On the utility of the P3 as a neuromarker of academic performance: A brief review

Utilizzo della P3 come neuromarker del rendimento accademico: una breve rassegna critica

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ABSTRACT Reliable and valid assessment of students' academic potential has huge consequences for their future success. To date, this has almost exclusively been achieved through the administration of pencil-and-paper aptitude assessments or self-report instruments. Performance on these assessments can be influenced by factors such as test anxiety, providing an inaccurate prediction of a student's potential. These methods also ignore that academic performance is the product of brain activity. Limits associated with these past practices can be addressed through the identification of robust neuromarkers of academic performance. The P3 component of the event-related potential, thought to index cognitive processes underlying learning, is one such promising candidate. Previous studies have identified significant associations between temporal characteristics of the P3 and a number of academic performance measures, highlighting its utility as a neuromarker. This brief review summarizes previous work on the P3 component and academic performance, and outlines considerations for future research.

KEYWORDS Educational Neuroscience; Neuromarkers; Academic Performance; Assessment.

SOMMARIO Una valutazione affidabile del potenziale accademico degli studenti può avere enormi conseguenze sul loro successo futuro. Ad oggi, questo risultato è ottenuto quasi esclusivamente attraverso la somministrazione di valutazioni attitudinali o di strumenti self-report. Tali risultati, possono essere influenzati da fattori come l'ansia da test e fornire quindi previsioni imprecise. Questi metodi non considerano che il rendimento scolastico è il prodotto dell'attività cerebrale. I limiti associati a tali pratiche possono essere affrontati attraverso l'identificazione di neuromarker del rendimento scolastico. Uno di questi candidati è la componente P3 del potenziale evento-correlato, che si ritiene sia indice dei processi cognitivi alla base dell'apprendimento. Studi precedenti hanno evidenziando la sua utilità come neuromarker, identificando associazioni significative tra le caratteristiche temporali della P3 e alcune misure del rendimento scolastico. Questa breve review presenta alcuni lavori sulla relazione fra la componente P3 e il rendimento scolastico e delinea considerazioni per la ricerca futura.

PAROLE CHIAVE Neuroscienze Educative; Neuromarkers; Prestazioni Accademiche; Valutazione.

1. INTRODUCTION

Academic performance has been defined as "*The outcome of education— the extent to which a student, teacher, or institution has achieved their educational goals*" (Ward, Stoker, & Murray-Ward, 1996). In this definition, we can identify the significance that is placed on this concept by those in the field of education. Academic performance, sometimes referred to as academic achievement, is an important metric used by schools in order to make decisions regarding admission, placement, retention, and graduation. Given the importance of this measure to educational institutions, it is not surprising that much effort has been invested into developing ways to predict differences in academic performance. Considering that students enrolled in a single institution are often heterogenous in regard to their performance, the ability to predict their academic trajectory can support the continued improvement of students' educational experiences (Helal et al., 2018).

The majority of research on predicting academic performance has focused on its relationship with cognitive and executive processes (Cortés Pascual, Moyano Muñoz, & Quilez Robres, 2019; Rohde & Thompson, 2007), personality traits (e.g., Duckworth, Taxer, Eskreis-Winkler, Galla, & Gross, 2019), and factors such as socioeconomic status (SES) and prior performance (Lee & Shute, 2010; Richardson, Abraham, & Bond, 2012). These studies typically employ the use of aptitude tests, self-report survey instruments, or behavioral tasks, in order to measure a psychological construct and assess how strongly that measure is correlated with academic performance, commonly operationalized as a student's grade point average (GPA) or performance on a standardized assessment (e.g., Wilkinson & Robertson, 2006). Studies of this nature generally report that academic performance is, in fact, correlated with one or more psychological constructs, explaining a significant amount of variance observed between individual students.

While the assessment of psychological constructs can provide insight into how well a student may perform, these measures ignore that academic performance is the product of neural processes. Even the best cognitive assessment batteries cannot provide direct information about the organ underlying measured performance. Interest in the development of brain-based biomarkers (i.e., neuromarkers) of academic performance began development over 50 years ago (Pinney, 1968). The benefits of studying the neural correlates of academic performance extend far beyond the accumulation of knowledge about this important link. The study of neural processes can allow for assessment of individual differences in students that are not impacted by factors such as test anxiety (von der Embse, Jester, Roy, & Post, 2018). The directness of this measure can better inform admission, placement, and other decisions based on a less biased indicator of a student's future performance. Additionally, because impediments to learning may be difficult to detect using traditional self-report or behavioral methods, the development of neuromarkers of academic performance can support the identification of students in need of intervention, mirroring a current trend in psychiatry (Jollans & Whelan, 2018).

Development of robust neuromarkers of academic performance can provide an innovative solution to the issue of student assessment. Currently, many markers used in education are based on behavioral measures which at times can be misleading (reviewed in Thomas, Ansari, & Knowland, 2019). In the decades since the initial investigation of neuromarkers of academic performance (Pinney Jr, 1968), little work has further explored this topic. Despite this limited inquiry, one candidate neuromarker, the P3 component of the electroencephalogram (EEG) event-related potential (ERP), has shown considerable promise. The P3 is a widely-studied component thought to reflect a range of cognitive processes underlying learning (reviewed in Linden, 2005; Ranganath & Rainer, 2003). Given the P3's role in cognitive processes, it is an attractive candidate for further investigation as a neuromarker of academic performance.

2. THE P3 COMPONENT OF THE ERP

The P3 is among the most studied components of the ERP over the last 50 years (Donchin & Coles, 1988; Huang, Chen, & Zhang, 2015; Linden, 2005; Polich, 2007, 2012; Polich & Kok, 1995; Sutton, Braren, Zubin, & John, 1965; Wood, Allison, Goff, Williamson, & Spencer, 1980). This component was initially studied using the oddball paradigm where the brain shows an enhanced response to low probability stimuli presented among high probability stimuli (Sutton et al., 1965). Additional work has identified this component under a wide range of experimental manipulations of stimulus, response, and stimulus-response contingency (Courchesne, Hillyard, & Galambos, 1975; Picton, 1992; Ritter & Vaughan, 1969). It is characterized by a large amplitude response in the ERP peaking around or after 300 ms from stimulus onset in the temporal domain, and a theta power increase in the frequency domain (Demiralp & Başar, 1992). Spatially, the P3 component is characterized by a broad, bilaterally symmetric scalp projection pattern, which is typically based on the ERP's voltage average within a wide post-stimulus window beginning after 300 ms across all electrodes (Kutas, McCarthy, & Donchin, 1977; Picton, 1992; Simson, Vaughan, & Ritter, 1976, 1977).

Functionally, the P3 component is thought to reflect context updating (i.e., the updating of working memory) when determining an appropriate response, a process requiring both attention and working memory (Donchin, 1981; Donchin & Coles, 1988; Polich, 2003), although some describe this as an updating of expectations (e.g., Verleger, 1988). In the event that no difference is detected between the previous and present stimuli, early sensory potentials are generated with no apparent P3. However, if a novel stimulus is presented, the current schema must be updated, resulting in P3 generation. The amplitude of the P3 has been shown to be negatively correlated with the probability of stimulus presentation (Duncan-Johnson & Donchin, 1982; Squires K.C., Wickens, Squires N.K., & Donchin, 1976), as well as the amount of attention focused on a competing task (Wickens, Kramer, Vanasse, & Donchin, 1983). Additionally, P3 amplitude is sensitive to habituation in paradigms using the repeated exposure of visual (Ravden & Polich, 1998) or auditory stimuli (Polich, 1989). P3 latency, on the other hand, is thought to reflect the amount of time needed in order to evaluate a stimulus with longer latencies associated with more difficult to discriminate target and standard stimuli (Verleger, 1997). The latency of the P3 may reflect the connection between stimulus detection and reaction (Verleger, Jaśkowski, & Wascher, 2005). Both the amplitude and latency of the P3 show age-related changes across the lifespan with amplitude at its highest and latency at its shortest in the late teens (reviewed in van Dinteren, Arns, Jongsma, & Kessels, 2014).

Previous work exploring the use of the P3 as a neuromarker has been predominantly in the domain of clinical assessment. This work has been focused on the temporal characteristics of the P3, chiefly its amplitude and latency, and their relationship to psychiatric and neurological disorders (Hansenne, 2000; Polich & Herbst, 2000). For example, the P3 has been used as a neuromarker in populations diagnosed with alcohol use disorder (Mumtaz, Vuong, Malik, & Rashid, 2018), epilepsy (Sowndhararajan, Kim, Deepa, Park, & Kim, 2018; Zhong et al., 2019), bipolar disorder (Wada et al., 2019), depression (Bruder et al., 2009), Alzheimer's disease (Hedges et al., 2016), and schizophrenia (Tang et al., 2019). The P3 has also been used to study age-related changes in cognitive function in non-clinical populations (Pavarini et al., 2018). In this work, pathology is typically associated with increased latency and decreased amplitude of the P3 component. Its utility as a neuromarker is strengthened, in part, due to the P3's insensitivity to response selection processes and independence from behavioral reaction time (Duncan-Johnson, 1981; McCarthy & Donchin, 1981; Verleger, 1997).

3. LITERATURE SEARCH METHODOLOGY

A literature search was conducted using PubMed in order to identify all published articles investigating the relationship between the P3 component and academic performance. Final search terms used were: (P3* OR ERP OR "event-related potential*" OR "evoked potential*") AND ("school performance" OR "grade point average" OR "academic performance" OR "academic achievement" OR "scholastic performance" OR "GPA").

To be included, a paper must:

1) include a temporal or spatial domain measure of the P3 component;
2) report a measure of academic performance (e.g., GPA);
3) be published in a peer-reviewed journal;
4) include only healthy human participants;
5) not include a manipulation (e.g., neurofeedback training), and;
6) be written in English.

Initially, abstracts were reviewed in order to exclude unrelated articles that may have been returned due to the search terms used. Next, the methods section for all remaining articles were read in order to determine if the above-mentioned criteria were met. It was during this time that studies conducted in atypical student populations (e.g., students with autism spectrum disorder) were excluded. Finally, both forward and backward reference checking were conducted for each selected article in order to collect relevant papers that were missed using the search criteria. Due to study heterogeneity, a narrative synthesis was performed.

4. RESULTS: THE P3 AND ACADEMIC PERFORMANCE

While there are only a small number of studies investigating the P3 as a potential neuromarker of academic performance, their findings are promising. The first known inquiry into this topic was by Polich and Martin (1992) looking at the relationship between the auditory oddball generated P3 at electrode Pz, personality, cognitive ability, and academic performance. This study was the first to identify a negative correlation between P3 latency and academic performance, operationally defined as GPA. No significant association between academic performance and P3 amplitude was found. Interestingly, the authors concluded that the lack of relationship between the P3 component and performance on a measure of fluid intelligence was evidence that intellectual ability was not related to the P3 component. This conclusion contrasts with more recent work supporting the existence of a positive correlation between P3 amplitude and intelligence (Amin, Malik, Kamel, Chooi, & Hussain, 2015; Hillman et al., 2012). One possible explanation for this study's inability to identify a relationship between P3 amplitude and intellectual ability or academic performance could relate to the P3 amplitude's sensitivity to habituation to auditory stimuli (Polich, 1989). In this study, participants completed three experimental conditions that differed only in the probability of the auditory target stimulus. While the order was counterbalanced, participants were still exposed to repetitive target stimuli, likely reducing P3 amplitude with each successive trial and block.

An entire decade would pass before the relationship between the P3 and academic performance was investigated again (Hillman et al., 2012). In this study, academic performance was operationally defined as performance on the Wide Range Achievement Test (WRAT3), specifically the reading, spelling, and arithmetic subtests. A diverse sample of primary school students were asked to complete a Go/NoGo task. In comparison with a traditional oddball task where the P3 is considered a marker of context updating (Donchin, 1981; