effect group, in order to assess additivity. Interestingly, there were no latency differences, only amplitude variations.

One of the most compelling examples of additivity in ERP data has been reported by Johnson (1986), who examined three factors that have been shown to affect P300 amplitude: Probability, stimulus meaning⁵, and information

⁴ There is an obvious confound here in that the former sentence is true while the latter is false. The ‘truth value’ effect was analyzed by presenting untrue semantically congruous sentences (e.g., All animals are horses,) and comparing them to semantically congruous true sentences. No differences in N400 amplitude were found.

⁵ Stimulus meaning is a global term for any factor that affects the importance a subject attaches to a particular task

transmission or equivocation⁶. For two of these factors, there is strong evidence for additivity. Decreases in probability and increases in stimulus meaning, both of which are strongly correlated with increases in P300 amplitude, appear to have additive effects on P300 amplitude (as an example, in an auditory oddball design, in which subjects are played tones of a particular hertz interspersed with target's which were of a different hertz, the frequency with which the targets appear would be a reflection of stimulus probability. The action required by the subject—for instance, to respond when the target is present as compared to passively monitoring—would be a reflection of the stimulus value. Both of these factors have also been associated—although somewhat weakly—with changes in latency in the same directions as amplitude: increases in probability and decreases in stimulus meaning both increase P300 latency (cf. Johnson 1986). One crucial caveat, however, is that both factors can be further decomposed into sub-factors, some of which have effects on latency and some of which do not. As previously discussed for stages of processing, many factors can be reduced into sub-factors, which themselves can be reduced ad nauseam. The specific sub-factor of stimulus meaning that seems to have the greatest additive effect on the P300 in relation to probability is stimulus complexity⁷. (Although Johnson's review is thorough and compelling, it

⁶ Equivocation refers to the attenuation of information transmission, and, by definition, will modulate any other effects. I have omitted a discussion of its affect on additivity because it is not modulating the neural response to a stimulus, but rather the quantity of the stimulus that is received by the subject. And so, its additive properties are of a wholly different type than those germane to a discussion of additive factors theory as applied to ERP research.

⁷ Although this is probably a more appropriate term to use than 'stimulus meaning' in this context, Johnson's terms have been maintained for the sake of consistency.

is unfortunate that none of the individual studies he describes report an explicit quantification of the degree of additivity as a function of stimulus manipulation; these values must be extrapolated from the published data.) Johnson posits multiple generators for the P300, which are selectively influenced by varying factors. His reasoning is that the independence of the factors influencing amplitude and latency requires separate neural generators.

However, Johnson's (1986) reasoning is not universally valid. A major flaw in his assumption (namely, that additivity necessarily reflects independent processes) is that single components can be gradedly affected by a single factor. P300 amplitude, for instance, is proportional to the probability of the infrequent stimulus that evokes it, with amplitude increasing as probability decreases (Polich 2007). This is directly analogous to RT studies where single factors can have graded effects, presumably on the same stage of processing task. For instance, in McCarthy and Donchin's (1980) study, in one condition, subjects had to discriminate a target word embedded in a 6x4 matrix of letters. Presumably, increasing the size of the matrix would increase the difficulty in recognizing the target, and a graded effect could be found, and as the target discrimination became more difficult, reaction time would increase. This feature of individual stages of processing on ERP waveforms means that it is plausible that multiple factors can affect the same stage of processing and have additive effects. So although additive factors logic can reveal that multiple factors do indeed affect reaction time or a single ERP component, they cannot definitively describe the cognitive architecture underlying the process of interest, as it is impossible to rule out the possibility that there are non-interactive additive

effects of multiple factors on a single stage. (This assumes a non-deconstructable task; see footnote 1.) Certainly, for simple models of processing that seem to be comprised of discrete stages (e.g., stimulus discrimination, stimulus evaluation, and response) it seems highly implausible that factors such as the complexity of the required response and the difficulty of discriminating the stimulus would be affecting the same stage of processing. However, for more subtle distinctions between stages, non-interacting additivity of multiple factors within stage (or single ERP component) cannot be ruled out. Simultaneously occurring processes, each of which is being affected by changes of a discrete stimulus feature, cannot be differentiated to a single process that is affected by changes in multiple stimulus features.

Although this is true for single component ERP studies, it is not true of multiple component additivity studies. Multiple component ERP studies essentially allow the decomposition of the processing stages in any given task (see footnote 1). Many investigators have sought to determine the cognitive architecture of language processing by examining the P600 component⁸ that is evoked by violations of syntax and the previously described N400 component that is sensitive to violations of semantics. Because the P600 component is not evoked by semantic violations, and the N400 component is not evoked by syntactic violations, it is possible to compare individual violations of syntax and violations of semantics to double violations in

⁸ There is ongoing debate in the literature regarding the nature of the P600 component, specifically, whether it is a member of the P300 'family'. Although we will present evidence suggesting that these two components are almost completely independent, descriptively, the P600 is a positive deflection evoked by violations of morpho-syntax (as well as other stimuli) that peaks approximately 600ms after stimulus presentation.

which syntax and semantics are violated simultaneously. If syntactic and semantic processing are truly independent, the double violation should equal the sum of the two individual violations (Ainsworth-Darnell et al., 1998; Gunter et al., 1997; Hagoort, 2003; Palolahti et al., 2005). The ability of ERP research to isolate what are effectively stages of processing reflected by different components allows an application of additive factors logic that does not rely on the assumptions that are necessary in behavioral studies.

Scaling

One of the fundamental issues in cognitive neuroscience is determining the design of the neurocognitive architecture underlying various behaviors. Neurocognitive architecture refers to the mapping of cognitive processes onto the neural substrates that subserve them and describing the nature of neural modularity. Although the event-related potential (ERP) methodology does not allow localization of the sources for the electrophysiological signals it measures⁹, it does allow the determination of the overlap of the neural sources that subserve the processing of multiple stimulus features through comparisons of the scalp topographies and additive factors. Although these methods do not allow localization of a source, they do allow the determination of whether a particular

⁹ There are several methodologies for estimating source localization from ERP data, however, the results they yield are either unreliable or give too large a volume estimation of source to make them appropriate measures for assessing cognitive architecture. Also they are, at best, estimates.

neural generator—regardless of location—is activated by multiple stimuli, and of the degree of overlap in the sum of all the generators.

Electrical fields mathematically sum over time and space (Helmholtz, 1853 as reported in Kahl, 1971). Event-related potentials are measurements of voltage at individual locations on the scalp referenced to a common site and thus subject to Helmholtz's rule of superposition. The reason source localization from distributions of current across the scalp is an intractable problem is due to the inverse problem, which states that any given scalp distribution could be generated by a theoretically infinite set of source configurations. This problem can be demonstrated with a simple thought experiment: imagine recording from two diametrically opposed points on a perfect sphere with an indeterminate number of current generators contained within, but with equivalent conductivity at all locations. If current values were equal at each recording location, the generator(s) could be a single source in the origin of the sphere, or any number of sources equidistant from each recording source. Although the geometry gets more complex with increases in the number of sources being recorded, and variations in shape and conductivity that are entailed by actual scalp further add to this complexity, the basic principle remains the same. The reverse of this principle, however, is not true: Different scalp distributions necessarily require differing configurations of neural generators or differences in their relative strength, i.e., the voltages they produce (McCarthy and Wood, 1985; Haig et al., 1997).

One of the primary methods used for assessing differences in scalp topography—and therefore source differences—is to perform a statistical

comparison that evaluates whether or not there is an interaction between conditions and scalp location¹⁰. Theoretically, if there is a difference between conditions in the relative distributions of current across multiple scalp locations, then there must be at least partially different activation of the neural generators of this current (Johnson, 1993). This differential activation could be the result of either differing neural generators or differences in the relative amount of current produced by generators.

However, relative differences in current amplitude across condition do not necessarily reflect differences in source distribution between the generators. McCarthy and Wood (1985) describe a situation in which variance in amplitude across sites, although trending in the same direction, is not additive. An ANOVA when performed in such circumstances will yield an interaction. Although this interaction statistically implies differences in generator configuration, identical anatomical distributions can lead to such statistical differences. Consider scalp sites A, B, and C, whose current measurements are 5, 10, and 20¹¹, respectively, above a baseline condition given a particular experimental condition. And consider a second

¹⁰ This statistical procedure addressed superficially by McCarthy and Wood is an ANOVA, the procedural details of which are not important for a discussion of the argument they put forth. Haig et al. (1997) note that McCarthy and Wood's claims do not rest on the particular statistical procedure used. For ease of discussion, and since it is a particular test used by McCarthy and Wood, the following discussion will address the ANOVA procedure.

¹¹ These are arbitrary units. As noted, they are variations from some given baseline condition given a particular experimental condition.

experimental condition that yields values of 10, 20, and 40¹², respectively, at these respective scalp locations. An ANOVA will yield a condition by location interaction, therefore implying a difference in the distribution of the sources responsible for these two scalp measurements. However, this interpretation does not necessarily follow (cf. McCarthy and Wood 1985). The statistical reason for this is that an ANOVA only produces interactive variations if there are identical additive differences between conditions. Multiplicative differences, however present as an interaction, i.e., if the relative difference between the conditions was the sum of the values present in a particular condition and any single number, an ANOVA would not produce a result indicating an interaction.

ERP differences between conditions are often multiplicative rather than additive, a fact that often leads to false-positive errors in the interpretation of interactions. One possible explanation for the multiplicative rather than additive nature of the differences in ERP waveforms between conditions comes from the nature of the response of single cells to variations in stimuli (cf. Covey and Cassidy, 1991 and Kutcher and Covey, 2009. Although neither of these papers directly addresses this issue, the data they present reflect the pattern described.). To borrow from the jargon of the single-cell literature, consider the 'tuning' of individual ERP responses. Just as individual cells can be differently tuned to a particular stimulus parameter (e.g., frequency or amplitude), the nature of the ERP signal (i.e., its reflection of the summed simultaneous firing of populations of cells,

¹² McCarthy and Wood (1985) refer to this as a multiplicative transformation as it involved multiplying the values at each electrode site by a fixed amount rather than adding that amount to each location.

Rugg and Coles, 1995), is such that it is entirely possible that it has similar tuning properties, although the stimuli it is responsive to may be much more complex than those of single cells.

A common means of addressing the inability of statistical procedures to deal with both the theoretical (i.e., the multiplicative rather than additive), and the applied (i.e., the noise that is present in all ERP recordings as well as individual variation), is that of scaling, as proposed by McCarthy and Wood (1985). They suggest that before statistics are performed on ERP distributions that are the result of differing experimental conditions, data should be normalized (i.e., transformed to z-scores) by site location (i.e., distributions should not be normalized within condition, but between condition for every individual scalp location at which a signal was recorded). Normalization will eliminate most artificial interaction effects that result from the use of ANOVAS to assess interactions in situations where multiplicative rather than additive effects are present.¹³

Several criticisms have been raised about the value of scaling as proposed by McCarthy and Wood (1985). Haig et al. (1997) note first that there are several assumptions about the nature of the distribution of ERP signals which are not empirically demonstrated, and that scaling in general may reduce the ability to statistically identify differences in scalp distributions that reflect genuine

¹³ McCarthy and Wood (1985) propose two methods that may be employed for scaling: scaling before any statistical computations are performed and comparing ERP data after it has been transformed into vector distributions in which the axis orientation of the vector reflects the relative distribution of current and the amplitude of the current distribution is reflected in the length of a given vector (cf. Johnson, 1993 for a thorough discussion of the latter method). The issue of scaling in this discussion will focus on its overall merits rather than the different methods that can be used in order to normalize.

differences in source distribution or, conversely, suggest differences in scalp distributions between two conditions which are not actually present. Haig et al. (1997) make the point that a false positive interaction response rests on the particular nature of the variance between electrode sites. Strangely, since part of their criticism rests on the employment of hypothetical data, this point is illustrated by example of a particular configuration of source attributes: that variability in source strengths within a particular condition reflects purely between- subjects' variability, given identical generators with identical relative strength. Given this highly particular situation, however, an ANOVA would not produce an interaction effect. Although theoretically true, such a situation not only seems highly unlikely, but also poses no issue with regard to scaling. As discussed, no interaction would be found, and therefore scaling would offer no particular benefit with regard to the analysis of whether an interaction existed. It would also offer no drawback, as an ANOVA performed on data in this situation after scaling had been performed would offer the same result as that performed on the data without scaling.

The second, and much stronger criticism presented by Haig et al. (1997) of the scaling approach in ERP statistical analysis, is that scaling, although it eliminates false negatives, might by its very nature obscure some genuine topographical differences in data sets between conditions or, conversely, create the appearance of differences which do not actually exist. They present hypothetical data which, when scaled, reveals both of these possibilities. As noted earlier, one of the major criticisms of the original description of the scaling approach (McCarthy and Wood, 1985) put forward by Haig et al. (1997) was that it relied on hypothetical data, and

that the trends in the data presented were not based on any empirical evidence regarding typical ERP data. Unfortunately, this very real methodological flaw is twice repeated by Haig et al. (1997): initially, in reference to a situation in which an ANOVA would not produce a false positive interaction between location and condition (this aforementioned situation) and, secondly, and much more importantly, the two examples of the possible skewing of the data after the effects of scaling which alter the outcome of a statistical analysis, one by creating a false positive effect, the other by obscuring a genuine effect, are both premised on ERP effects having a non-multiplicative nature, an assumption which, to use their own terminology, has “no physiological justification. . . .” It is possible that the ERP signal is not in fact multiplicative (although see McCarthy and Wood, 1985, for a review of empirical evidence that it is). However, without evidence to the contrary, the possibility of typical multiplicity cannot be dismissed and the strength of the arguments of Haig et al. (1997) lose strength.

A much more thorough and theoretically sound argument against scaling is put forward by Urbach and Kutas (2002, 2006) who raise three basic conceptual problems with scaling: comparison of the ERP signal to differing baselines, noise in the signal, and individual subject differences. All of these factors are relevant to a discussion of the appropriateness of scaling; however, there also seems to be a difference in what is meant by neural generators as referred to by Urbach and Kutas (2003, 2006) as compared to McCarthy and Wood (1985). McCarthy and Wood specifically state that differences in scalp topography require different spatial distributions of their neural generators. Although, as Urbach and Kutas point out,

this is not technically correct, a thorough discussion of what is meant by spatial distributions is appropriate. Urbach and Kutas (2003) show by example that differences in scalp topography can be produced by variations in any one of three aspects of the neural generators of an ERP signal: the spatial distribution of the neural generators themselves, the polarity of the generators, and the amplitude of the signal produced by one neural generator relative to another. Although McCarthy and Wood (1985) did not specifically address any of these possibilities aside from spatial configuration, their specific claim that any differences in scalp topography necessarily reflect differences in neural generators makes it appropriate to consider whether variation in any of the three factors indicates true difference in generator configuration.¹⁴

With respect to scaling per se, the initial objection of Urbach and Kutas (2006) is that an ERP signal is always measured with reference to a baseline, which is usually the averaged amplitude of the current for a given electrode site for some period of time before stimulus onset. Although baselines are calculated individually for every electrode site, their parameters, i.e., the duration of the signal averaged, remains constant across locations and conditions. Urbach and Kutas (2007) make the point that because such comparisons are used to compute amplitude, amplitude is not necessarily an accurate measure for making spatial comparisons. Differences in baseline amplitude between conditions can result in the appearance of differing distributions of neural generators when there are none, because the measured

¹⁴ Urbach and Kutas address the semantics of ‘spatial configuration’ and what is meant by it in reference to all three of these factors thoroughly (2007).

strengths, relative to amplitude, differ after scaling. Noise in the signal and individual differences between subjects can both result in statistical analysis of scalp distributions, even after scaling procedures have been applied, indicating differences in source configuration when none is actually present—i.e., noise can appear to be differences between conditions (Urbach and Kutas, 2007). Although this may make scaling ineffective, such artificial differences would still manifest themselves in statistical analyses of the unscaled data; thus scaling, although useless, does not in such a situation pose any problems beyond wasting the time of an investigator.

One of the better approaches to the issue of whether or not to scale is that put forth by Johnson (1993). He proposes performing statistical analyses on both the unscaled data and on the data after scaling has been done. A comparison of the results of the two analyses should allow discrimination of differences artificially introduced by scaling as well as recognition of differences that are a result of statistical procedures rather than actual differences in the neural generators of a signal. In addition, Johnson advocates the use of additive factors methodology. The additive factors paradigm as applied to ERP methodology (cf. Johnson 1986), will not necessarily reveal any differences in scalp distribution. However, the combination of the examination of the distribution of current across the scalp as well as the discrimination of factors which are additive in nature provide a much more thorough appraisal of neurocognitive architecture than either methodology used alone.

Since the Additivity Index is essentially an additive factors approach to electrophysiological measurements, the Additivity Index itself should be relatively immune to the kind of effects that would skew absolute results. For instance, it has been well documented that task relevance affects the amplitude of the P300 component (Polich, 2007; Polich et al., 1996; Johnson, 1986; Johnson, 1993). Given the classic double anomaly paradigm using syntax as one violation as well as some sort of physical anomaly (like capitalization), subjects will show larger P300 deflections if they are told to respond to unusual capitalization as an anomaly as compared to when they are told to ignore capitalization with regards to their anomaly/no anomaly responses. Although this difference in task relevance will modulate the amplitude of the P300 (larger for relevant capitalization than for irrelevant capitalization) it should have no effect on the ERP response to the syntactic violations as long as subject instructions with regards to responses to syntactic violations remain consistent. Given these two pools of data--with identical stimuli but with instructions that make capitalization more salient, thus increasing P300 amplitude relative to the group which was told to ignore capitalization--this might, at first glance, seem like a situation in which scaling would be useful. However, because the amplitude of the capitalization-related P300 is being compared to itself rather than to the amplitude of the capitalization-related P300 in the other group, scaling is unnecessary. Whether the P300 is (relatively) large or small, it should contribute equally to both the single violation as well as the double

violation, and it is this comparison—the contribution to the signal in isolation and in association with a second anomaly—that the Additivity Index captures.¹⁵

Constraints

Although the summation of the electrical signal over time and space as described by Helmholtz allows additivity comparisons to be made, it is necessary to verify that it is not the differences in the spatial and temporal origins of the signals being compared do not introduce excessive noise in signal.

