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Using Event-Related Potentials in educational research: a contextualized presentation and a review

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Abstract

Cognition could be seen as a cascade of top-down and bottom-up processes across behavioural and psychophysiological layers in a cognitive architecture. Typical behavioural measurements used in education do not give information about lower cognitive layers. Event-Related Potentials (ERPs) derived from electroencephalography allow researchers to look at and assess these lower cognitive layers in tasks pertinent for education, such as reading. This methodology can also record ERPs, which are neural responses linked with particular sensory, cognitive or motor events. Despite some limitations, ERPs are useful in educational settings because they allow to measure processes that are very fast, which is the case in many simple cognitive tasks. They are also very helpful when behavioural measurements cannot be used. However, a challenge in leveraging the potential of neuroscience in education is the requirement for interdisciplinary work. Besides, the technical aspects of the electroencephalogram (EEG) and ERP research represent a huge challenge for the typical educational researcher. The goal of this article is to present a brief contextualized view about the use of ERPs in educational research based on the book written by Luck (2014). This article presents the common challenges in designing ERPs experiments accompanied by a range of possible solutions. The approach is augmented with examples from a review of a field of educational research, which has drawn heavily on neuroscience experiments, namely, reading. This paper extends to current and cutting-edge research by concluding with emerging methods in education such as fixation-related potentials. The EEG can also be very useful to answer particular research questions in education because it provides continuous information in the timescale of milliseconds to assess cognition and affectivity.

Keywords: Educational neuroscience, electroencephalogram; Event-Related Potentials

Introduction

The optimization of learning contexts requires pertinent information corresponding to the rate of change of characteristics of interest pertaining to the learner and to the learning context. Such characteristics can change from state to state very rapidly. Indeed, cognition is seen as a cascade of top-down and bottom-up processes across behavioural and psychophysiological layers in a cognitive architecture (Anderson, 2002). Moreover, a learning task and accompanying context can be conceived of as a hierarchical decomposition of operations which, cumulatively and sequentially, are necessary to complete the task successfully. As represented in Table 1, in the biological band, organelles, neurons and neural circuits exchange chemical and electrical information; this is the biological implementation which produces cognitive behaviour. In the cognitive band, lower-level deliberate and automatic operations are performed. Cognitive activities occurring in the rational band are more complex. Longer sequences of actions take place and those actions are oriented toward goals. In the last band, the social band, activities concern communication and relationships between individuals.

Such a multi-layered view of cognition, learning tasks and contexts provides a property than can serve as a cornerstone for the neuroscience of learning: as complexity increases, speed decreases, and as complexity decreases, speed increases. Capturing change at these various timescales and complexity levels requires both psychophysiological and behavioural data recorded concomitantly and presents significant challenges (Mercier & Charland, 2013a; 2013b). These challenges can be subsumed by the

Table 1. A hierarchical, multi-layered view of the human implementation of cognition and affect (adapted from Newell, 1990)

Timescale	Band	System layers
Days to months	Social	Social interactions
Minutes to hours	Rational	Task
10sec		Unit task
1sec	Cognitive	Operations
100msec		Deliberate act
10msec	Biological	Neural circuit
1msec		Neuron
100µs		Organelle

overarching difficulty of establishing “vertical” causality across layers as well as “horizontal” causality over time within a layer, without speaking of the additional need for “diagonal” causality.

As can be seen in Table 1, a hierarchical, multi-layered view of the human implementation of cognition and affectivity articulates the interplay of behavioural and neurological data in explaining learning across a broad range of time scales. Most of what we need to know to teach and learn comes from studies of the cognitive, rational and social bands. These bands and associated layers provide an integrative framework to describe in great details the structural changes attributable to learning (from neural connectivity to declarative knowledge), for example by superimposing processes posited by a prediction-action view (Clark, 2013). In some instance, lower levels corresponding to the biological implementation of human cognition and affect are necessary when the observation of the behaviour does not lead to fully determined theoretical models (de Smedt, 2014). These layers only provide additional explanations of processes in the form of neurological correlates, which may be used to pinpoint the foci of educational interventions. Because of the indeterminacy of the directional relation between brain activity and the cognitive and affective processes, these correlates do not provide the causal information needed to decide which intervention should be more efficient. This causal information is derived from experiments in psychology which show behavioural changes attributable to interventions. In such studies, neurological correlates may contribute explanations regarding the gains and shortcomings of these interventions. In turn, these additional explanations may be critical in improving and fine-tuning interventions. These should then be subjected to additional causal validation with behavioural data.

An applied cognitive science perspective on learning aiming at fostering learning whenever needed, should benefit from the previous approach. The computational modelling of learning, especially in authentic contexts (and with notable and very inspiring exceptions), has been generally hampered by a lack of data in three respects: temporal information has been largely neglected (Kapur, 2011), the timescales of learning have not been put in relation (VanLehn, 2011), and the bulk of the studies focusing on the previous challenges are based on relatively thin human data streams and corresponding theories (Azevedo & Gasevic 2019). The contexts of application of the previous advances abound. For example, the interventions in the fields of learning difficulties and learning disabilities, learning with technology, and science education to name a few, could all be optimized by additional causal information relating intervention and outcomes. The computational modelling can be used to better understand the learning mechanisms when they are functional and pinpoint the origins of difficulties or disabilities in order to better target interventions (remedial or compensatory). This knowledge can then be used in designing human interventions, computer-based interventions or better learning contexts, interfaces with learning tools, etc.

A challenge in leveraging the potential of neuroscience in education is the requirement for interdisciplinary work. Besides, the technical aspects of the electroencephalogram (EEG) and Event-Related Potentials (ERP) research represent a huge challenge for the typical educational researcher.

Therefore, the objective of this paper is twofold: to provide a synthesis of the classic technical reference on ERPs, an introduction to the ERP technique presented by Steven J. Luck (2014), and to contextualize ERP research in education by a brief overview of previous research and emerging work.

This paper begins with a brief introduction to ERPs and the classic oddball paradigm using this methodology. Then, ERPs and ERP components are described followed by the most common ERPs in extent research. After, the design of ERP experiments is presented. In the last part of this paper, future directions in using ERP in education are discussed.

The electroencephalogram in brief

The electroencephalogram is the continuous recording of brain electrical activity with electrodes placed on the scalp. From it, ERPs and ERP components can be extracted. Furthermore, in its raw form, the EEG has both directly observable temporal and topographical properties, whereas source localization within the brain must be subjected to mathematical estimation and inference. Temporality refers to the exact timing of some given properties of the EEG, the topography refers to the recording site on the scalp, that is, at the surface of the skull, whereas the source localization concerns the actual neural network within the brain responsible for the observed ERPs.

ERPs and ERP components are made by neurons from two types of electrical activity: action potentials and postsynaptic potentials. Action potentials are voltage spikes that flow through the beginning of the axon in the cell body to axon terminals. The axon terminals are where the neurotransmitters are released. Action potentials from a single neuron can be isolated by inserting a microelectrode in the brain and positioning it close to the neuron of interest. Thus, action potentials cannot be detected from scalp electrodes. The second type of electrical activity, the post-synaptic potentials, are the voltages emitted by the post-synaptic cells that occur when the neurotransmitters link to receptors on the membrane of the post-synaptic cells. ERPs are made from post-synaptic potentials and they are extracted from the waveform at an electrode site. This waveform is always the sum of all source waveforms from the group of neurons involved. At a given electrode site, the voltage is also a sum of all the underlying components. Up to a dozen components are then present at every electrode site so it is very difficult to isolate them. This is called the superposition problem. However, some solutions exist to retrieve individual components: dipole localization methods, principal component analysis, independent component analysis, Fourier analysis, and time-frequency analysis.

When the superposition problem is overcome and individual components are retrieved, peaks and ERP components can be distinguished. Peaks are present in ERP waveforms. They can be modulated by the underlying components (shift in latency and peak). ERP components are "[…] electrical activity within a given region of the brain that reflects some neural process occurring in that region […]" (Luck, 2014, p. 52). It is important to make that distinction to avoid misleading representations of ERP components. Those components are defined as "[…] a set of voltage changes that are consistent with a single neural generator site and that systematically vary in amplitude across conditions, time, individuals, and so forth. That is, an ERP component is a source of systematic and reliable variability in an ERP data set" (Luck, 2014, p. 68). In those waveforms it is also possible to extract peaks, waves and components. ERPs are always labelled first by the letter N or P. N is for negative deflection and P for positive deflection. After N or P, a number follows. This number means the latency of the peak (e.g., N400 occurs 400ms after the presentation of the stimulus) or the position of the peak (e.g., N1 is the first peak after the presentation of the stimulus).

Temporality is the principal aspect of the EEG. Event-related potentials are "[e]embedded within the EEG, […] [and] are the neural responses associated with specific sensory, cognitive, and motor events, and it is possible to extract these responses from the overall EEG […]. Event-related potentials […] are electrical potentials that are related to specific events" (Luck, 2014, p. 4). These ERPs could be used in a classic oddball paradigm which consists on presenting to participants 80% of the time a frequent stimulus and 20% of the time an infrequent stimulus. After this task, it is possible to extract two ERP waveforms: one for frequent stimuli and one for infrequent stimuli at each electrode sites.

There are many advantages of using ERPs, the most important being the high temporal resolution. Indeed, EEG and ERPs are the most precise in terms of time compared to other brain-imaging techniques, with a resolution to the millisecond. It is then very useful for the study of processes that are very fast, which is the case in many tasks about cognition. ERPs are also useful because they can inform about the state of the brain after the stimulus presentation. In the same line, ERPs could give information about brain impairments. These are called biomarkers. ERP recording also gives good data to determine the link between an experimental manipulation and the cognitive processes. ERPs are also very helpful when behavioural measurements could not be used because behavioural responses are not possible to be taken (not aware of the cognitive processes) or induce disruption in the normal processing of the task (e.g., asking too many questions during a reading comprehension task).

The second aspect of EEG recording is its topographical properties. They provide limited but important information in interpreting the ERPs, because true localization of the activity is unavailable. In short, it is useful to note that the activity reported for a given site is not necessarily located at this site, or even close to this site. it is possible to extract ERP waveforms from EEG signals captured on the scalp according to a conventional topography, which can be very informative irrespective of their localization within the brain. Indeed, compared to other brain-imaging techniques such as fMRI, ERPs cannot be readily mapped to the source of the activity within the brain, despite recent advances in probabilistic source localization, which infer probable localizations (Sabeti, Katebi & Rastgar, 2015).

The third aspect of EEG recording is the source localization within the brain. This aspect remains underdeveloped in the context of EEG research. Nevertheless, source localization techniques based on likelihood estimations are still another way to identify underlying ERP components. Although difficult, it is possible to estimate the source localization by looking at the scalp distribution of the dipoles. Dipoles are created by the flow of current and “[…] are a pair of positive and negative electrical charges separated by a small distance” (Luck, 2014, p. 40). Multiple configurations of dipoles could explain a voltage distribution on the scalp, and it is arduous to determine the most plausible configuration among alternatives. Often, the number of plausible dipole configurations could be up to ten. This difficulty of selecting the right distribution is called the inverse problem or underdetermined problem.

One strategy to address the shortcomings of source localization is to determine if a component observed in a given experiment has the same patterns of interaction with other factors compared with the same component in other experiments. If so, this strengthens the case that it is the same component if they have the same pattern of interaction. This technique needs to be based on firm theory about these interactions.

Finally, it is noteworthy that when ERPs are recorded from EEG, they are very small compared to all the noise present in the signal. Consequently, in traditional methodology, it is essential to repeat the trials many times and to have a large sample of participants. Clean ERP recording can also be hard to obtain when participants are moving too much as part of the experimental task (facial expressions, mouse, keyboard, ambulatory EEG, etc.). Because ERPs are all about precision in time, the task and apparatus need to be very well designed and configured in terms of timing of events.

Common ERP components

Many ERP components are used frequently in psychophysiological experiments. They could be divided in three types: exogenous sensory components (triggered by a stimulus), endogenous components (represent neural processes; these components are task-dependent) and motor components (preparation and execution for a motor response). Each component reflects a psychophysiological or

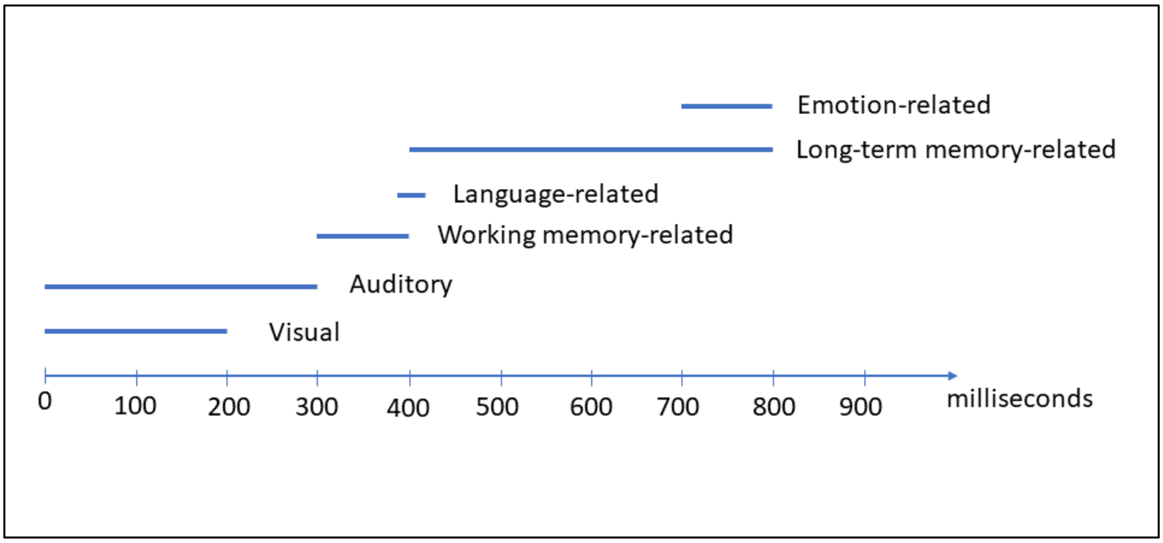

Figure 1. Main types of ERPs

neural process. Because those components are responses to a sensory input, they can be categorized as visual, auditory, language-related, long-term memory-related and emotion-related. The timeline in Figure 1 illustrates these categories of components.

Visual components occur during the time range of 0 to 200ms. Few visual ERPs are used in studies like the Contingent Negative Variation (CNV), the Stimulus-Preceding Negativity (SPN), C1, P1, N1, vertex positive potential, P2 and N170. The latter component is often used in studies that are interested in analysis of faces versus non faces because this component is face sensitive. N170 also reflects images expertise, which means that experts in one particular domain like dogs will react differently to dogs than other images. Neuhaus et al. (2016) conducted a study that involves the N170 component. They investigated social functioning and social behaviour with twins with and without autism spectrum disorder. They did a detection task with images of faces placed upright and inverted and images of houses placed upright and inverted. N170 components for faces were very similar for autistic twins and non-autistic twins but this component had a more negative amplitude for autistic twins for faces instead of non faces. Also, autistic twins had a greater latency for upright faces. This latency is linked with more social behaviour problem. Furthermore, these last results were more correlated for monozygotic twins that dizygotic twins. This study started to lead the way to other researches on autism spectrum disorder genetics.

Auditory components are in the time range of 10 to 300ms. These components are useful to assess the functionality of the auditory pathways with young children. Few auditory components had been discovered like N100, N2 and its subcomponents, posterior N2 or N2c, N2pc, distractor positivity, contralateral delay activity and the mismatch negativity. The latter is defined as an automatic response to auditory stimulus when the stimulus that preceded was different. It seems that the mismatch negativity reflects the comparison between a stimulus in the short-term memory and the other stimulus presented before. For example, this component could be present when two different tones are presented one after the other. Because the mismatch negativity appears even if the stimulus is not associated with a particular task, this component is also called pre-attentive or automatic. This component is often used in studies with young children or with people in coma because they could not give a behavioural response. Yamamuro et al. (2016) measured the latency and the amplitude of the mismatch negativity component of children with attention deficit/hyperactivity disorder (ADHD) to correlate with subscales of ADHD diagnosis. For those children, the mismatch negativity had a smaller amplitude for central electrodes and had a larger amplitude for parietal electrodes than controls. The amplitude at Pz site was negatively correlated with ADHD full-scale scores, hyperactivity-impulsivity subscales scores, and inattention subscales scores. For the latency at Pz site, it was positively correlated with hyperactivity-impulsivity subscales scores. It seems that the mismatch negativity reflects the severity of ADHD symptoms, and this component could be used to assess ADHD in children and adolescents. As seen with this example, auditory components are very helpful to assess ADHD or auditory impairments.

The P3 components family is related to context updating, more precisely updating of working memory. The amplitude of P3 is elicited for later memory of a stimulus. Except those data, the significance of P3 family is still not clear. Also, it is not clear what affects the amplitude of the latency of P3 except that P3 wave is sensitive to target probability and difficulty of the task. Indeed, if the probability is smaller, the P3 signal is larger. P3 amplitude is also affected by temporal probability and is also larger when the task is more difficult. Thus, P3 waves could be used to measure resource allocation also called cognitive load or workload. Papagiannopoulou and Lagopoulos (2017) studied the timing and the nature of neural dysfunctions in children with dyslexia in a comparative oddball P300 paradigm. The dyslexic brain seems to differ from neurotypical brain. The P300 latency was present for dyslexic children mostly at frontal brain regions and P300 amplitude was decreased in central brain regions. Those results were present even if the performance of dyslexic and control children was the same when detecting frequent and infrequent tones. The results could be explained by the poor capacity of process mental workload and delayed processing of information for the dyslexic children. This study gives some future directions for therapeutic interventions because P300 could be used to assess progress of a process. Indeed, when the children’s workload capacity increases, the latency of P300 decreases.

After the P3 family, there is the language-related ERP components around 400ms. These components are very sensitive to linguistic variables. The most studied language-related ERP component is the N400 which is associated with finding and meaning of words. It is elicited by violations in semantic predictions. This component would have a larger amplitude in the case of violations of meaning. This component could be observed when words are read or heard. The effect of N400 is also observed when a list of words is presented, and a word is semantically related or not to the one presented before. The amplitude of N400 would be larger for words not related semantically. Also, infrequent words elicited a larger amplitude of N400 than frequent words. Coch and Benoit (2015) searched for a possible relation between behavioural and electrophysiological measures (N400) on reading with typically developing children in late elementary school. Behavioural measures were taken along with the N400 elicited by real words, pseudowords, unpronounceable letters string, and strings of letter-like symbols. The only correlation observed was between the behavioural measures of vocabulary and the N400 amplitude for real words and pseudowords. The N400 was only related to semantic processing. The authors of this study claim that N400 could give complementary information to the vocabulary test. Indeed, the N400 represents the cognitive process of word comprehension while vocabulary test could give only information about results of this word comprehension. These findings could not directly affect how a teacher should teach but they still have an echo in the classroom. In fact, by using both types of measure it could be useful to unravel the full picture of reading development.

After the language-related ERP, there are the long-term memory-related ERP components in the time range of 400–800ms (Wilding & Ranganath, 2012). To measure these ERP components, ERP waveform of encoding of what is later remembered and ERP waveform of encoding of what is later forgotten need to be extracted. Then, the differences between these two waveforms need to be calculated. This difference is called a Dm effect. These Dm effects have a positive voltage at 400ms to 800ms. The distribution on the scalp of these effects depend on the type of stimuli presented (pictures or words). Dm effects represent multiple processes that are implicated in later remembering of a stimulus. Dm effects could be, then, observed in the recollection task.

The last type of ERP components is an emotion-related ERP component (Hajcak et al., 2012). It is the last category of ERPs because experiencing an emotion takes some time. It is difficult to interpret emotion-related waveforms because many other components could be observed at the same time within a task. For example, there is a potential to draw wrong conclusions about the nature of the processes elicited by photographic images because they caused emotion-related potentials but they also elicited many different categories of components like N170 visual component or P3 working memory component. Two main emotion-related ERP components have been described in previous studies: the early posterior negativity and the late positivity potential. The first one is a negative voltage that has the same latency as N2. This component is enhanced by emotional stimuli that have a positive valence. The early posterior negativity reflects adding more perceptual processing for emotional stimuli. On the other hand, the late positivity potential is a component with a positive voltage that occurs in similar latency and has the same scalp distribution as the P3 signal. It reflects an effect on task relevance emotional stimuli.

After having described all the types of ERP components, critical aspects regarding the design of ERP experiments with these ERP components follow.

Designing ERP experiments

Designing ERP experiments entails many challenges. Firstly, the superposition problem is a big challenge because when an effect occurs in a time range of a component, it could affect multiple components that are present in the same time range. Another challenge is that an effect in a particular experiment is not necessarily representing the same component that was observed in other studies. Along the same lines, change in amplitude of one component could conduct to a change in peak latency, and the change in peak latency of one component could conduct to a change in peak amplitude. Also, a change in component timing could conduct to a change in peak amplitude. Another challenge is that the onset and the offset of an effect in a waveform represents the earliest single-trial and the latest single-trial offset times respectively.

The first strategy is to focus on a maximum of one or two components. The other components should be controlled across conditions. This is very useful to interpret these two components in an experiment where multiple components are present. It is also easier to make conclusions about these two components when experimental manipulations impact only a single computational operation that has been represented by one component.

The second strategy is to focus on a large component like P3 or N400. It is much easier to isolate a large component from other components. Also, larger components have a greater impact on the ERP waveform. That means that ERP waveform has less chance to present distortion from other smaller components.

The third strategy consists on hijacking useful components from other domains than the one in which the experimental study takes place. For example, LRP is often used in experiments for motor preparation to a task, but it is also used to examine the nature of perception without awareness and syntax processing.

The fourth strategy is to refer to well-studied experimental manipulations to replicate the same conditions in another experiment. In fact, it is easier to use an ERP component in similar conditions that have already been studied than to use it in other conditions.

The fifth strategy is to use difference waves. For example, if two types of stimuli are presented in an experiment, it is possible to extract two waveforms. It is, then, possible to calculate the difference between them. If it is still difficult to determine that the difference in these two waveforms are due to the studied component, it is possible to make four types of stimuli to isolate this component.

The sixth strategy consists on focusing on components that are easier to separate from other components.

The seventh strategy is to use a component to study a process that occurs just before it. For example, as said earlier, P3 amplitude would be larger for infrequent stimuli that frequent one. The difference between infrequent and frequent stimuli could not be observed in ERPs before the brain starts to categorize. The P3 wave is then helpful to study the categorization process that occurs right before this component.

The last strategy is to toss apart the idea to isolate a component when it is not easy to do so. This strategy is called “component-independent experimental design”. This strategy is relevant when experiments do not depend on which component is observed. It is also helpful when conclusions of experiments depend only on the time of an effect. For example, when participants are looking at pictures of animals or non-animals, the difference in waveforms between these two conditions appears around 150ms. That means that brain detects a presence of animals around this time.

In brief, according to Luck (2014) when ERP experiments are well designed, it is possible to get valid information about cognitive processes. In many studies in education the use of ERPs components is relevant to answer research questions about those cognitive processes.

The Use of ERPs in education

ERP components are already used in education in line with the conventional paradigm. In studies of reading development for example, EEG and ERPs have been used because of their precision in time. Indeed, in the complex task of reading few subprocesses could be attested by ERPs as soon as 100ms. It is then possible to determine which process has been activated by the reader and the timing of each process (Osterhout & Holcomb, 1995).

In fact, the first subprocess that can be observed is P100. This ERP component is sensitive to semantic and morphological information (Davis, Libben & Segalowitz, 2019). Then, the Early Left Anterior Negativity (ELAN) component appears in the cognitive activity of reading. This component reflects processing of syntactic violations (Friederici, 2004). As seen earlier, the N170 is a component used often to study face processing, but this component is also present when a person is reading. Indeed, the N170 reflects the ability to recognize words instantly like a photo (logographic process). This ability is mainly observed with frequent words (Simon et al., 2006; Jucla et al., 2010; González et al., 2016; González et al., 2017). The reduced amplitude of this component could also be used as a sign that is present in children with family history of dyslexia (Hruby & Goswami, 2011).

Further in time, the N250 is a component related to complex word decomposition that are related to later access to comprehension (Lemine et al., 2018). To access to comprehension, grammatical functions are also very useful. N280 is a component link to grammatical functions of closed class words. This component is used to evaluate grammatical competence in readers (Osterhout & Holcomb, 1995).

In the time range of 300ms, many components are present. The first, the N300, is related to the integration of orthographic and phonological information. This component is also used to evaluate deficient integration of this information with children with dyslexia (Hasko et al., 2012). Also linked to phonology, the N320 is a process that reflects grapheme to phoneme mapping (alphabetic process) (Simon et al., 2006).

Further in the timeline, processes related to the analysis of sentences and comprehension appear. For example, LAN components which peak at 300ms to 500ms reflect morpho-syntactic information related to identification of grammatical relation between words in a sentence (Friederici, 2004). Then, the N400 as said earlier is related to violations of semantic productions (Coch & Benoit, 2015; Friederici, 2004). In the time range of 600ms, the P600 reflects violations in morphosyntax in sentences (Friederici, 2004; Friederici & Kotz, 2003).

In brief, all these components in reading tasks are represented by the timeline in Figure 2.

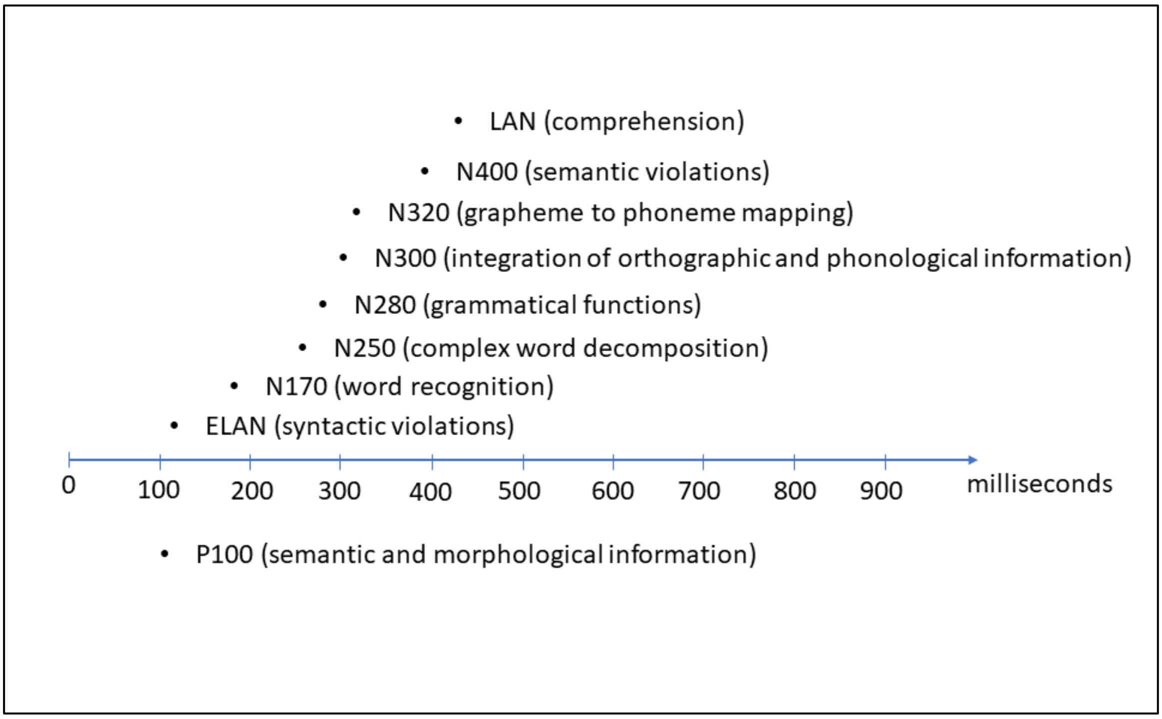

Figure 2. ERPs associated with reading

The information presented about ERP components used in education could provide insights regarding where process deficits in reading are in a learner (Osterhout & Holcomb, 1995). Interventions could then be designed to specifically address those deficits to overcome reading difficulties.

Conclusions

Human performance involves cognitive and affective processes unfolding moment by moment over the entire episode of performance, learning, etc. However, traditional data such as observations and self-report measures are not sufficient to accurately model how cognition and affect unfold in time. Self-report measures cannot be administered according to the rate of change of constructs of interest, while concurrent verbalizations are incomplete. To more fully explain the requirements and eventual support strategies for a successful performance or learning, ways to measure and link these processes over time are needed. Psychophysiological measures, coupled with behavioural observations, can bridge this gap in time by providing continuous information about cognitive and affective processes. The emerging field of "online measures of learning" currently focuses on finding strategies and establishing paradigms for the analysis of such data. Questions involve which data channels to consider, which constructs can be measured, and which analysis is appropriate for answering time-oriented research questions. Our current work hinges on continuous measures at the one-second time scale (Mercier, 2018).

In this line of thought, single ERPs could be the key in completing the span of time scales of learning and performance by going further down three orders of magnitude in time resolution — from second to millisecond. According to Freeman, Quiroga and Quian (2013), the traditional repetition of stimuli and averaging of ERPs, despite the significant scientific advances, was mostly a way to improve the signal-to-noise ratio, and in doing so, resulted in a loss of information. Indeed, the background information that is being cancelled out by averaging could be critical in uncovering aspects of brain functions and moreover, the ERP themselves, when averaged, loose their particularities (for example in terms of latency and amplitude). Freeman, Quiroga and Quian (2013) suggest that rather than denoising by averaging, each ERP can be denoised using wavelets and temporally aligned through latency correction. The gain in this approach is that characteristics of individual ERPs are conserved and, importantly, the changes in individual ERPs throughout the experiment can be examined, assessed and explained. Also, in this approach, what was considered background noise is now a source of information affecting the ERP in a way amenable to scientific exploration and explanation. Without going into all the details, the single ERPs approach consists of: 1) decomposition of the averaged ERPs using wavelet multiresolution decomposition, 2) identification of the wavelet coefficients correlated with the ERPs and zeroing of the uncorrelated coefficients, 3) calculation of the inverse transform to create the denoised average ERP, 4) application of the previous denoising procedure to individual ERPs. This procedure can be performed by using the most commercial EEG analysis software.

Because of the current measurement rates of mid-range eye-trackers (usually above 300 data points per second or one data point per 3.3 milliseconds) Fixation-Related Potentials (FRP) is another type of events that can be situated precisely in time so that it can be used to index ERP components. According to the eye-mind hypothesis (Just & Carpenter, 1980), a fixation corresponds to a specific information intake and processing from the visual channel. Furthermore, the duration of a fixation corresponds exactly to the time required to process the stimulus fixated. Therefore, it is possible to index and segment the EEG with the beginning and duration of a fixation, and then extract ERP components within this segment. The decontamination procedures due to eye movement at the onset of a fixation should be straightforward, especially since the timing of the eye movement is indexed by the eye tracker (Reilly, 2014). The gain in this method is the ability to study ERPs in an ongoing task, which may provide insights into ERP in more complex tasks or in more authentic settings. For example, while classic ERP research focused on word reading, FRPs can be used in the context of reading passages and whole texts to study the effect of context and other properties of text on reading processes. It is also possible to index and segment the EEG with the beginning and duration of a saccade in order to establish the impact of a saccade on the FRP (Kliegl et al., 2014). In principle, FRPs could be freed from the need to average within categories as it is done in traditional ERP research by applying the wavelet denoising method described by Freeman and Quiroga (2013).

Finally, in our opinion, ERPs, wavelet-denoised single ERPs, FRPs, potential wavelet-denoised single FRPs, could finally represent the temporal limit of educational research by going down to the millisecond (or more practically the 100 milliseconds) timescale of learning while preserving the authenticity of the learning context. Online measures of learning can represent the layer above, at the second level, whereas the higher-level layers continue to be represented by behavioral information. We suggest that the relatively recent developments should be implemented cautiously on the basis of the achievements and challenges of extent reading research, which seems to offer one of the best illustrations of the caveats and gains in the use of these advanced approaches.

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