Consider a situation in which ERPs are being recorded from three locations on the scalp: central, anterior, and posterior. In addition, there are four conditions: a control condition in which a stimulus is presented, a condition in which there is an anomaly in one particular feature of the stimulus (A_1), a condition where there is an anomaly in a second feature of the stimulus (A_2) and a condition in which both anomalies are simultaneously present on the stimulus (A_D). In order to be able to perform an additivity analysis, each of the single anomaly responses¹⁶ must be compared to the response from the double anomaly. This requires that the single

¹⁵ Indeed, visual inspection seems to support that there were these exact saliency differences between Osterhout et al.'s (1996) syntax/capitalization double anomaly experiment and our replication of this study in Experiment 1. Visual inspection shows that the P300s produced by capitalization errors in Osterhout et al. (1996) were larger in amplitude than those we found in our replication. However, both studies show very high additivity reflecting high levels of independence between the anomalies. Regardless of whether the P300 is relatively large or small, it should (given complete independence) contribute an equal amount to both the single and the double violation. Given non-independence, the difference in its contribution, since it is computed as a ratio, is not subject to change based upon the absolute amplitude.

¹⁶ See formula 1. The waveforms from the single anomalies are mathematically summed into a single composite wave for the comparison

anomaly responses co-occur in both time and space. For instance, if the source of the response to A_1 is in frontal areas, then the signal it produces will most likely be highly represented at the anterior electrode location and poorly represented at the posterior site. Similarly, if A_2 elicits a response from sources located in occipital areas, this signal will most likely be well represented at the posterior electrode site and poorly represented at the anterior site. Although in an ideal (i.e., noise-free) environment the additivity analysis would be unaffected by differences in the relative contributions of A_1 and A_2 based on signal attenuation due to differences in location¹⁷, the actual comparisons are highly susceptible to artifact introduced by noise, and therefore maintaining the highest signal to noise ratio for all signals is of the utmost importance.

In order to ensure that the waveforms used for additivity comparisons have the highest signal-to-noise ratio, it is necessary to be selective when choosing an electrode site (or group of sites) to perform an additivity comparison on. Sites must only be used, therefore, when the waveforms elicited by each single anomaly as well as the double anomaly are statistically significantly different from the control waveform. If any of the individual anomalous conditions do not meet these criteria, then it can be assumed that the signal is underrepresented enough that the comparisons may be capturing artifact rather than signal.

¹⁷ The additivity comparison itself is not comparing A_1 to A_2 , rather it is comparing the contribution of A_1 to the control signal when it is presented by itself to the contribution to the control signal in the presence of A_2 . Although the absolute amplitude will vary across scalp locations, the ratio, and therefore the additivity, will remain constant.

Similarly, it is also important that a time window be selected in which the components of interest are all represented in the signal. Analogous to the issues involving differences in spatial location, the signal elicited by A_1 might be present in a different temporal interval than the signal elicited by A_2 , which requires caution with the selection of the temporal window over which to perform the additivity analysis. The same selection criteria should therefore be applied to the temporal range that was applied to the spatial. After the selection of an electrode (or population of electrodes) in order to minimize the introduction of noise, a temporal window should be selected in which both individual anomalies as well as the double anomaly produce components that are significantly different from the control condition.

Adhering to these constraints on when to perform additivity analyses (namely that there are significant effects of the anomalies relative to the control condition in both the spatial and temporal domains) should ensure that the additivity analysis represents the actual contributions of the signals of interest and captures a minimal amount of noise.

CHAPTER 2: ADDITIVITY EXPERIMENTS

Introduction

The event-related potential (ERP) signal reflects the summed post-synaptic potentials of large numbers of cortical pyramidal neurons, measured at the scalp (Luck, 2005). This signal provides an online measurement of the processing dynamics that underlie the response to a particular stimulus feature. One of the ways ERPs have been used in the past has been to determine the degree of neural independence of the responses to specific stimulus features by assessing the degree of additivity in the ERP responses (Hagoort, 2003; Osterhout, McKinnon, Bersick, & Corey, 1996; Osterhout & Nicol, 1999). In these studies, subjects were presented with a first stimulus with a particular feature, a second stimulus with a different feature, and a third stimulus with both features. Following Helmholtz's Rule of Superposition, the responses to each feature independently generated should summate when they are presented simultaneously, if they are represented independently. These studies have adopted an "anomaly" paradigm. For example, prior work has shown that semantic (e.g., "The cat will *bake* the food.") and syntactic (e.g., "The cat will *eating* the food".) anomalies elicit distinct ERP responses (the N400 and P600 effects, respectively). Osterhout and Nicol (1999) assessed the independence of these responses by adding a third condition that was anomalous both syntactically and semantically (e.g., "The cat will *baking* the food."). The doubly anomalous stimuli elicited a response that approximated the summation of the two effects as elicited in isolation, indicating that the effects are generated in an

approximately independent manner (see also Ainsworth-Darnell, Shulman, & Boland, 1997; Hagoort, 2003).

A similar result was reported by Osterhout, McKinnon, Bersick, and Corey (1996), who studied the independence of two positive waves that overlap in time and space: the P600 and the P300, a large, positive wave that is elicited by a wide range of task-relevant, unexpected events. Participants read sentences that contained a syntactic anomaly, a word that was in an unexpected physical form (all uppercase letters), or a word that was both in uppercase and syntactically anomalous. Because the effects are superficially similar—both are late positivities broadly distributed with maximal effects over central posterior sites—there has been a debate over whether the P600 is member of the P300 ‘family.’ Applying the additivity paradigm, Osterhout et al. (1996) reported an approximately (but not perfectly) additive function when a syntactic anomaly and unexpected uppercase word were presented simultaneously. This result was taken as evidence of the independence of the P300 and the P600 effects.

However, in these and related studies, the strength of the conclusions is limited by a binary logic, in which the two processes of interest are determined to be independent or not. One might surmise that meaningful gradations of neural independence exist. If so, then the relative neural independence of two brain responses could be quantified on a continuous scale of additivity, with the endpoints representing no independence (no additivity) and complete independence (perfect additivity). Here, we explore this possibility and also validate a simple scale of independence, the Additivity Index (AI). AI values range positively from 1 (reflecting

complete separation of the neural mechanisms underlying processing of the two stimuli) to 0 (reflecting the complete overlap of the neural responses)¹⁸. The AI represents a straightforward application of Helmholtz's Rule of Superposition (Kahl, 1971).

For our purposes, a stimulus feature is any aspect of a stimulus that can be manipulated independently of some other feature or set of features. For example, the frequency and amplitude of an auditory stimulus can be manipulated independently, and so would constitute separate features. In order to assess the degree of neural independence of the processing of two stimulus features, we chose pairs of features that can co-occur within a single stimulus. Neural independence, in this case, refers specifically to the degree to which the brain response elicited by manipulation of one stimulus feature summates with the brain response elicited by manipulation of a second stimulus feature.

The degree of neural independence can be described as a parametric function that has a uni-dimensional range. At one end of this range, the brain is processing two features in an identical manner—the neural response to change in one feature is identical to the neural response to change in another feature. In such

¹⁸ AI values in the negative range all reflect complete overlap in neural processing, but also capture the degree of inhibition the processing of one feature produces on the processing of a second feature. 0 reflects an absence of inhibition -.5 reflects complete uni-directional inhibition, wherein the presence of one feature prevents the processing of a second feature. The range from -.5 to -.1 reflecting super-inhibition wherein the presence of two stimulus features inhibits the processing of either feature. This will be discussed later.

cases, the neural responses would not summate at all¹⁹. At the other end of the range, the brain is processing the two features using separate (independent) systems—changes in one feature elicit a response that is completely separate from the response elicited by changes to another feature. One would predict an additive (or near-additive) function in such instances. Our approach, using the AI, represents a fundamentally different method for examining the “neural independence” of stimulus features, one that might allow us to define feature categories in terms of neural activity. Features that are within a category should have a much lower Additivity Index than features that are between categories.

Perhaps the most common method for assessing neural independence is to image the brain during the presentation of a stimulus and then assess which regions in the brain become selectively active in response to the presence of the stimulus. If activity occurs in similar regions across two different types of stimuli—or stimulus features, we can infer that the processing of these two stimuli recruit similar neural resources. This is essentially a ‘where does it live’ approach and, as such, is both theoretically and methodologically problematic when applied to scalp-recorded electrical potentials. Event-related potentials (ERPs) reflect voltages at individual locations on the scalp, referenced to a common site, and summed over multiple events. The individual measurements of voltage may represent current generated by many separate sources. Multiple independent neural generators producing separate electrical potentials will, when sampled from a single location on the scalp,

¹⁹ The term ‘neural response’ here refers to both the individual cells involved in the processing as well as their changes in firing rate.

result in a single waveform that represents the sum of the multiple original signals after their respective attenuation, which is caused by travel through the various tissues between the generator and the electrode. Due to this property of electrical fields, there are an infinite number of source configurations that could result in any observed distribution of current measured across the scalp. Although this renders definitive source localization a mathematical impossibility, the summation of electrical signals provides us with another means for comparing sources. Rather than asking 'where it lives' in the brain, we can assess instead the degree to which the measured electrical fields elicited by two stimuli summate, a 'how do they interact' approach. It is worth noting that there are several methods for estimating current source distribution using only ERP data; however, they all rely on assumptions in their determination of the source estimated that provide overly general solutions²⁰ (Luck, 2005; Rugg and Coles, 1995), and require recording from more scalp locations than are necessary for the use of the AI. Another method commonly used with electrophysiological data is Independent Component Analysis, which attempts to isolate individually driven components of the ERP waveform; but this is also an assumption-laden method.

Because independent current sources sum across space and time, the brain responses to two simultaneously presented stimulus features will summate to the extent that they are independently generated in the brain. Therefore, the ERP waveform resulting from the simultaneous presentation of two stimulus features

²⁰ i.e., the estimations of localization include large portions of the brain and are unable to differentiate between subtle differences in source configurations.

that activate independent neural sources will be identical to a composite waveform generated by mathematically summing the waveforms that result from their individual presentations (assuming no noise). Degrees of non-additivity would reflect degrees of non-independence with respect to how the brain is processing the two stimulus features.²¹ Sub-additivity would reflect overlap in the processing of the two stimulus features; super-additivity would reflect synergy wherein the presence of two features would recruit more neural resources than the sum of the resources of their independent presentation.

Mathematically, the Additivity Index is a simple ratio represented by Equation (1):

$$(1) AI = 1 - ((A + B) - A\&B) / A\&B$$

where $A + B$ represents the sum of the mean amplitudes of the difference waveforms elicited by two different stimulus features during a particular temporal window, and $A\&B$ ²² represents the mean amplitude when both features are presented simultaneously in that same window. Assuming that the effects elicited by each stimulus feature are sufficiently robust (that is, statistically significant), the range of the equation is from -1 to 1, wherein complete overlap in sources is reflected by the value of 0 and complete separation of sources is represented by the

²¹This only holds true if the waveform is not sensitive to gradations of “wrongness” within a feature. See discussion section.

²² The purpose of normalizing by dividing by $A+B$ is to fit the scale into the range of -1 to 1 which allows ease of interpretation.

value of 1 (see figure 2). Negative values in the AI reflect non-independence wherein multiple stimulus features are processed by the same sources, however the presence of one stimulus feature mediates the response of the sources to the other stimulus features it processes. Thus, AI values in the negative range all reflect complete overlap in neural processing, but also capture the degree of inhibition the processing of one feature produces on the processing of a second feature. 0 reflects an absence of inhibition; -.5 reflects complete uni-directional inhibition, wherein the presence of one feature prevents the processing of a second feature. The range from -.5 to -.1 reflects super-inhibition, wherein the presence of two stimulus features inhibits the processing of either feature. This can occur for attentional reasons where two stimuli, although processed by the same sources, are differently salient such that the presence of one feature captures enough attention that a second feature is not even processed. Negative values can be easily visually detected in the waveforms, with negative values between 0 and -.5 reflecting a double violation waveform whose amplitude is between the amplitudes of either single violation. AI values between -.5 and -1 are reflected by a double violation waveform, the amplitude of which is less than the amplitude of either single violation.

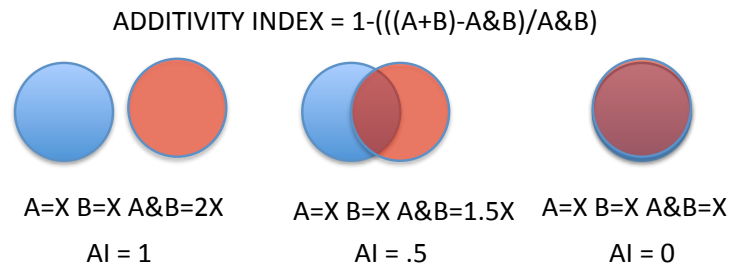


Figure 2. Visual representation of the hypothetical overlap in neurocognitive resources given three different AI values.

In order to empirically demonstrate the validity of the Additivity Index, we recorded ERPs to anomalies involving four distinct stimulus features: font type, font capitalization, font color, and syntax. We then constructed a set of sentences, each of which contained a critical word that was anomalous with respect to one of the features, or a pair of features (i.e., anomalous capitalization paired with anomalous font, color, or grammar). Given prior work, we expected that each anomalous feature would elicit a robust positive-going shift in the ERP²³.

Grammatical anomalies elicit a large positive-going wave (Osterhout & Holcomb, 1992; Hagoort, 1993), as do a wide variety of expectation violations (Polich, 2007; Polich et al., 1996; Johnson, 1986; Johnson, 1993). Of particular interest were the ERP responses to pairs of feature anomalies, which systematically differed with respect to their similarity. These three pairs reflect a manipulation of the degree of similarity of the within-pair violations, such that the three pairs form a putative continuum of similarity of their constituent features. Violations of both font and capitalization involve manipulating the shape of individual letters, i.e., the changes necessary to go from a well-formed word to an anomalous word are purely orthographic in nature. Capitalization and color, however, require more varied changes to produce the violations. For capitalization, we continue to create a violation by changing the shape of the individual letters; but a color anomaly, although still a manipulation of the physical properties of the stimulus, is not a change in orthography. Similarly, for the capitalization and syntax pair, the physical form is manipulated through an orthographic change, whereas the syntactic

violation reflects an anomaly of abstract linguistic form. (For a graphic representation of these cross-condition differences, see table 1). The appearance of each stimulus category was equiprobable. Therefore, the additivity of the neural response to these features is expected to approximate the inverse of feature similarity, with increasing additivity for pairs that are decreasingly similar. Given prior work, we expected that each anomalous feature would elicit a robust positive-going shift in the ERP (Osterhout & Holcomb, 1992; Polich, 2007; Polich et al., 1996; Johnson, 1986; Johnson, 1993).

Although in many contexts changes in word form such as capitalization may serve a linguistic function (e.g., capitalization can be used to emphasize a word), within the context of the experiment, subjects were clearly responding to the anomalous features as anomalies rather than linguistic features. This is demonstrated in both the behavioral data in which they rejected sentences that contained an anomalous feature, as well as their electrophysiological responses that contained late positivities that are classically elicited by violations of expectancy (Polich et al., 1996) (see results).

The capitalization/syntax experiment also served to replicate Osterhout's (1996) study in which the critical word was either anomalous in its capitalization²⁴, syntactically anomalous, or anomalous in both capitalization and syntax. This feature pair was chosen because it has been a point of contention in the psycholinguistic literature. Violations of linguistic syntactic expectancy elicit the P600 component of the ERP waveform (Osterhout, 1996), while a wide range of

violations of expectancy across many domains elicits a P300 (Polich, 2007).

Although superficially similar—both are late positivities broadly distributed with maximal effects over central posterior sites—Osterhout (1996) has previously demonstrated near perfect additivity. Although the existence of additivity strongly suggests independence according to the summative nature of electrical fields described above, without some sort of empirical index of the range of additivity, claims made about ‘near’ additivity are difficult to evaluate. We report here systematic covariation between the additivity of the ERP responses and the similarity of stimulus features, validating the ERP Additivity Index as a tool for assessing processing independence.

Methods

Participants

Our participants included 42, 32 and 31 individuals for the capitalization/syntax, capitalization/color, and capitalization/font comparisons respectively. 17, 7, and 6 subjects’ data were excluded due to excessive eye movement or other artifact in the raw EEG, leaving 25 subjects per comparison included for analysis. All participants were strongly right-handed as assessed by an abridged version of the Edinburgh Handedness Inventory, and all had normal or corrected-to-normal vision.

Participants provided informed consent and received a small amount of class credit for participation.

Procedure

Participants were tested in a single session lasting approximately eighty-five minutes (including about thirty minutes of experimental preparation). Upon arrival to the laboratory, each participant was asked to fill out an abridged version of the Edinburgh Handedness Questionnaire and a language history questionnaire. Each participant was randomly assigned to one of the stimulus lists and was seated in a comfortable recliner in front of a CRT monitor. Participants were instructed to relax and minimize movements while reading and to read each sentence as normally as possible. Each trial consisted of the following events: each sentence was preceded by a blank screen for 1000ms, followed by a fixation cross, followed by a stimulus sentence that was presented one word at a time. The fixation cross and each word appeared on the screen for 475ms followed by a 250ms blank screen between words. Sentence-ending words appeared with a full stop followed by a response prompt asking participants if the sentence was “good” or “bad”. Participants were instructed to respond “good” if they felt it was a well-formed normal sentence “bad” if they felt it abnormal. Subjects were not explicitly informed of what constituted a “bad” sentence aside from abnormality²⁵ and were not given feedback as to whether or not their response was correct. Participants were randomly assigned to use either their left or right hand for the “good” response.

²⁵ Although the P300 amplitude is modulated by attention and task relevancy, the additivity function should be unaffected by any amplitude differences as long as the sources of the P300 do not vary with task relevancy.

Stimuli

For each of the three violation pairs, four word lists were constructed using 120 target sentences. Each sentence was between six and 14 words long. Four differing versions of each sentence were created using a Latin square design reflecting the different conditions as shown in table 1. The four versions of the sentences were identical except for the target word that was always at least two words from the sentence initial position and two words from the sentence final position. Each subject saw only one version (condition) of each sentence; the conditions were equally distributed between the four lists such that each contained a combination of 30 sentences that contained a capitalization violation, 30 that contained a violation of a second type (font, color or syntax), 30 that contained a double violation (capitalization as well as font, color or syntax) and 30 that were well-formed. Each sentence appeared only once per list, and each list contained a different form of the sentence so that within each stimulus pair, each subject was exposed to the same 120 sentences of interest, 30 of which were in one of four different conditions. The sentences were of the type shown in table 1.

The boy will _____ the meal.

Violation	Syntax/ Capitalization	Color/ Capitalization	Font/ Capitalization
CONTROL	eat	eat	eat
A	eats	eat	eat
B	EAT	EAT	EAT
AB	EATS	EAT	EAT
	N=25	N=25	N=25

Table 1. The differing word forms for all conditions across the three additivity experiments.

In addition, each list contained 120 filler sentence that were well-formed distractor sentences. Finally each list had a version in which a well-formed sentence called for a button press from the left hand, and a version in which a well-formed sentence called for a button press from the right hand, which was noted in the instructions as well as the order of the yes/no prompt which occurred as “yes/no” or “no/yes” respectively.

Data Acquisition and Analysis

Continuous EEG was recorded from 19 tin electrodes attached to an elastic cap (Electro-cap International) in accordance with the extended 10-20 system. Vertical eye movements and blinks were monitored by two electrodes, one placed beneath the left eye and one placed to the right of the right eye. The 19 electrodes were referenced to an electrode placed over the left mastoid and were amplified with a bandpass of 0.01-100Hz (3db cutoff) by an SAI bioamplifier system. Impedances at scalp and mastoid electrodes were held below 5 $\mu\Omega$ and below 15 $\mu\Omega$ at eye electrodes.

Continuous analog-to-digital conversion of the EEG and stimulus trigger codes was performed at a sampling frequency of 200Hz. ERPs, time-locked to the onset of the critical word, were averaged off-line for each participant at each electrode site in each condition. Grand average wave forms were created by averaging over participants. Trials characterized by eye blinks, excessive muscle artifact, or amplifier blocking were not included in the averages; additionally, subjects who had rejections in over one-third of trials were not included in the

analysis. The number of rejections did not differ significantly between conditions or groups.

ERP components of interest were quantified by computer as mean voltage within a window of activity. Based on visual inspection of the waveforms, and in order to make meaningful comparisons between the three experiments, we compared mean amplitude across a large window, 300-900ms after stimulus presentation, and comparisons were made relative to a 100ms prestimulus baseline. This window was chosen because it encompasses the entire range of the divergence of any of the experimental conditions from the baseline (well-formed) condition as measured by visual inspection. As the latencies for the onset of the individual violations vary widely, it is important that a large window is used so that the comparison encompasses the entirety of both deflections. Using smaller time windows would obscure the additivity in the function if it cut off part of the deflection.²⁶ In order to demonstrate that this window was indeed optimal for additivity comparisons, the analyses were also performed on the classic language related ERP time windows (0-150, 150-300, 300-500, 500-800).

Within each time window, ANOVAs were calculated with violation type (no violation, syntax/color/font, capitalization, double violation and composite—the mathematical sum of the two single violations) as a within-subjects factor. Data from midline (Fz, Cz, Pz), medio-lateral (right hemisphere: Fp2, F4, C4, P4, O2; left hemisphere: Fp1, F3, C3, P3, O1), and latero-lateral (right hemisphere: F8, T8, P8; left hemisphere: F7, T7, P7) were treated separately in order to identify topographic

and hemispheric differences. ANOVAs on midline electrodes included electrode as an additional within-subjects factor (3 levels), ANOVAs on medio-lateral electrodes included hemisphere (2 levels) and electrode (5 levels) as additional within-subjects factors, and ANOVAs over latero-lateral electrodes included hemisphere (2 levels) and electrode (3 levels) as additional within-subjects factors. The Greenhouse-Geisser correction for inhomogeneity of variance was applied to all repeated measures on ERP data with greater than one degree of freedom in the numerator. In such cases, the corrected p-value is reported.

Additionally, a composite condition was created for each electrode site at all time points by summing the two singles violations. Pairwise comparisons were carried out with this composite condition relative to all other conditions.

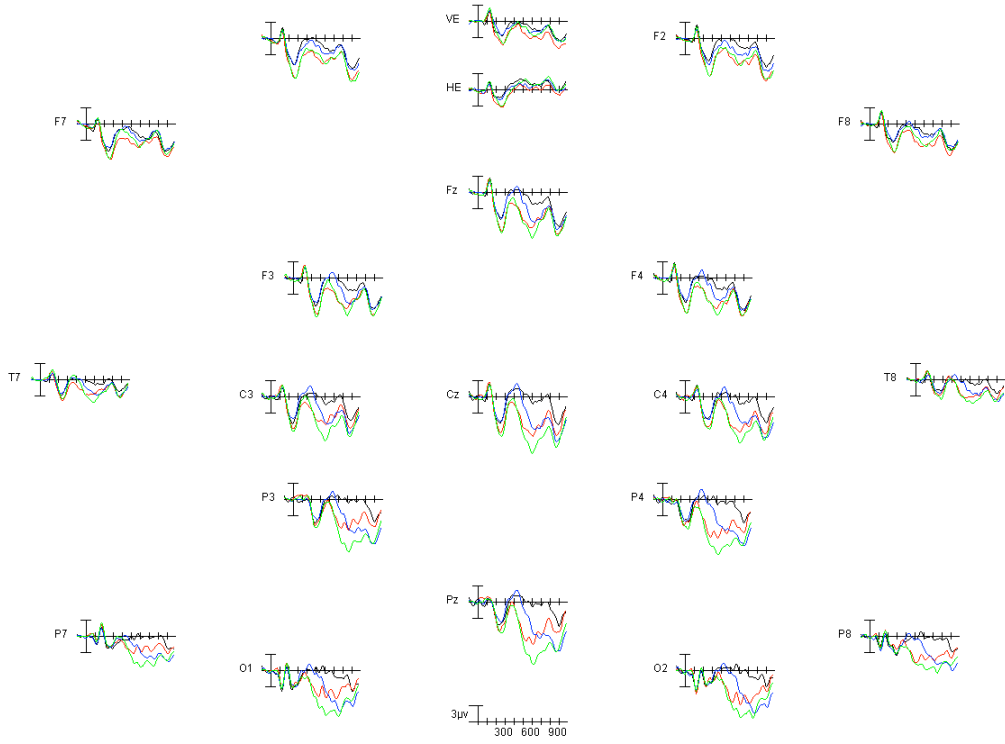
Results

All three experiments showed effects that were largest over posterior sites as indicated in the condition by electrode interactions. The medio-lateral and lateral electrodes showed effects that trended in the same direction but were not as robust as midline electrodes

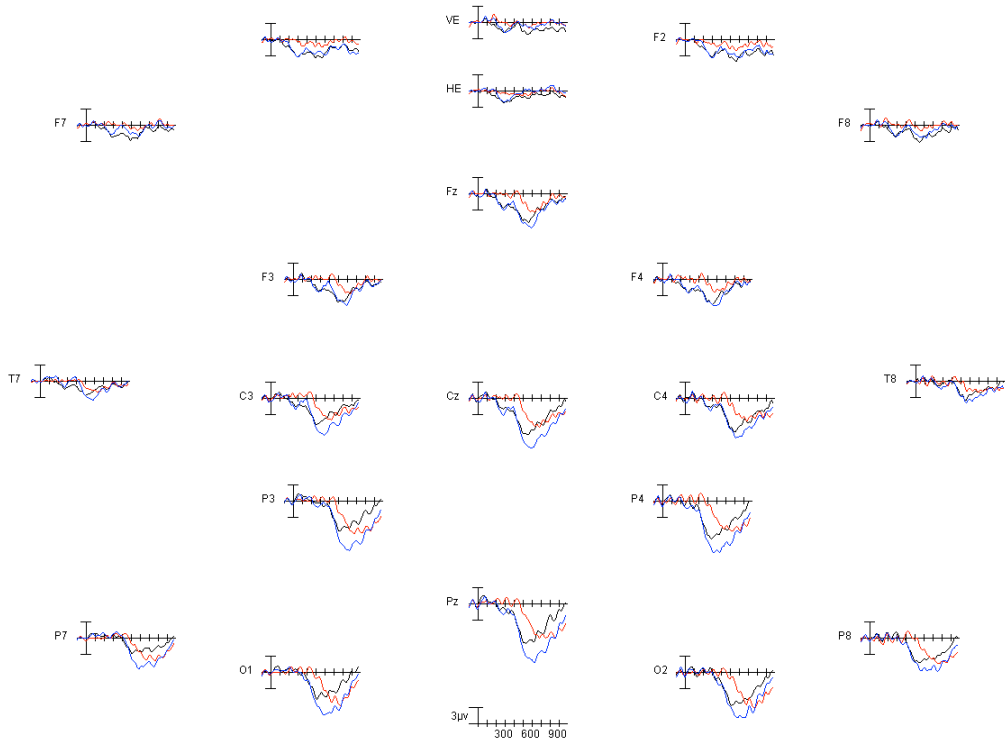
Capitalization and Syntax

Grand average ERPs for the four critical words are shown in figure 3. The capitalization violation as well as the double violation showed a positive-going deflection, relative to the control condition, beginning at approximately 200ms. The syntactic violation begins to diverge from the control condition at approximately

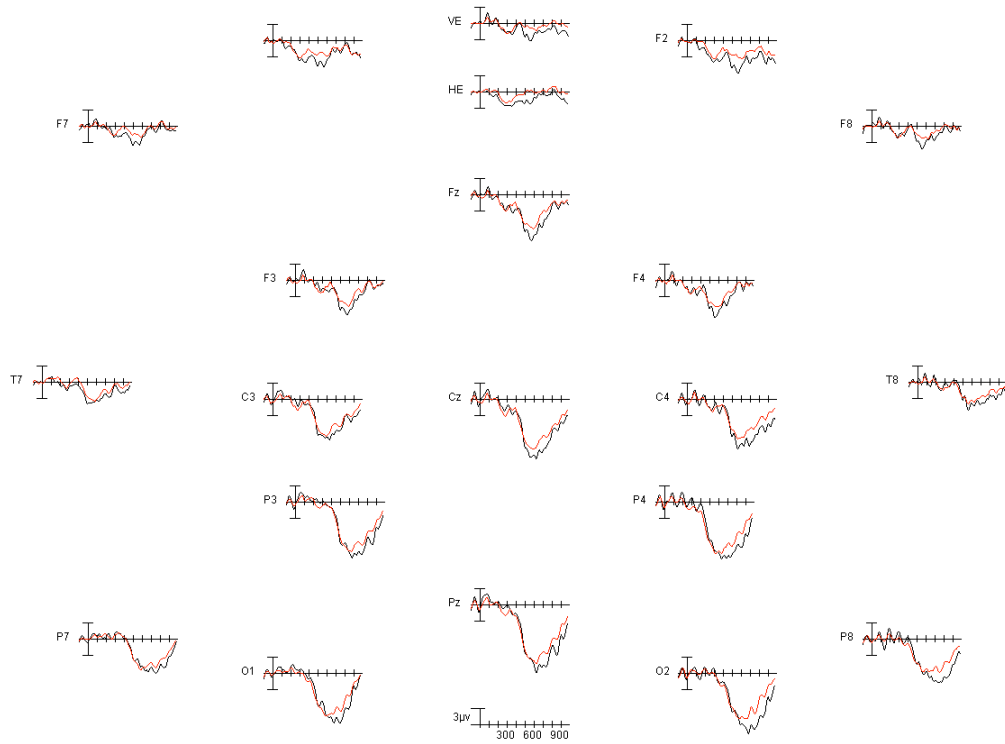
300ms, showing a large positive deflection that is maximally represented at centro-posterior sites. The capitalization and the double condition also show an increased positivity beginning at 300ms. All three experimental conditions continue to show a positive-going mean amplitude throughout the rest of the epoch, at which point the responses to the following word begin to manifest. The omnibus ANOVA on the mean amplitude in the 300 to 900ms latency range across midline sites yielded a significant effect of word type $F(3,72) = 20.49$, $MSE = 23.29$, $P < .001$, as well as a word type by electrode interaction $F(6,144) = 8.02$, $MSE = 2.26$, $P < .001$. The Additivity Index = .85. See figure 3.



A) CONTROL CAPITAL SYNTAX DOUBLE



B) CAPITAL SYNTAX DOUBLE



C) **DOUBLE** CAPITAL+SYNTAX

Figure 3. Waveforms for the Capitalization/Syntax comparison. A) raw waveforms B.)difference waves C)double violation and composite violation.

Simple effects analysis for the individual violations along the midline sites reveal no significant differences between the experimental conditions and the control condition during the 0-150ms window. There was no significant difference between the double violation and the composite condition for the midline condition. See table 2 for all pairwise comparisons.

Midline

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	2.19	.02	.01	2.74
	$MSE=$	3.09	5.17	5.68	9.27
capitalization	$F(1,24)=$		1.29	1.04	.02
	$MSE=$		4.14	5.39	5.17
syntax	$F(1,24)=$			.00	2.19
	$MSE=$			5.76	3.09
double	$F(1,24)=$				.73
	$MSE=$				9.59

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	.60	.01	.03	.05
	$MSE=$	8.19	10.12	13.34	17.92
capitalization	$F(1,24)=$		.60	.22	.01
	$MSE=$		10.61	12.35	10.12
syntax	$F(1,24)=$			.07	.60
	$MSE=$			10.42	8.19
double	$F(1,24)=$				.11
	$MSE=$				17.13

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	1.13	.01	.78	.21
	$MSE=$	3.49	3.03	4.57	6.10
capitalization	$F(1,24)=$		1.39	.00	.01
	$MSE=$		3.43	3.94	3.03
syntax	$F(1,24)=$			1.49	1.13
	$MSE=$			2.92	3.49
double	$F(1,24)=$				.00
	$MSE=$				5.37

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 2. Capitalization and syntax pairwise comparisons 0-150ms.

For the 150-300ms time window across midline sites there was a significant difference between capitalization and control conditions $F(1,24) = 4.28$, $MSE = 11.42$, $P < 0.05$, no significant differences between the syntax and control condition, and a significant difference between the double violation and control condition $F(1,24) = 6.95$, $MSE = 8.85$, $P < 0.05$. There was no significant difference between the double violation and the composite condition. See table 3 for all pairwise comparisons.

Midline

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	4.28*	.11	6.95*	31.6***
	$MSE=$	11.42	12.04	8.85	19.12
capitalization	$F(1,24)=$		5.88*	.08	.11
	$MSE=$		11.19	9.25	12.04
syntax	$F(1,24)=$			8.99**	4.28*
	$MSE=$			8.9	11.42
double	$F(1,24)=$				.18
	$MSE=$				21.62

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	4.03	.14	3.78	36.64***
	$MSE=$	20.29	21.70	18.60	38.64
capitalization	$F(1,24)=$		4.64*	.02	.14
	$MSE=$		25.01	18.76	21.70
syntax	$F(1,24)=$			6.04*	4.03
	$MSE=$			16.89	20.29
double	$F(1,24)=$				.03
	$MSE=$				34.04

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	2.44	.31	.51	23.97***
	$MSE=$	7.35	5.79	7.77	15.43
capitalization	$F(1,24)=$		3.26	.66	.31
	$MSE=$		9.54	7.66	5.79
syntax	$F(1,24)=$			1.76	2.44
	$MSE=$			6.33	7.35
double	$F(1,24)=$				.08
	$MSE=$				9.83

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 3. Capitalization and Syntax pairwise comparisons 150-300ms.

For the 300-500ms time window across midline sites there was a significant difference between capitalization and control conditions $F(1,24) = 24.53$, $MSE = 16.00$, $P < 0.001$, no significant differences between the syntax and control condition, and a significant difference between the double violation and control condition $F(1,24) = 17.22$, $MSE = 23.51$, $P < 0.05$. There was no significant difference between the double violation and the composite condition. See table 4 for all pairwise comparisons.

Midline

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	24.53***	.06	17.22***	9.27**
	$MSE=$	16.00	13.59	23.51	31.94
capitalization	$F(1,24)=$		18.66***	.01	.06
	$MSE=$		19.11	10.77	13.59
syntax	$F(1,24)=$			24.62***	24.53***
	$MSE=$			14.97	16.00
double	$F(1,24)=$				.03
	$MSE=$				12.71

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	22.04***	.05	11.92**	13.46***
	$MSE=$	33.37	28.30	58.27	62.74
capitalization	$F(1,24)=$		15.86***	.03	.05
	$MSE=$		42.45	21.60	28.30
syntax	$F(1,24)=$			17.01***	22.04***
	$MSE=$			37.29	33.37
double	$F(1,24)=$				.189
	$MSE=$				19.84

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	8.86**	.16	3.43	8.85**
	$MSE=$	13.61	6.30	17.57	25.97
capitalization	$F(1,24)=$		11.20**	1.29	.16
	$MSE=$		12.81	8.06	6.30
syntax	$F(1,24)=$			8.35**	8.86**
	$MSE=$			9.18	13.61
double	$F(1,24)=$				.73
	$MSE=$				6.78

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 4. Capitalization and syntax pairwise comparisons 300-500ms.

For the 500-800ms time window across midline sites there was a significant difference between capitalization and control conditions $F(1,24) = 26.30$, $MSE = 30.20$, $P < 0.001$, a significant difference between the syntactic violation and the control $F(1,24) = 16.10$, $MSE = 31.27$, $P < .001$ and a significant difference between the double violation and control condition $F(1,24) = 39.17$, $MSE = 45.46$, $P < 0.001$. There was no significant difference between the double violation and the composite condition. See table 5 for all pairwise comparisons.

Midline

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	26.30***	16.10***	39.17***	51.38***
	$MSE=$	30.20	31.27	45.46	56.76
capitalization	$F(1,24)=$		1.41	16.50***	16.10***
	$MSE=$		23.36	11.91	31.27
syntax	$F(1,24)=$			19.73***	26.30***
	$MSE=$			19.80	30.20
double	$F(1,24)=$				2.91
	$MSE=$				24.36

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	25.91***	14.26***	29.39***	45.30***
	$MSE=$	60.84	61.44	110.89	132.08
capitalization	$F(1,24)=$		2.37	12.34**	14.26***
	$MSE=$		43.145	24.50	61.44
syntax	$F(1,24)=$			15.83***	25.91***
	$MSE=$			47.73	60.84
double	$F(1,24)=$				3.69
	$MSE=$				40.48

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	14.85***	11.34**	19.07***	29.86***
	$MSE=$	24.15	14.97	33.59	49.14
capitalization	$F(1,24)=$		2.75	5.62*	11.34**
	$MSE=$		12.70	7.22	14.97
syntax	$F(1,24)=$			11.29**	14.85***
	$MSE=$			13.36	24.15
double	$F(1,24)=$				3.31
	$MSE=$				13.41

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 5. Capitalization and syntax pairwise comparisons 500-800ms.

For the 300-900ms time window across midline sites there was a significant difference between capitalization and control conditions $F(1,24) = 25.65$, $MSE = 19.90$, $P < 0.001$, a significant difference between the syntactic violation and the control $F(1,24) = 10.79$, $MSE = 19.29$, $P < .001$ and a significant difference between the double violation and control condition $F(1,24) = 35.14$, $MSE = 35.14$, $P < 0.001$. There was no significant difference between the double violation and the composite condition. See table 6 for all pairwise comparisons.

Midline

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	25.65***	10.79**	35.14***	46.30***
	$MSE=$	19.90	19.29	28.43	36.58
capitalization	$F(1,24)=$		4.10	9.23**	10.79**
	$MSE=$		16.24	8.80	19.29
syntax	$F(1,24)=$			23.08***	25.65***
	$MSE=$			12.78	19.90
double	$F(1,24)=$				1.82
	$MSE=$				16.10

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	syntax	double	composite
no violation	$F(1,24)=$	25.47***	10.20**	25.24***	47.04***
	$MSE=$	39.97	37.14	71.81	80.08
capitalization	$F(1,24)=$		4.79*	6.32*	10.20**
	$MSE=$		32.34	17.99	37.14
syntax	$F(1,24)=$			15.80***	25.47***
	$MSE=$			33.80	39.97
double	$F(1,24)=$				3.13
	$MSE=$				24.75

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

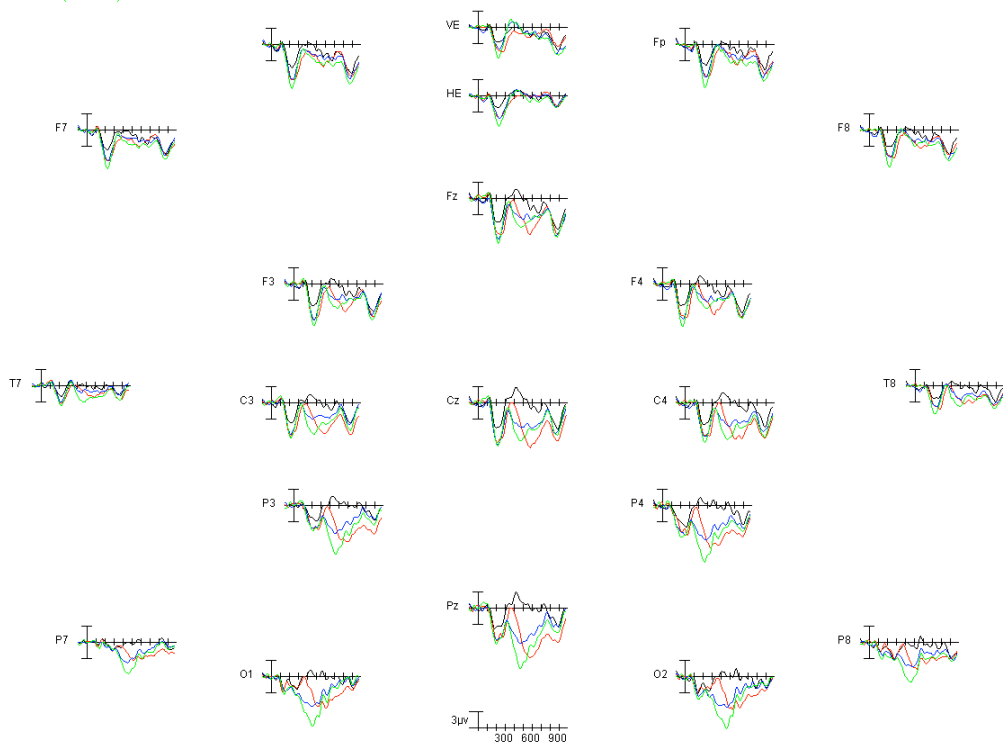
		capitalization	syntax	double	composite
no violation	$F(1,24)=$	12.94***	7.48*	13.77***	28.51***
	$MSE=$	17.00	8.66	21.92	33.16
capitalization	$F(1,24)=$		4.72*	1.04	7.48*
	$MSE=$		9.76	6.19	8.66
syntax	$F(1,24)=$			10.15**	12.94***
	$MSE=$			8.32	17.00
double	$F(1,24)=$				3.57
	$MSE=$				8.50

*** $P < .001$, ** $P < .01$, * $P < .05$

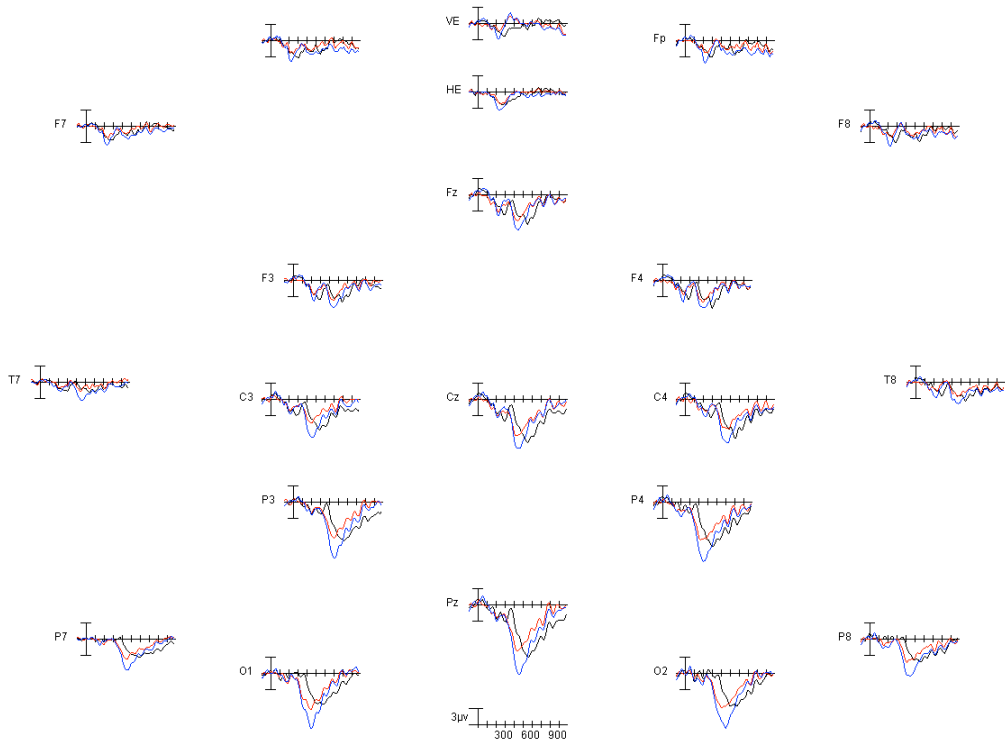
Table 6. Capitalization and syntax pairwise comparisons 300-900ms.

Capitalization and Text Color

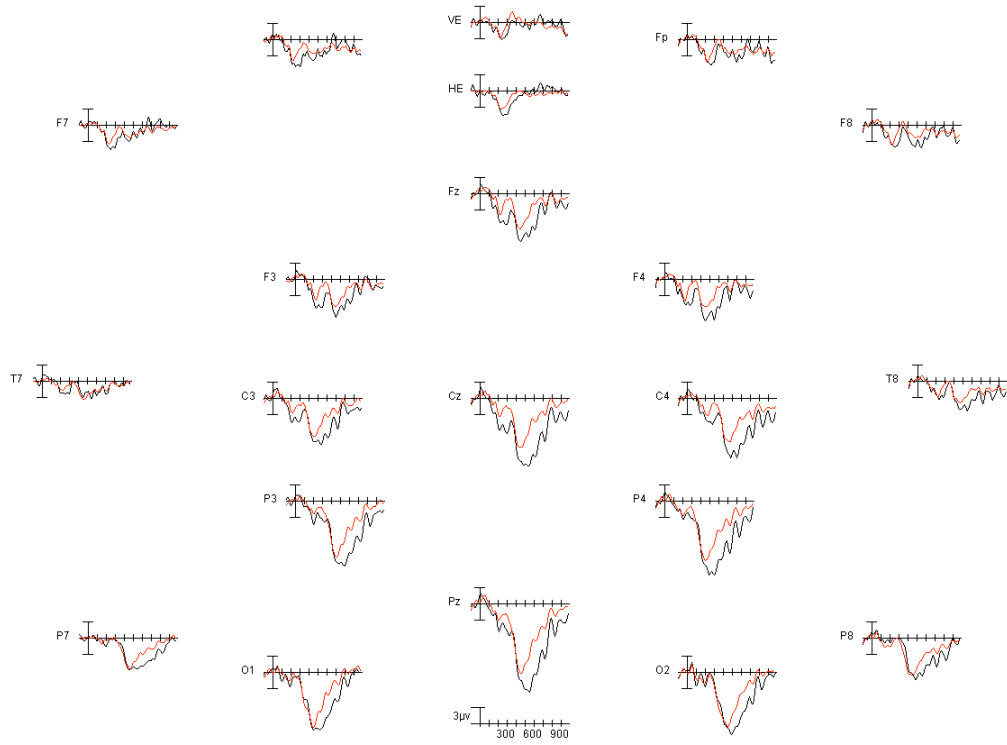
Grand average ERPs for the four critical words are shown in figure 4. The capitalization violation, the color violation, and the double violation all showed a positive-going deflection relative to the control condition, beginning at approximately 200ms. Although broadly distributed, all three deflections are maximal at centro-posterior sites. All three experimental conditions continue to show a positive-going mean amplitude throughout the rest of the epoch at which point the responses to the following word begin to manifest. The omnibus ANOVA on mean amplitude in the 300 to 900ms latency range across midline sites yielded a significant effect of word type $F(3,72) = 25.61$, $MSE = 15.17$, $P < .001$ as well as a word type by electrode interaction $F(6,144) = 9.26$, $MSE = 3.07$, $P < .001$. The Additivity Index calculated at electrode site Pz is $AI = .42$. See figure 4.



A) CONTROL CAPITAL COLOR DOUBLE



B) CAPITAL COLOR DOUBLE



C) **DOUBLE** CAPITAL+COLOR

Figure 4. Waveforms for the Capitalization/Color comparison. A) raw waveforms B.)difference waves C)double violation and composite violation.

Simple effects analysis for the individual violations along the midline sites reveal no significant differences between the experimental conditions and the control condition during the 0-150ms window. There was no significant difference between the double violation and the composite condition for the midline condition. See table 7 for all pairwise comparisons.

Midline

		capitalization	color	double	composite
no violation	$F(1,24)=$	0.22	1.63	0.00	0.68
	$MSE=$	3.84	5.98	7.35	9.20
capitalization	$F(1,24)=$		4.00	0.18	1.63
	$MSE=$		4.09	5.84	5.98
color	$F(1,24)=$			1.57	0.22
	$MSE=$			5.87	3.84
double	$F(1,24)=$				0.44
	$MSE=$				10.09

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	0.03	1.66	0.14	3.09
	$MSE=$	7.53	9.84	11.94	18.02
capitalization	$F(1,24)=$		2.77	0.31	1.66
	$MSE=$		7.34	10.21	9.84
color	$F(1,24)=$			0.83	0.03
	$MSE=$			8.99	7.53
double	$F(1,24)=$				0.30
	$MSE=$				17.30

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	1.16	1.93	0.48	1.39
	$MSE=$	2.89	2.97	4.17	5.52
capitalization	$F(1,24)=$		8.27**	2.44	1.93
	$MSE=$		2.16	4.32	2.97
color	$F(1,24)=$			0.30	1.16
	$MSE=$			3.20	2.89
double	$F(1,24)=$				0.10
	$MSE=$				7.04

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 7. Capitalization and text color pairwise comparisons 0-150ms.

For the 150-300ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 21.77$, $MSE = 7.21$, $P < 0.001$, a significant differences between the color and control condition $F(1,24) = 24.00$, $MSE = 6.03$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,24) = 15.06$, $MSE = 15.15$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 9.52$, $MSE = 9.38$, $P < 0.01$. See table 8 for all pairwise comparisons.

Midline

		capitalization	color	double	composite
no violation	$F(1,24)=$	21.77***	24.00***	15.06***	99.95***
	$MSE=$	7.21	6.03	15.15	19.72
capitalization	$F(1,24)=$		0.04	0.82	24.00***
	$MSE=$		6.53	8.10	6.03
color	$F(1,24)=$			0.97	21.77***
	$MSE=$			9.74	7.21
double	$F(1,24)=$				9.52**
	$MSE=$				9.38

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	14.92***	17.54***	18.24***	71.02***
	$MSE=$	19.74	13.75	30.21	48.92
capitalization	$F(1,24)=$		0.20	2.48	17.54***
	$MSE=$		13.07	16.08	13.75
color	$F(1,24)=$			3.78	14.92***
	$MSE=$			16.70	19.74
double	$F(1,24)=$				3.70
	$MSE=$				22.98

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	10.53**	9.31**	18.19***	53.79***
	$MSE=$	7.16	6.15	11.19	17.82
capitalization	$F(1,24)=$		0.32	4.34*	9.31**
	$MSE=$		3.90	7.19	6.15
color	$F(1,24)=$			9.69**	10.53**
	$MSE=$			4.63	7.16
double	$F(1,24)=$				0.39
	$MSE=$				10.05

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 8. Capitalization and text color pairwise comparisons 150-300ms.

For the 300-500ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 26.19$, $MSE = 16.60$, $P < 0.001$, a significant difference between the color and control condition $F(1,24) = 53.87$, $MSE = 19.08$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,24) = 47.68$, $MSE = 38.97$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 6.51$, $MSE = 14.76$, $P < 0.05$. See table 9 for all pairwise comparisons.

Midline

		capitalization	color	double	composite
no violation	$F(1,24)=$	26.19***	53.87***	47.68***	40.53***
	$MSE=$	16.60	19.08	38.97	54.04
capitalization	$F(1,24)=$		8.40**	24.19***	53.87***
	$MSE=$		14.96	20.48	19.08
color	$F(1,24)=$			9.74**	26.19***
	$MSE=$			12.54	16.60
double	$F(1,24)=$				6.51*
	$MSE=$				14.76

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	20.68***	44.52***	51.08***	40.05***
	$MSE=$	37.47	40.59	72.05	114.98
capitalization	$F(1,24)=$		7.63*	28.25***	44.52***
	$MSE=$		28.22	38.16	40.59
color	$F(1,24)=$			15.96***	20.68***
	$MSE=$			20.66	37.47
double	$F(1,24)=$				2.56
	$MSE=$				36.61

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	10.71**	19.14***	28.54***	30.08***
	$MSE=$	11.86	13.75	24.19	29.54
capitalization	$F(1,24)=$		2.82	15.27***	19.14***
	$MSE=$		8.71	14.75	13.75
color	$F(1,24)=$			16.48***	10.71**
	$MSE=$			6.13	11.86
double	$F(1,24)=$				0.11
	$MSE=$				13.59

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 9. Capitalization and text color pairwise comparisons 300-500 ms.

For the 500-800ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 46.37$, $MSE = 23.00$, $P < 0.001$, a significant difference between the color violation and the control $F(1,24) = 19.84$, $MSE = 16.99$, $P < 0.001$ and a significant difference between the double violation and control condition $F(1,24) = 44.88$, $MSE = 66.88$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 19.87$, $MSE = 32.12$, $P < 0.001$. See table 10 for all pairwise comparisons.

Midline

		capitalization	color	double	composite
no violation	$F(1,24)=$	46.37***	19.84***	33.58***	44.88***
	$MSE=$	23.00	16.99	19.76	66.88
capitalization	$F(1,24)=$		16.49***	4.48*	19.84***
	$MSE=$		12.40	10.63	16.99
color	$F(1,24)=$			4.01	46.37***
	$MSE=$			13.66	23.00
double	$F(1,24)=$				19.87***
	$MSE=$				32.12

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	41.18***	19.22***	38.62***	44.60***
	$MSE=$	44.37	31.51	33.54	123.71
capitalization	$F(1,24)=$		15.06***	1.80	19.22***
	$MSE=$		21.83	25.32	31.51
color	$F(1,24)=$			6.05*	41.18***
	$MSE=$			21.39	44.37
double	$F(1,24)=$				14.64***
	$MSE=$				67.22

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	27.03***	13.90***	31.54***	37.06***
	$MSE=$	13.21	10.79	11.44	34.42
capitalization	$F(1,24)=$		7.24*	0.00	13.90***
	$MSE=$		6.11	8.09	10.79
color	$F(1,24)=$			8.92**	27.03***
	$MSE=$			5.11	13.21
double	$F(1,24)=$				7.51*
	$MSE=$				19.64

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 10. Capitalization and text color pairwise comparisons 500-800ms.

For the 300-900ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 43.79$, $MSE = 14.67$, $P < 0.001$, a significant difference between the color violation and the control $F(1,24) = 32.03$, $MSE = 13.27$, $P < 0.001$ and a significant difference between the double violation and control condition $F(1,24) = 42.28$, $MSE = 19.49$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 15.99$, $MSE = 18.63$, $P < 0.001$. See table 11 for all pairwise comparisons.

Midline

		capitalization	color	double	composite
no violation	$F(1,24)=$	43.79***	32.03***	42.28***	56.68***
	$MSE=$	14.67	13.27	19.49	43.46
capitalization	$F(1,24)=$		2.24	1.26	32.03***
	$MSE=$		10.01	8.95	13.27
color	$F(1,24)=$			5.82*	43.79***
	$MSE=$			11.25	14.67
double	$F(1,24)=$				15.99***
	$MSE=$				18.63

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	color	double	composite
no violation	$F(1,24)=$	40.65***	30.65***	50.13***	56.74***
	$MSE=$	27.64	24.96	32.61	84.55
capitalization	$F(1,24)=$		1.87	2.45	30.65***
	$MSE=$		18.37	19.50	24.96
color	$F(1,24)=$			8.88**	40.65***
	$MSE=$			18.39	27.64
double	$F(1,24)=$				10.89**
	$MSE=$				39.52

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

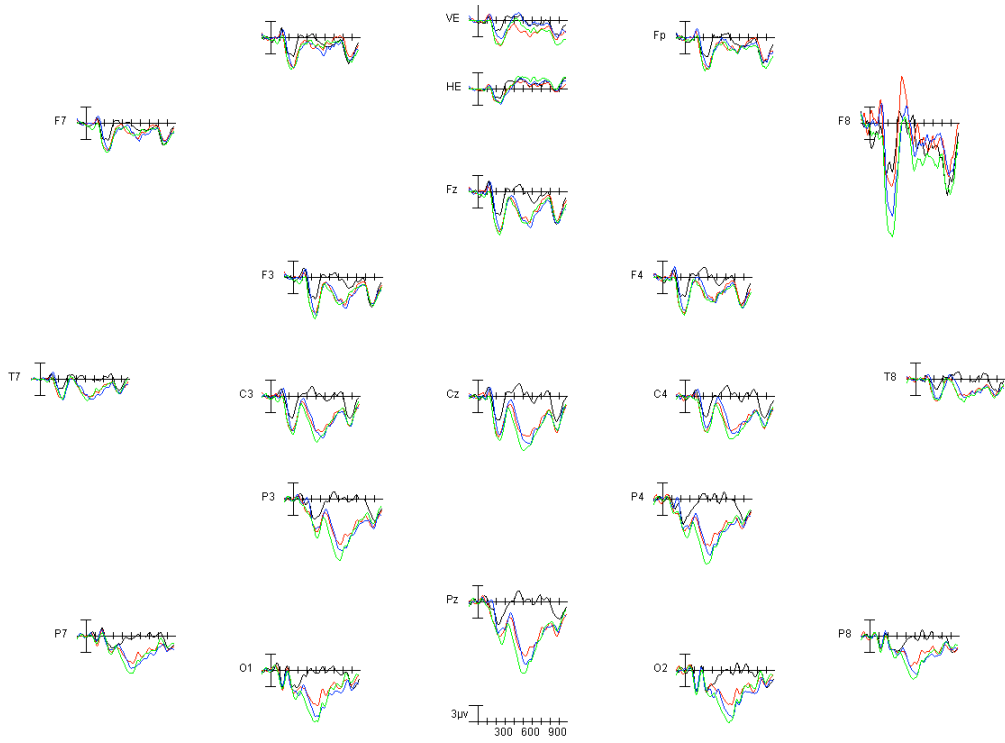
		capitalization	color	double	composite
no violation	$F(1,24)=$	25.71***	16.28***	33.37***	46.85***
	$MSE=$	8.36	9.24	11.78	22.83
capitalization	$F(1,24)=$		1.07	3.74	16.28***
	$MSE=$		5.38	7.13	9.24
color	$F(1,24)=$			12.25**	25.71***
	$MSE=$			4.67	8.36
double	$F(1,24)=$				4.12
	$MSE=$				12.25

*** $P < .001$, ** $P < .01$, * $P < .05$

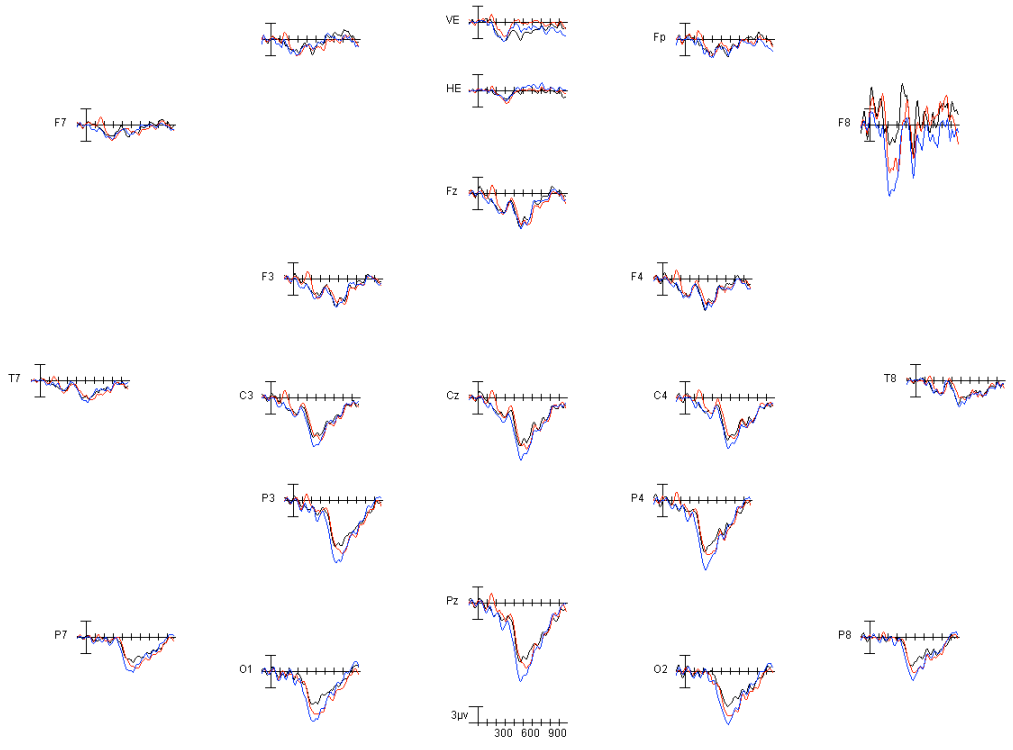
Table 11. Capitalization and text color pairwise comparisons 300-900ms.

Capitalization and Font

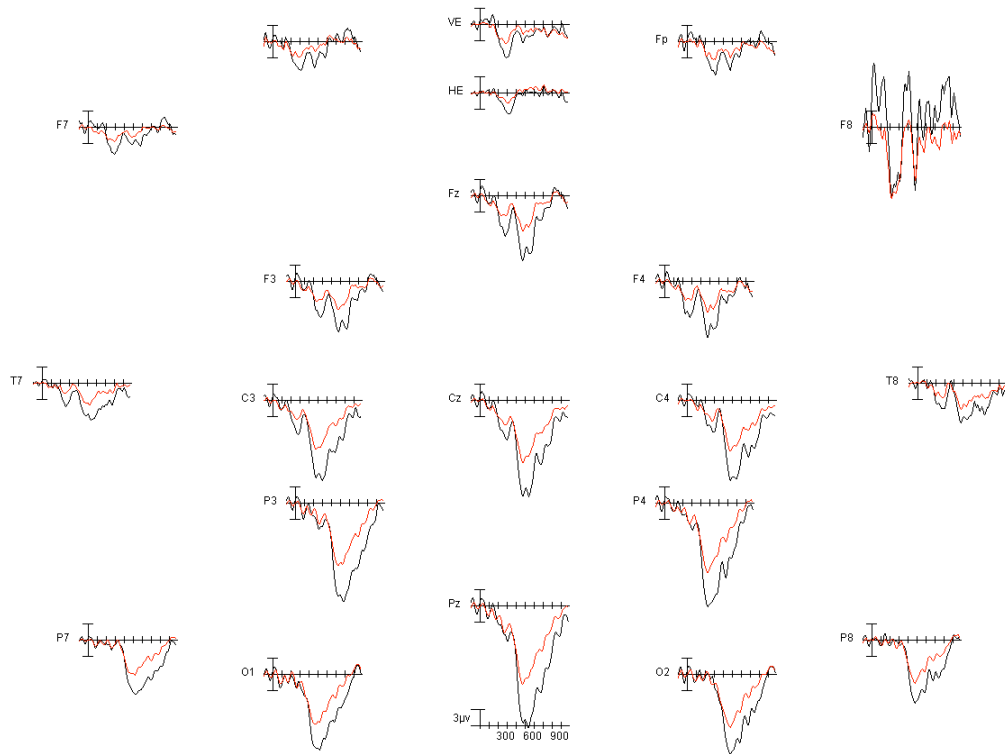
Grand average ERPs for the four critical words are shown in figure 5. The capitalization violation as well as the double violation showed a positive-going deflection relative to the control condition beginning at approximately 200ms. The syntactic violation begins to diverge from the control condition at approximately 300ms showing a large, positive deflection that is maximally represented at centro-posterior sites. The capitalization and the double condition also show an increased positivity beginning at 300ms. All three experimental conditions continue to show a positive-going mean amplitude throughout the rest of the epoch, at which point the responses to the following word begin to manifest. The omnibus ANOVA on the mean amplitude in the 300 to 900ms latency range across midline sites yielded a significant effect of word type $F(3,72) = 52.05$, $MSE = 14.35$, $P < .001$. as well as a word type by electrode interaction $F(6,144) = 32.99$, $MSE = 3.12$, $P < .001$. The Additivity Index = .20. See figure 5.



A) CONTROL CAPITAL FONT DOUBLE



B) CAPITAL FONT DOUBLE



C) **DOUBLE CAPITAL+COLOR**

Figure 5. Waveforms for the Capitalization/Font comparison. A) raw waveforms
 B.)difference waves C)double violation and composite violation.

Simple effects analysis for the individual violations along the midline sites reveal no significant differences between the experimental conditions and the control condition during the 0-150ms window. There was no significant difference between the double violation and the composite condition across the midline sites. See table 12 for all pairwise comparisons.

Midline electrode sites capitalization vs. font

		capitalization	font	double	composite
no violation	$F(1,24)=$	.02	.65	2.08	.01
	$MSE=$	5.57	8.39	5.15	9.34
capitalization	$F(1,24)=$		.66	2.58	.65
	$MSE=$		5.88	3.27	8.39
font	$F(1,24)=$			.11	.02
	$MSE=$			7.86	5.57
double	$F(1,24)=$				.02
	$MSE=$				14.07

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	.14	.53	2.42	.90
	$MSE=$	12.16	16.43	9.75	18.59
capitalization	$F(1,24)=$		.25	1.74	.53
	$MSE=$		10.94	7.27	16.43
font	$F(1,24)=$			.27	.14
	$MSE=$			13.55	12.16
double	$F(1,24)=$				.01
	$MSE=$				28.73

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	.68	.20	.97	.36
	$MSE=$	13.26	9.63	3.01	16.68
capitalization	$F(1,24)=$		.67	1.88	.20
	$MSE=$		3.84	11.83	9.63
font	$F(1,24)=$			1.14	.68
	$MSE=$			8.46	13.26
double	$F(1,24)=$				1.03
	$MSE=$				36.34

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 12. Capitalization and font pairwise comparisons 0-150ms.

For the 150-300ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 34.51$, $MSE = 7.63$, $P < 0.001$, a significant differences between the font and control condition $F(1,24) = 7.56$, $MSE = 10.56$, $P < 0.05$, and a significant difference between the double violation and control condition $F(1,24) = 37.28$, $MSE = 9.35$, $P < 0.001$. There was no significant difference between the double violation and the composite condition. See table 13 for all pairwise comparisons.

Midline

		capitalization	font	double	composite
no violation	$F(1,24)=$	34.51***	7.56*	37.28***	108.79***
	$MSE=$	7.63	10.56	9.35	17.96
capitalization	$F(1,24)=$		4.71*	.60	7.56
	$MSE=$		11.31	9.97	10.56*
font	$F(1,24)=$			12.73**	34.51***
	$MSE=$			7.45	7.63
double	$F(1,24)=$				2.82
	$MSE=$				14.95

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	28.15***	6.89*	29.21***	119.20***
	$MSE=$	14.56	20.55	19.82	32.61
capitalization	$F(1,24)=$		2.94	.74	6.89*
	$MSE=$		23.70	19.67	20.55
font	$F(1,24)=$			9.91**	28.15***
	$MSE=$			14.92	14.56
double	$F(1,24)=$				2.50
	$MSE=$				26.18

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	24.06***	2.97	4.84*	15.32***
	$MSE=$	5.11	25.81	60.91	95.34
capitalization	$F(1,24)=$		.23	.67	2.97
	$MSE=$		24.06	55.29	25.81
font	$F(1,24)=$			5.24*	24.06***
	$MSE=$			13.48	5.11
double	$F(1,24)=$				.49
	$MSE=$				14.72

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 13. Capitalization and font pairwise comparisons 150-300ms.

For the 300-500ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 120.05$, $MSE = 13.51$, $P < 0.001$, a significant difference between the font and control condition $F(1,24) = 47.30$, $MSE = 23.39$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,24) = 96.03$, $MSE = 27.66$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 26.27$, $MSE = 18.48$, $P < 0.001$. See table 14 for all pairwise comparisons.

Midline

		capitalization	font	double	composite
no violation	$F(1,24)=$	120.05***	47.30***	96.03***	78.95***
	$MSE=$	13.51	23.39	27.66	64.01
capitalization	$F(1,24)=$		3.14	10.72**	47.30***
	$MSE=$		15.67	11.84	23.39
font	$F(1,24)=$			25.69***	120.05***
	$MSE=$			13.00	13.51
double	$F(1,24)=$				26.27***
	$MSE=$				18.41

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	125.97***	47.48***	111.64***	87.69***
	$MSE=$	22.12	45.46	43.74	116.38
capitalization	$F(1,24)=$		1.17	13.26***	47.48***
	$MSE=$		34.20	22.03	45.46
font	$F(1,24)=$			19.61***	125.97***
	$MSE=$			27.98	22.12
double	$F(1,24)=$				21.75***
	$MSE=$				39.65

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	25.03***	25.87***	57.31***	55.47***
	$MSE=$	15.88	12.99	15.06	31.38
capitalization	$F(1,24)=$		.08	2.66	25.87***
	$MSE=$		31.30	33.53	12.99
font	$F(1,24)=$			18.59***	25.03***
	$MSE=$			6.57	15.88
double	$F(1,24)=$				3.50
	$MSE=$				22.61

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 14. Capitalization and font pairwise comparisons 300-500ms.

For the 500-800ms time window across midline sites, there was a significant difference between capitalization and control conditions $F(1,24) = 67.84$, $MSE = 22.25$, $P < 0.001$, a significant difference between the font violation and the control $F(1,24) = 56.34$, $MSE = 30.32$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,24) = 98.10$, $MSE = 15.50$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 36.59$, $MSE = 46.38$, $P < 0.001$. See table 15 for all pairwise comparisons.

Midline

		capitalization	font	double	composite
no violation	$F(1,24)=$	67.84***	56.34***	98.10***	72.92***
	$MSE=$	22.25	30.32	15.50	94.40
capitalization	$F(1,24)=$		.81	.00	56.34***
	$MSE=$		7.60	7.67	30.32
font	$F(1,24)=$			.59	67.84***
	$MSE=$			9.23	22.25
double	$F(1,24)=$				36.59***
	$MSE=$				46.38

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	64.58***	59.22***	109.58***	81.48***
	$MSE=$	39.25	51.35	24.05	151.49
capitalization	$F(1,24)=$		1.45	.06	59.22***
	$MSE=$		15.82	15.88	51.35
font	$F(1,24)=$			.78	64.58***
	$MSE=$			18.70	39.25
double	$F(1,24)=$				34.38***
	$MSE=$				85.31

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	36.13***	35.20***	83.67***	71.58***
	$MSE=$	17.52	20.66	8.48	46.15
capitalization	$F(1,24)=$		.55	.16	35.20***
	$MSE=$		5.99	14.00	20.66
font	$F(1,24)=$			.01	36.13***
	$MSE=$			14.71	17.52
double	$F(1,24)=$				12.40**
	$MSE=$				52.41

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 15. Capitalization and font pairwise comparisons 500-800ms.

For the 300-900ms time window across midline sites there was a significant difference between capitalization and control conditions $F(1,24) = 77.12$, $MSE = 14.22$, $P < 0.001$, a significant difference between the font violation and the control $F(1,24) = 57.56$, $MSE = 17.87$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,24) = 104.96$, $MSE = 12.53$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,24) = 32.47$, $MSE = 25.78$, $P < 0.001$. See table 16 for all pairwise comparisons.

Midline

		capitalization	font	double	composite
no violation	$F(1,24)=$	77.12***	57.56***	104.96***	91.37***
	$MSE=$	14.22	17.87	12.53	53.28
capitalization	$F(1,24)=$		.14	1.33	57.56***
	$MSE=$		7.90	7.41	17.87
font	$F(1,24)=$			2.62	77.12***
	$MSE=$			6.71	14.22
double	$F(1,24)=$				32.47***
	$MSE=$				25.78

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	74.10***	60.92***	128.66***	104.90***
	$MSE=$	24.75	31.02	18.29	87.22
capitalization	$F(1,24)=$		.03	2.26	60.92***
	$MSE=$		16.27	14.31	31.02
font	$F(1,24)=$			1.72	74.10***
	$MSE=$			14.78	24.75
double	$F(1,24)=$				28.38***
	$MSE=$				50.30

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		capitalization	font	double	composite
no violation	$F(1,24)=$	27.21***	36.50***	84.39***	80.70***
	$MSE=$	13.87	10.72	6.42	26.96
capitalization	$F(1,24)=$		.02	.89	36.50***
	$MSE=$		7.43	16.64	10.72
font	$F(1,24)=$			1.30	27.21***
	$MSE=$			9.42	13.87
double	$F(1,24)=$				6.90*
	$MSE=$				36.80

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 16. Capitalization and font pairwise comparisons 300-900ms.

Discussion

In order to test the validity of the Additivity Index (AI), we compared ERPs elicited by three pairs of distinct stimulus features: capitalization/syntax, capitalization/color and capitalization/font. Within each pair, neither, one, or both of the features appeared in an anomalous (unexpected) form. As described by Helmholtz (Kahl, 1971), electrical signals sum in time and space. Therefore, given complete independence of the neural responses to the two anomalies, the amplitude of the total ERP response elicited by two co-occurring anomalies should approximate the mathematical sum of the individual waveforms produced by each anomaly presented in isolation (assuming minimal noise). We report that the AI varied parametrically in the predicted direction with the least similar pair, capitalization/syntax, producing the largest Additivity Index, $AI = .85$; capitalization/color producing an $AI = .42$, describing partial independence; and capitalization/font producing an $AI = .20$, demonstrating a relative lack of independence (see figure 6).

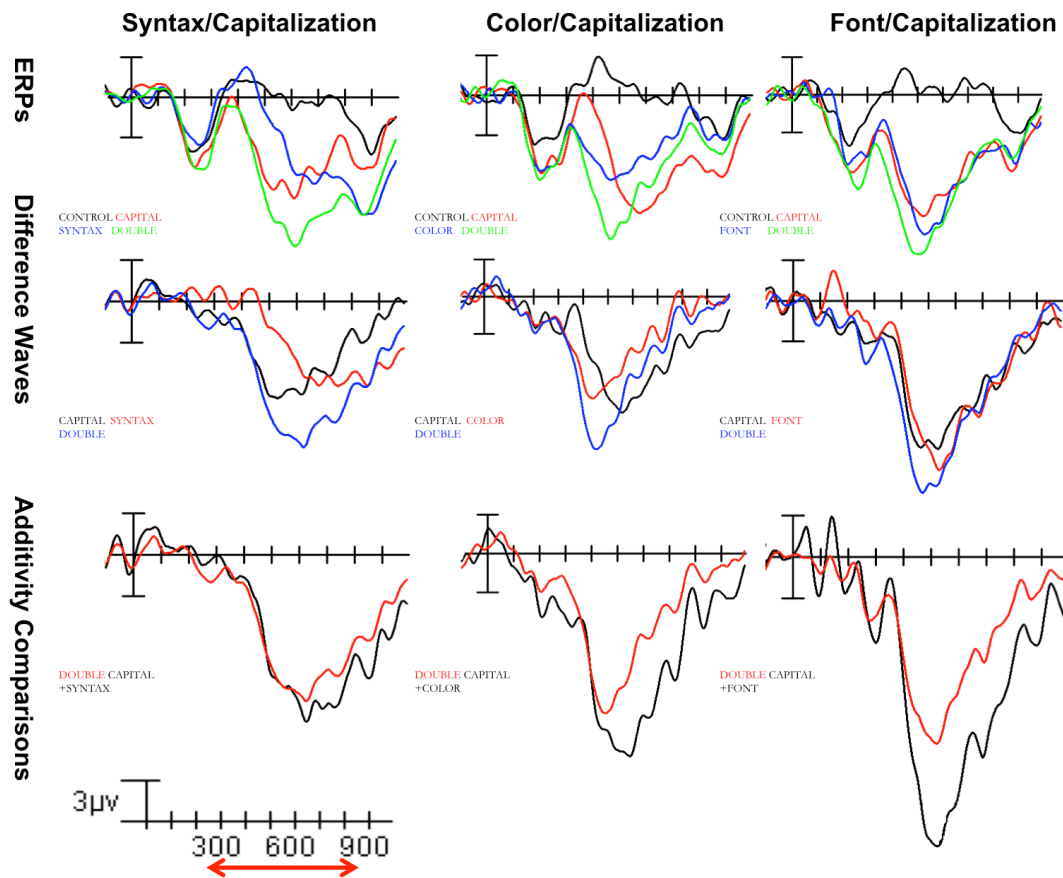


Figure 6. Waveform transformations at electrode site Pz for the three additivity comparisons.

Described in terms of overlap in processing, we can summarize this as follows: anomalies involving syntax and capitalization engage very different neural processes, or the brain 'considers' syntax and capitalization to be highly separate features. Anomalies involving capitalization and font, however, seem to engage very similar neural processes, i.e., the brain considers them to be in the same category (e.g., anomalies involving font). The pairing of capitalization and font color falls close to the midpoint between these two extremes (see figure 7).

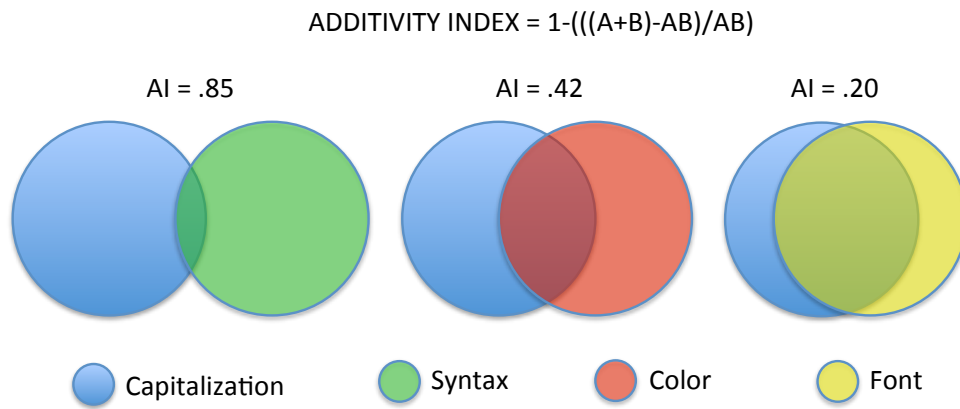


Figure 7. Visual representation of the overlap in neurocognitive resources for capitalization/syntax, capitalization/color and capitalization/font.

An alternative interpretation of our results is that the ERP effects reflect a single “anomaly response,” even for stimuli with two anomalous features, and that the amplitude of the response is a function of the “degree of oddness,” that is, the degree of deviation from what is expected. However, prior work has found that the degree of deviation (along a single dimension) is not associated with robust changes in amplitude of the ERP waveform and that the changes that do occur never approximate an additive function (i.e., a doubling of oddness does not result in a doubling of waveform amplitude). For example, Polich (2007) manipulated the deviance in pitch or loudness of occasional “oddball” stimuli, relative to a “standard” stimulus. These manipulations had robust effects on the peak latency of the P300 response to the oddballs, but minimal effects on P300 amplitude. Furthermore, in the present study, each of the doubly anomalous stimuli deviated in two ways from a “standard” (non-anomalous) stimulus. It therefore seems unlikely that our results reflect a generic, one-dimensional metric of deviance from a standard stimulus.

Historically, the standard method for assessing independence in the neural response to a pair of stimuli has relied on demonstrating anatomical segregation of the associated neural responses, through neuroimaging techniques in humans and staining or electrophysiological recordings in animals. Features are considered to be processed independently only to the degree that the relevant neural activation is segregated in different locations. By contrast, the Additivity Index would differentiate between processes that are subserved by different neural systems even when they are not anatomically distinct. For example, if two stimulus features were processed by independent populations of cells that happened to be interspersed

within the same gross anatomical area, then a localizationist approach would find it nearly impossible to discriminate between the possibility of one homogeneous population that processed both features and two separate populations that each processed a single feature independently. The Additivity Index, at least in many such instances, would be able to assess the neural independence of two sources even when they overlap in space. Another advantage of the present method is that it provides a means for isolating the brain activity of interest. For example, because difference waves were used to compute the Additivity Index (thereby removing effects of visual processing and other “shared processes”), the comparison of processing resources was limited to just those that are specific to the violation of a particular stimulus feature.

A third advantage of the method described here is that it provides a continuous scale ranging from 0 (no additivity) to 1 (perfect additivity). Previously, ERP investigators have tended to treat the “independence” of two putative processes or brain responses as a binary feature (“independent” vs. “not independent”; Osterhout 1996, King and Kutas; Osterhout and Nicol 1999; Coulson, King & Kutas, 1998). Although the binary characterization has theoretical value, it most likely oversimplifies the cortical dynamics underlying real-time cognition. Importantly, the AI might prove to be a remarkably transparent and general metric of similarity and categorization. Stimulus features that the brain treats as exemplars of a single category (such as the orthographic features of font type and shape), are likely to be processed more similarly (less independently) than stimulus features

that are from different categories (for example, case anomalies and syntactic anomalies).

There are, however, two fundamentally different possibilities as to why a particular set of features gets treated by the brain as categorically similar or dissimilar. The first is that the independence or non-independence of the response is a reflection of neural organization. The visual system, for instance, has partially independent circuitry for processing form and color. The strong non-independence ($AI = .20$) of font and capitalization relative to color and capitalization ($AI = .42$) may therefore reflect fixed fundamental differences in the circuits necessary to process the features unrelated to the particulars of the task. If this were the case, then the Additivity Index would be a measure of natural categories that are fixed and reflect the modular organization of the brain. In other instances, however, the neural categorization of features might be functional and context dependent. In these instances, the AI might change as a function of task demands. For instance, if subjects were given explicit instructions that an anomaly in font called for the participant to judge that trial to be “unacceptable,” whereas an anomaly in capitalization was to be judged as “acceptable,” a fixed categories explanation would predict that the Additivity Index would remain unchanged, while a fluid categories model would predict that separate processes would be engaged, as we have now explicitly informed subjects that font and capitalization are now members of separate categories—one a violation, one not—and we would expect the Additivity Index to increase substantially, reflecting the independence of the processing of the two features in this alternate context.

Although the current data do not allow us to differentiate between these two possibilities, the graded nature of the Additivity Index across the three different pairs, all of which were given in identical contexts, suggests that, at least to a degree, the AI is a reflection of natural categories. It is possible that both natural and contextual factors mediate functional categorization, such that part of the independence of two features is a reflection of some underlying fixed neural organization and another portion of their independence is reliant on whether task demands call for subjects to treat them the same.

One notable limitation of the Additivity Index is that it requires that the components be at least partially overlapping in time. This is necessary as, if the components of interest are completely separate, it is impossible to exclude the possibility that a single source is producing them consecutively, and given this case the Additivity Index would overrepresent their independence. One method of addressing this possibility is to examine the current distribution across the scalp of the components of interest. As long as the difference waves are used for these analyses, differing topographic distributions of current by definition reflects different source distributions and therefore can be used to rule out the possibility of the same source being active for consecutive feature violations. A second issue is that because there will often be some difference in the latencies of the current changes which are elicited by separately processed stimulus violations, it is important to choose an epoch for analysis that is large enough to encompass both deflections. Furthermore, when making comparisons across multiple stimulus pairs, it is important to keep the epochs identical so that there is the same amount of

overlap in the portions of the waveform that are not being driven by the processing of interest. This will serve to minimize distortions of the Additivity Index introduced by processing of common features.

CHAPTER 3: ITALIAN EXPERIMENTS

Introduction

There is significant evidence that learners of a second language (and presumptively children acquiring their L1) go through discrete stages of processing (McLaughlin et al., 2010; Tanner et al., in press.) As discussed previously, one classic division of linguistic processing is between syntax and semantics. Semantically anomalous words in sentences (i.e., words that have a very low or zero cloze probability, but do not violate grammatical rules) evoke a negative-going deflection peaking at approximately 400ms after onset, the N400 component. This is contrasted with words that create a syntactic anomaly by violating the grammar of a particular language although they might be lexically appropriate. Grammatical violations elicit a positive-going deflection peaking at approximately 600ms after stimulus onset.

Work by McLaughlin et al. (2010) has demonstrated that L2 learners do not always show this same segregation of responses (i.e., grammatical violations elicit a P600, and semantic violations elicit an N400). Instead, mounting evidence (McLaughlin, 2010; Tanner et al., in press *A*; Tanner et al., in press *B*) suggests that at early stages of acquisition both semantic and syntactic irregularities result in an N400 response. These studies have not been conducted using a double violation paradigm, so it is impossible to compute additivity and determine to what degree the N400s that are elicited by the grammatical violations are generated by the same sources as those elicited by semantic violations.

As acquisition progresses, various grammatical violations begin to elicit a biphasic (both N400 and P600) when averaged across trials and subjects. When data is examined on the individual subject level it appears as if particular individuals show a strong bias towards the production of a particular component, and indeed, it has been shown repeatedly there is a strong negative correlation between N400 amplitude and P600 amplitude for individuals. It is highly plausible that this pattern extends to the individual trial level with certain stimuli eliciting N400s and others eliciting P600s for a particular subject. However, trial-by-trial analyses are not appropriate using ERP data; just as averaging across subjects who show strong P600 biases and subjects who show strong N400 biases gives the impression that there is a general biphasic response instead of two separate groups of monophasic responses, it is possible that averaging across trials similarly distorts the appearance of patterns in the data (McLaughlin, 2010; Tanner et al., in press A; Tanner et al., in press B).

Furthermore, this line of inquiry into the nature of L2 acquisition has shown that not all grammatical violations transform from one stage to another (i.e., transition from eliciting N400s to eliciting P600s) at the same rate. Some of the factors that seem to influence the rate of what we will refer to as “grammaticalization” are the similarity of a grammatical rule to the rules of the L1 grammar and whether the grammar is phonologically realized, i.e., whether changes in word form are reflected in pronunciation. It has also been reported that grammatical rules in the L2 that have an analog in L1 are grammaticalized in that they transition from an

N400 response to a P600 response more quickly than those that have no L1 analog (McLaughlin, 2010; Tanner et al., in press *A*; Tanner et al., in press *B*).

Although there are several possible interpretations of these data, one major question they raise is whether different grammatical rules are subserved by distinct independent neurocognitive processes, the dynamics of which change over time, or whether there are multiple processing streams and individual grammatical rules that engage these streams to differing degrees based on how strongly they have been grammaticalized. This second possibility provides strong predictions as to what the Additivity Index for two grammatical rules should look like over time.

Assuming two fixed processing streams, one semantic or lexical, the other syntactic or grammar-based, and assuming there is differential activation of these streams by a syntactic violation as that syntactic rule becomes grammaticalized over time. Given two separate grammatical rules at an early stage of acquisition in which neither had been grammaticalized, we would expect violations of both rules to engage the semantic processing stream eliciting N400s and having an Additivity Index approaching 0, reflecting near-complete non-independence of the neural processes being engaged. Then, as one of the grammatical rules became crystalized before the second, we would expect the transition from N400 to P600 to result in a change in the Additivity Index as the relationship between the neural sources processing the two rules becomes independent (one rule engaging the syntactic stream, the other engaging the semantic), which should be reflected in an AI now approaching 1. Finally, as both rules become grammaticalized we should see a return of the Additivity Index towards near zero as both grammatical rules again align with

respect to which processing stream they engage, although it is a different stream than initially shared (now syntactic, previously semantic).

Assuming that L2 acquisition recapitulates L1 acquisition, this same pattern should be seen in children as they progress through language development. We would therefore predict that adult native speakers should engage the syntactic stream almost exclusively²⁷ for grammatical violations and therefore show almost complete non-independence of the processing of those two violations resulting in an Additivity Index approaching 0.

In two experiments, we compared the Additivity Index across two pairs of grammatical violations of article/noun agreement in native Italian speakers. In the first experiment, we examined the relationship between number agreement in article/noun pairs and phonological agreement in article/noun pairs. In the second experiment, we compared the relationship between violations of article noun agreement with respect to number and gender. Italian was chosen as number, gender, and phonological agreement are all marked morphologically at both the article and the noun, a linguistic feature that is not robustly present in English, in which the same article is often used across number (the ship sailed vs. the ships sailed) and gender is almost completely absent.

²⁷ There is evidence that there is a non-trivial degree of individual variation in terms of whether syntactic violations elicit N400s or P600s in native speakers (Inoue, personal communication). Especially when processing is taxed due to complexity of grammar or overall task difficulty, some subjects seem to be more likely to produce N400s in response to syntactic violations. To our knowledge, no one has investigated whether individuals who produce N400s in response to syntactic anomalies do so equally when differing grammatical rules are violated.

In Italian, articles and nouns must agree with respect to multiple grammatical features, among them grammatical number. Number is a semantically meaningful feature in that it reflects meaningful information i.e., quantity. Although articles are fixed in terms of the plurality they reflect (singular vs. plural), nouns are variable in terms of whether they are singular or plural depending on context, and number is marked by the morphology at the end of the noun. Compare this to a feature like grammatical gender which, although also marked by the morphological ending of the noun, is fixed and semi-arbitrary (i.e., an individual noun is either masculine or feminine across all contexts, and there is imperfect correlation between grammatical gender and biological gender) (Barber and Carreiras, 2005).

In Italian, number is marked on both the noun, through the use of affixes, as well as on the definite article, which has multiple complete forms depending on the syntactic context. Number, although semantically meaningful in that it reflects content-based information (i.e., quantity), is considered a grammatical feature. Osterhout and Mobley (1995), provide strong evidence that violations of number agreement engage the morpho-syntactic processing stream, by showing P600 like responses to violations of subject/verb number and reflexive/antecedent number, however, they did not investigate article/noun number. It is, however, possible that there is some degree of lexico-semantic as well as morpho-syntactic processing involved in particular number agreement violations, a possibility supported by Osterhout and Mobley's (1995) observation that, although not statistically significant, there was a tendency for number-agreement violations to elicit a

negative-going deflection for agreement violations relative to their well-formed counterparts, a pattern of response typical of semantic violations²⁸.

Italian article/noun agreement is also phonotactically constrained. There are context-dependent rules that determine which phonological sounds are appropriate depending on the phonology of adjacent words. For masculine article/noun pairs, there are multiple allomorphs of the article depending on the phonology of the noun, particularly the initial phonemes. This is analogous to the use of the indefinite article 'a' or 'an' in English which is constrained by the phonology of the word immediately following. (Molinara et al., 2008, Russi, 2006).

These two rules of article/noun agreement were chosen because of their dissimilarity. As mentioned, number is a semantically meaningful feature that, although engaging morpho-syntactic processing, marks information about quantity on both the article and noun. The allomorphy of masculine definitive articles with respect to phonological agreement with the nouns they use as a referent, however, carries no semantic meaning, and instead is a reflection of surface phonological constraints. These two forms of agreement are therefore a logical place to look for differences in the neural processes subserving different rules for article/noun agreement, and there have been multiple lines of research suggesting that there are processing and representational differences between the allomorphy of the Italian masculine definite article. Molinaro et al. (2008), for instance, present evidence that

²⁸ Osterhout and Mobley (1995) were examining subject/verb agreement in English, and it is possible that the relative employment of the lexico-semantic and morpho-syntactic processing streams differs for subject/verb and article/noun agreement.

phonological and number agreement violations in Italian article/noun pairs each elicit a P600, but with different amplitudes in late time windows (700-900ms), which, along with slight topographic differences, they interpreted as evidence for independence in neural processing.

Methods

Participants

Fourteen native Italian and fifteen native Italian speakers participated in the number/phonology and number/gender experiments, respectively. All participants were right-handed and had normal or corrected-to-normal vision. Participants were paid \$30 for volunteering in the study.

Stimuli

200 Italian sentences were created or edited by native Italian speakers. The experiment used four different lists containing 128 experimental and 72 filler sentences. Each set of experimental sentences contained 32 well-formed and 96 ill-formed article/noun pairs (32 ill-formed each for number, phonology, and double violations). Every list had a different version of each experimental sentence. The article/noun pairs had four forms: correct, numerically anomalous, phonologically/gender anomalous, and doubly anomalous (See tables 17 and 18). Of the 72 filler sentences, 10 contained semantic errors and 10 contained verb agreement errors. The remaining filler sentences were well-formed sentences.

Overall, there were 116 sentences (58%) containing anomalies and 84 (42%) well-formed sentences.

Native Italian speakers read sentences of the type:

Il vecchio legge _____ giornale.

*The old man reads the newspaper.

<i>Experiment 1</i>	<i>Article</i>	<i>Noun</i>
Control	<i>il</i>	<i>giornale</i>
	<i>gli</i>	<i>stivali</i>
Number	<i>i</i>	<i>giornale</i>
	<i>lo</i>	<i>stivali</i>
Phonology	<i>lo</i>	<i>giornale</i>
	<i>i</i>	<i>stivali</i>
Double	<i>gli</i>	<i>giornale</i>
	<i>il</i>	<i>stivali</i>

Table 17. The differing word forms for all conditions in the number/phonology Italian experiment.

Native Italian speakers read sentences of the type:

*Ho comprato _____ **camicia** costosa.*

*I bought the expensive shirt.

<i>Experiment 2</i>	<i>Article</i>	<i>Noun</i>
Control	<i>il</i>	<i>giornale</i>
	<i>la</i>	<i>camicia</i>
Number	<i>i</i>	<i>giornale</i>
	<i>le</i>	<i>camicia</i>
Gender	<i>la</i>	<i>giornale</i>
	<i>il</i>	<i>camicia</i>
Double	<i>le</i>	<i>giornale</i>
	<i>i</i>	<i>camicia</i>

Table 18. The differing word forms for all conditions in the number/gender Italian experiment.

Procedure

Participants read a randomly assigned list of 200 sentences while 19 tin electrodes fitted on an elastic cap (Electro-cap International) at standard positions (10-20 system) recorded continuous EEG. Two electrodes, one placed under the left eye and one placed to right of the right eye, monitored vertical and lateral eye movements, respectively. The 19 scalp electrodes were referenced to an electrode located on the left mastoid bone. The raw EEG was amplified with a bandpass of 0.01-40Hz and sampled at 250Hz. Both the scalp and mastoid electrodes had impedances that were held below 5 k Ω . Only trials during which there was not excessive eye movement, or heart and muscle activity, were used for data analysis.

All participants completed the experiment in an isolated room containing an 18" CRT monitor and amplifying equipment. The stimuli were displayed one word at a time in the center of the monitor. Each sentence began with a fixation cross, followed by the text, and ended with a "Yes/No" screen. The experiment's instructions asked participants to make an acceptability judgment of the sentences using a hand-held controller with buttons that were counter-balanced across sentences. The testing sessions lasted about 1.5 hours.

Continuous analog-to-digital conversion of the EEG and stimulus trigger codes was performed at a sampling frequency of 200Hz. ERPs, time-locked to the onset of the critical word, were averaged off-line for each participant at each electrode site in each condition. Grand averages wave forms were created by averaging over participants. Trials characterized by eye blinks, excessive muscle artifact, or amplifier blocking were not included in the averages; additionally,

subjects who had rejections in over one-third of trials were not included in the analysis. The number of rejections did not differ significantly between conditions or groups.

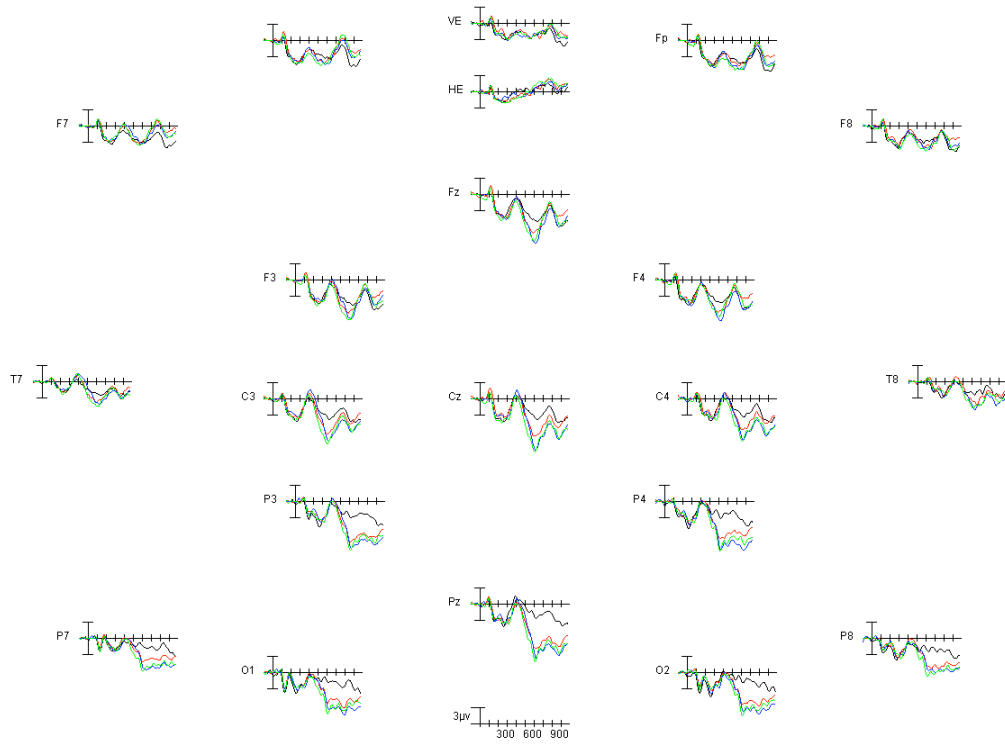
ERP components of interest were quantified by computer as mean voltage within a window of activity. Based on visual inspection of the waveforms, and in order to make meaningful comparisons between this experiment and the initial additivity experiments, we compared mean amplitude across a large window, 300-900ms after stimulus presentation, and comparisons were made relative to a 100ms prestimulus baseline

Within each time window, ANOVAs were calculated with violation type (no violation, number, phonology/gender, double violation, and composite—the mathematical sum of the two single violations) as a within-subjects factor. Data from midline (Fz, Cz, Pz), medio-lateral (right hemisphere: Fp2, F4, C4, P4, O2; left hemisphere: Fp1, F3, C3, P3, O1), and latero-lateral (right hemisphere: F8, T8, P8; left hemisphere: F7, T7, P7) were treated separately in order to identify topographic and hemispheric differences. ANOVAs on midline electrodes included electrode as an additional within-subjects factor (3 levels), ANOVAs on medio-lateral electrodes included hemisphere (2 levels) and electrode (5 levels) as additional within-subjects factors, and ANOVAs over latero-lateral electrodes included hemisphere (2 levels) and electrode (3 levels) as additional within-subjects factors. The Greenhouse-Geisser correction for inhomogeneity of variance was applied to all repeated measures on ERP data with greater than one degree of freedom in the numerator. In such cases, the corrected p-value is reported.

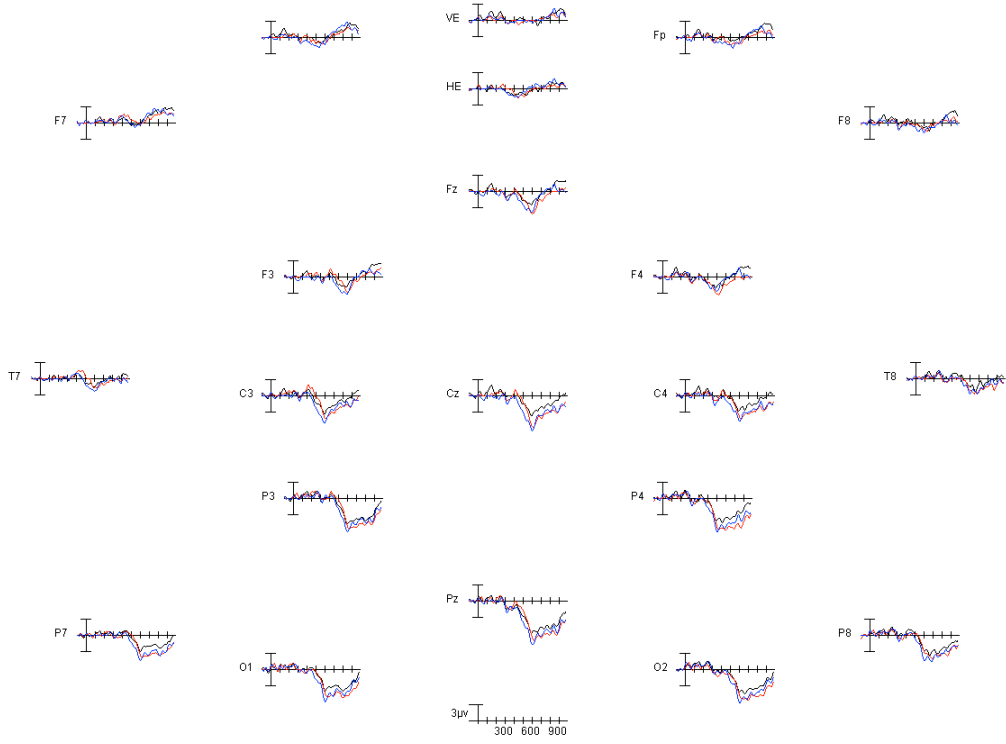
Results

Number/Phonology

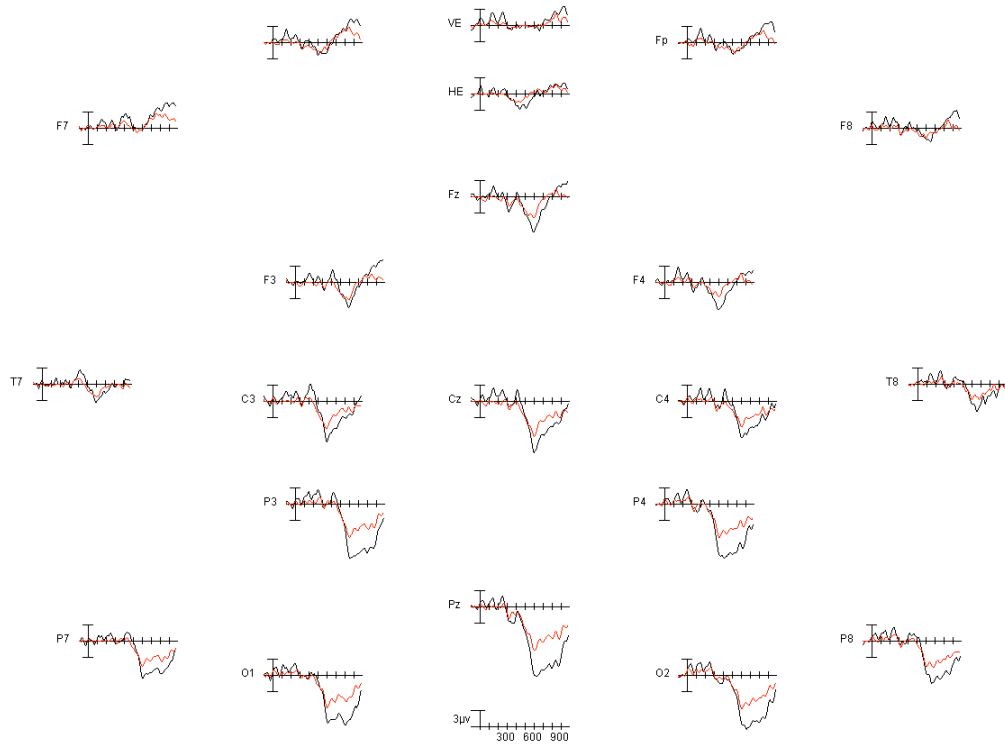
Grand average ERPs for the four critical word types are shown in figure 8. Both single violations (number, phonology) as the double violation showed a large centro-posteriorly-distributed, positive-going deflection relative to the control condition. This deflection begins at approximately 400ms and peaks at approximately 600ms, and continues throughout the epoch. Additionally, visual inspection shows that the double violation waveform overplots the phonology waveform, the amplitude of which is larger than the number waveform. The Additivity Index = .21. See figure 8.



A) Control **Number** Phonology **Double**



B) Number Phonology Double



C) Phonology + Number **Double**

Figure 8. Waveforms for the number/phonology comparison. A) raw waveforms B.)difference waves C)double violation and composite violation.

For the 300-900ms time window across midline sites, there was a significant difference between number and control conditions $F(1,13) = 21.34$, $MSE = 72.84$, $P < 0.001$, a significant difference between the phonology violation and the control $F(1,13) = 29.02$, $MSE = 139.35$, $P < 0.001$, and a significant difference between the double violation and control condition $F(1,13) = 17.96$, $MSE = 164.70$, $P < 0.001$. There was also a significant difference between the double violation and the composite condition $F(1,13) = 6.50$, $MSE = 56.33$, $P < 0.05$. See table 19 for all pairwise comparisons.

Midline electrode sites number vs. phonology

		Number	Phonology	double	composite
no violation	$F(1,13)=$	21.34***	29.02***	17.96**	103.26***
	$MSE=$	72.84	139.35	164.70	916.08
Number	$F(1,13)=$		1.76	2.14	29.02***
	$MSE=$		10.69	18.48	139.35
Phonology	$F(1,13)=$			0.15	21.34***
	$MSE=$			1.059	72.84
double	$F(1,13)=$				6.50*
	$MSE=$				56.33

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		Number	Phonology	double	composite
no violation	$F(1,13)=$	10.00**	14.56**	14.42**	76.71***
	$MSE=$	71.68	184.58	201.60	1699.37
Number	$F(1,13)=$		2.69	3.23	14.56**
	$MSE=$		26.21	32.86	184.58
Phonology	$F(1,13)=$			0.029	10.00**
	$MSE=$			0.38	71.68
double	$F(1,13)=$				3.22
	$MSE=$				61.68

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

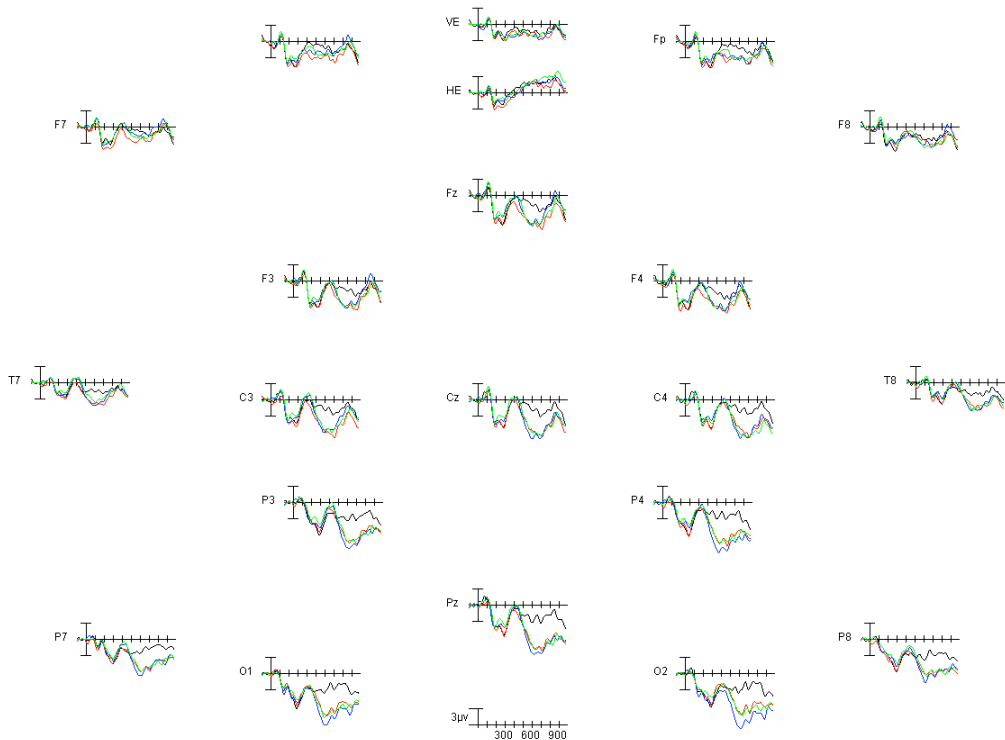
		Number	Phonology	double	composite
no violation	$F(1,13)=$	2.06	8.90*	10.46**	39.15***
	$MSE=$	5.38	25.91	34.37	363.38
Number	$F(1,13)=$		2.38	4.95*	8.90*
	$MSE=$		7.68	12.56	25.91
Phonology	$F(1,13)=$			0.15	2.06
	$MSE=$			0.60	5.38
double	$F(1,13)=$				0.44
	$MSE=$				2.39

*** $P < .001$, ** $P < .01$, * $P < .05$

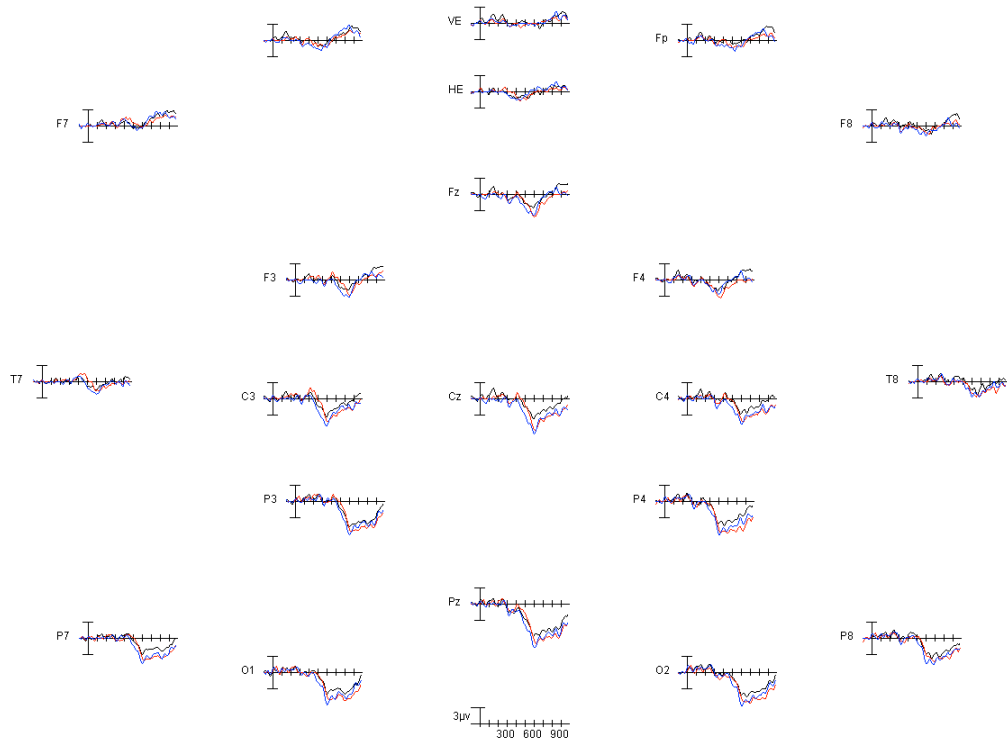
Table 19. Number and phonology pairwise comparisons 300-900ms.

Number/Gender

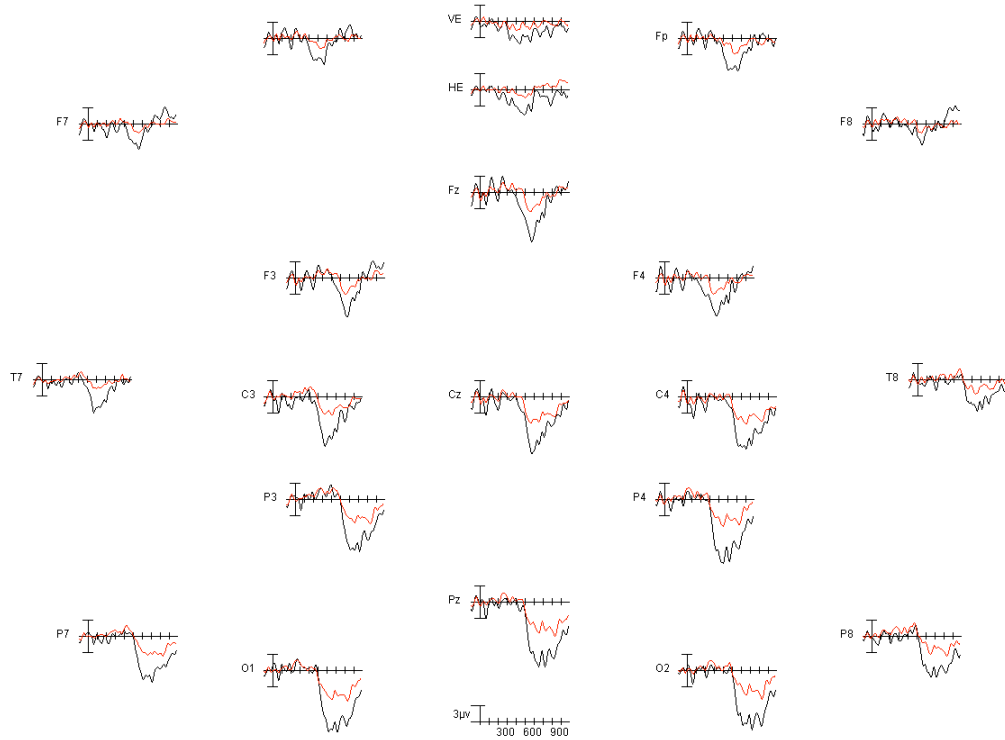
Grand average ERPs for the four critical word types are shown in figure 9. Both single violations (number, phonology) as well as the double violation showed a large centro-posteriorly-distributed, positive-going deflection relative to the control condition. This deflection begins at approximately 400ms and peaks at approximately 600ms and continues throughout the epoch. Interestingly, visual inspection shows that the double violation waveform overplots the number violation waveform, the amplitude of which is smaller than the gender violation waveform. The Additivity Index = -.17. See figure 9.



A) Control **Number** Gender **Double**



B) Number Gender Double



C) Phonology + Gender **Double**

Figure 9. Waveforms for the number/gender comparison. A) raw waveforms B) difference waves C) double violation and composite violation.

For the 300-900ms time window across midline sites, there was a significant difference between number and control conditions $F(1,14) = 11.99$, $MSE = 131.72$, $P < 0.01$, a significant difference between the gender violation and the control $F(1,14) = 6.45$, $MSE = 112.29$, $P < .05$, and a significant difference between the double violation and control condition $F(1,14) = 5.61$, $MSE = 89.28$, $P < 0.05$. There was also a significant difference between the double violation and the composite condition $F(1,14) = 7.45$, $MSE = 159.39$, $P < 0.05$. See table 20 for all pairwise comparisons.

Midline electrode sites number vs. gender

		Number	Gender	double	composite
no violation	$F(1,14)=$	11.99**	6.45*	5.61*	22.40***
	$MSE=$	131.72	112.29	89.28	897.76
Number	$F(1,14)=$		0.073	0.31	6.45*
	$MSE=$		0.78	4.11	112.29
Gender	$F(1,14)=$			0.20	11.99**
	$MSE=$			1.32	131.72
double	$F(1,14)=$				7.45*
	$MSE=$				159.39

*** $P < .001$, ** $P < .01$, * $P < .05$

Medio-lateral

		Number	Gender	double	composite
no violation	$F(1,14)=$	12.96**	7.08*	6.40*	29.44***
	$MSE=$	257.22	275.43	203.64	2465.85
Number	$F(1,14)=$		0.02	0.18	7.08*
	$MSE=$		0.31	3.13	275.43
Gender	$F(1,14)=$			0.29	12.96**
	$MSE=$			5.41	257.22
double	$F(1,14)=$				7.70*
	$MSE=$				337.23

*** $P < .001$, ** $P < .01$, * $P < .05$

Latero-lateral

		Number	Gender	double	composite
no violation	$F(1,14)=$	9.48**	3.61	2.82	23.02***
	$MSE=$	55.18	37.80	29.25	643.92
Number	$F(1,14)=$		0.25	0.55	3.61
	$MSE=$		1.64	4.08	37.80
Gender	$F(1,14)=$			0.05	9.48**
	$MSE=$			0.55	55.18
double	$F(1,14)=$				3.94
	$MSE=$				66.72

*** $P < .001$, ** $P < .01$, * $P < .05$

Table 20. Number and gender pairwise comparisons 300-900ms.

Discussion

The application of the Additivity Index (AI) to multiple rules of grammatical agreement, specifically the morpho-syntax of article/noun agreement allow the evaluation of the independence of the neural substrate subserving the processing of these seemingly different syntactic rules. We report an AI = .20 for number and phonology and AI = -.17 for number and gender (see figure 10).

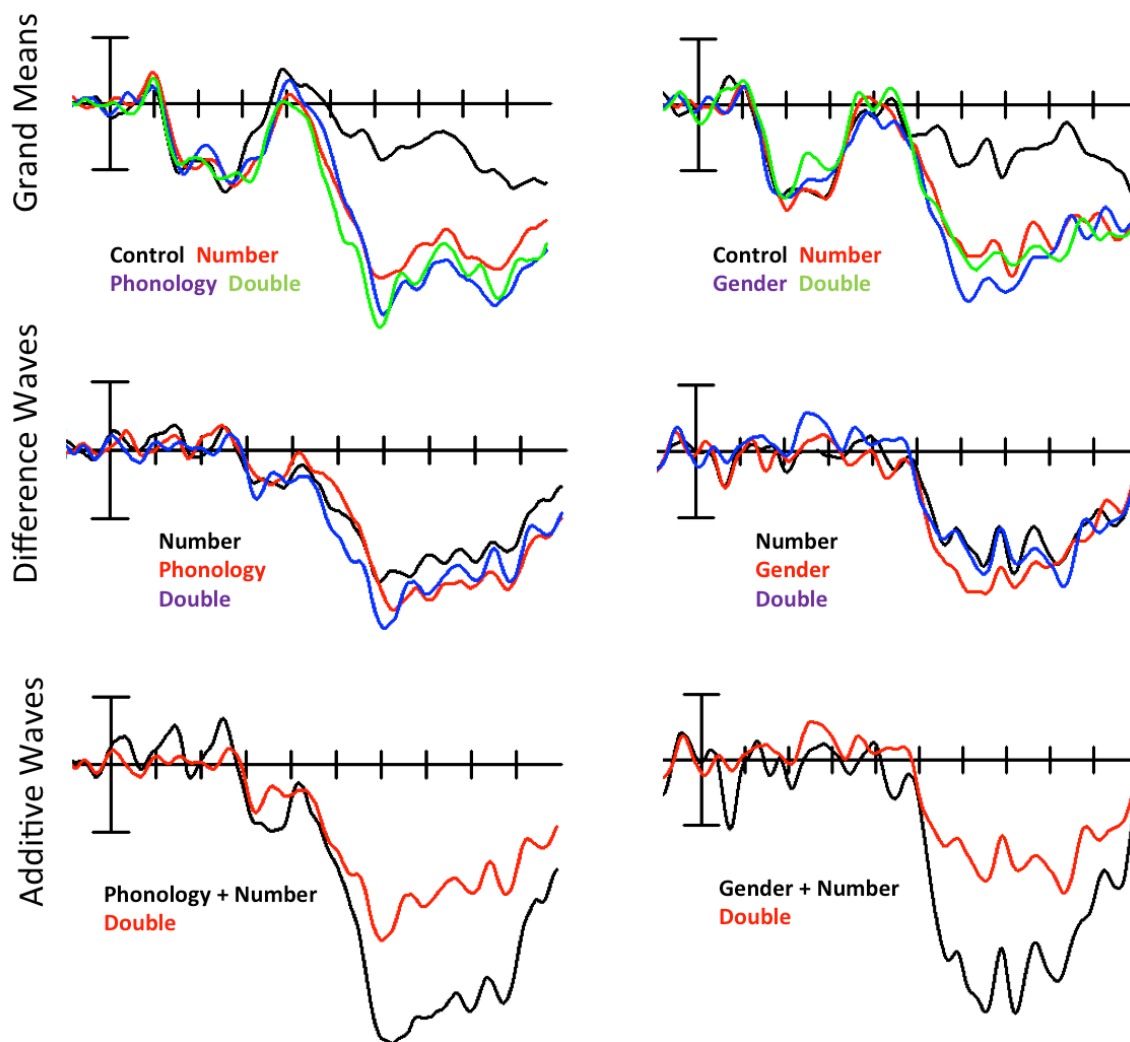


Figure 10. Waveform transformations at electrode site Pz for the two Italian additivity comparisons.

Several investigators have made the argument that differences in the relative amplitude of the waveforms elicited by differing violations of article/noun agreement imply differing and independent processes at work (Molinaro, Vespignani, and Job 2008; Barber and Carreiras, 2005). We suggest that such a binary approach is an inappropriate framing of the dynamics of the underlying processing. We suggest that moving beyond a binary description to a graded one which allows the determination of the degree of independence of the processes at work is a more naturalistic and accurate way of interpreting relationships between the neural generators that underlie the processing of differing syntactic rules.

Furthermore, we suggest that even in the binary framework established by investigators who have used tools that cannot give incremental estimations, such as raw amplitude comparison or topographic analysis, researchers have made an incorrect estimation of the independence of the processors, a claim that demonstrates the fallibility of these binary methods. Both of the comparisons, between article/noun phonological agreement violations and number agreement violations, as well as between article/noun gender agreements violations and number agreement violations yield AI values ($AI = .20$ and $AI = -.17$ respectively) that are insufficiently far from zero to claim independence even if one were to force them into a binary framework (see figure 11).

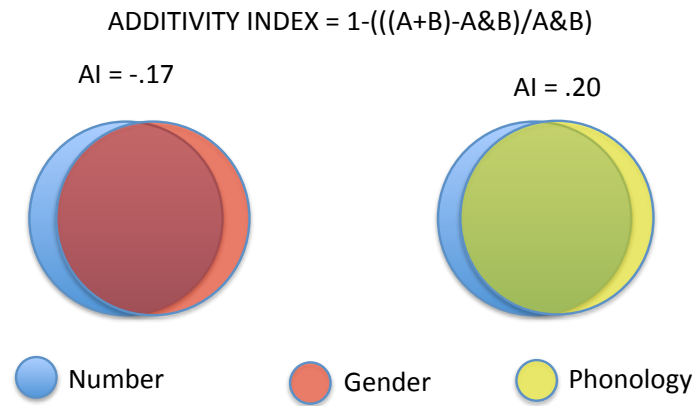


Figure 11. Visual representation of the overlap in neurocognitive resources for number/phonology and number/gender in Italian.

Our interpretation of the negative-going Additivity Index is, as described earlier, a reflection of near complete overlap in resources with the presence of one stimulus feature mediating the response of its shared sources to a second stimulus feature. This interpretation is supported by the overplotting of the double violation to the smaller of the single violations (number). Although when compared independently violations of gender cause a larger positive-going deflection than violations of number, when they co-occur, the waveform elicited by the double violation has the same amplitude as a number violation. Presumably, this has to do with the salience of number and gender violations when they co-occur on the same word. The number violation being so salient it 'captures' the putative processing stream underlying morpho-syntactic evaluation resulting in sub-additivity. We therefore interpret number and gender as being almost completely non-independent in terms of the neural sources that subserve their processing.

Therefore, we think a much more accurate description of the processors is that number and phonological article/noun agreement share a significant amount of processing resources, and number and gender also share a significant number of processing resources.

This difference between the interpretations drawn through the classic methods of amplitude comparison and topographic comparisons and through the novel AI comparisons demonstrates the benefits of using a graded metric for evaluation. We are currently involved in two ongoing lines of research that we think will be greatly benefitted by the application of the Additivity Index, which we describe in chapter 4.

CHAPTER 4: CONCLUSION

Future directions

One problem that is intrinsic to language-related ERP investigations is the need, in many circumstances, to have differing critical words in control and experimental conditions. This creates systematic differences between the words in differing conditions, and these systematic differences often involve differences in the complexity of the morphology. Syntactic violations, for instance, just as in the first experiment reported here, are often created by adding a morpheme to the verb in order to create an ungrammatical sentence “The cat will bake...” as compared to “The cat will bakes...”²⁹. Some preliminary evidence suggests that increases in morphological complexity are correlated with increased positivities in the 500-800ms time window typically associated with the P600 effect which is elicited by, among other things, violations of syntactic agreement. Since many times it is violations of syntactic agreement that are being investigated through the use of critical words with differing morphological complexity, this is problematic. In order to determine if morphological complexity does indeed contribute a positive deflection to the ERP waveform in the 500-800ms time window, and, further, whether this deflection is generated by the some neural processes that underlie the classic syntactic P600, we are currently carrying out two experiments using the double anomaly paradigm that allows the use of the Additivity Index. These two experiments will each be examining the independence of syntactic violations with

²⁹ Although it is possible to address this issue by keeping the critical words constant and altering precritical words, this introduces baseline issues.

morphological complexity. By examining two different ‘quantities’ or morphological complexity between the two experiments, we will also be able to determine whether morphological complexity, if it is a factor that affects the amplitude of the P600 component, is itself graded or binary by examining its relative contribution across the two experiments.

A second issue we will be investigating is the dynamics of second language (L2) acquisition and attrition. As previously described, it has been demonstrated that at the initial stages of L2 acquisition, a wide range of linguistic anomalies, including violations of both lexico-semantic and morpho-syntactic features elicit an N400 effect that is typical of lexico-semantic violations in native speakers but atypical of violations of morpho-syntax (Tanner et al., *B in press*). As acquisition progresses, in most cases, the ERP response elicited by violations of morpho-syntax shifts from an N400 to a more native-like P600. During attrition this process is reversed. As the L2 attrites, morpho-syntactic violations revert from eliciting a P600 to eliciting an N400 effect (Pitkanen et al., *in prep*). In order to determine whether this early-learner syntactic N400 is generated by the same neural substrates that are responsible for generating the classic lexico-semantic N400, we will be carrying out a study using the double-violation paradigm that allows for additivity comparisons examining the relative independence of the components elicited by lexico-semantic violations as well as morpho-syntactic violations in a second language as L2 is acquired and attrited. Understanding the dynamics of acquisition and attrition in L2 is not only interesting on its own, but also may offer insight into the dynamics of the acquisition of a first language by children.

Discussion

Although we believe the Additivity Index is a powerful tool for investigating the cognitive architecture subserving high-level cognitive processing, there are several issues that must be addressed. We suggest that it would be inappropriate to perform an analysis of the Additivity Index if there are not significant differences between both the individual violations as well as the double violation relative to the control condition. Furthermore, we offer a suggestion as to the time windows on which the analysis should be performed, which should include a large enough portion of the waveform to include all components of interest even if they are not present. This window should also minimize the portion of the waveform where there is overlap between the violations and the control condition. We suggest that the best way to determine the appropriate window is through visual examination, noting the time at which there is first differentiation of an experimental condition from the control condition and when all of the experimental conditions return to overplotting the control condition. Two caveats to this are that it may be appropriate to open the window after the initial divergence in the waveforms of one of the experimental conditions and the control condition if there are previously known components that are not of interest in terms of independence, but are present in some of your experimental conditions and not others. For language-related studies, this may include differences in the N1 P2 complex resulting from the visual properties of the stimuli or differences in the P3a (as seen in the first additivity experiment). For such situations, it is important to note when the

divergence is being driven by the components of interest. Furthermore, when judging the end of the window, it is often the case that the waveforms will not resolve and return to overplotting by the end of the typical one-second epoch. For many experimental situations, depending on stimulus presentation rate, this means that the end of a one-second epoch may contain variations in amplitude elicited by downstream stimuli, as is the case in the additivity experiments, and the window used for analyses should not include those time points.

The most significant issue with regards to the interpretation of the Additivity Index is the current inability to determine the amount of noise it captures and therefore the amount of possible error in its measurement of independence. Error is introduced in both trial-by-trial variation within subjects and individual differences between subject responses. Although this noise is in some degree inherent in ERP methods, our inability to estimate its effects on individual Additivity Indices is problematic. Although we cannot estimate the actual amount of noise in the signal, proper time window selection as well as the exclusion of non-significant experimental conditions in additivity calculations should serve to minimize it.

In order to insure that the Additivity Index is providing an accurate measure of the independence of the putative generators responsible for the processing on separate stimulus features, we encourage other investigators to employ it in conjunction with classic methods for source localization. Although imaging methods and electrophysiological source estimation algorithms are, as previously discussed, not ideally suited to answering questions about source independence, they make

excellent confirmational tools when used in addition to the first-principles based

Additivity Index.

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Evaluating models of noun phrase agreement: Evidence from additive ERP techniques

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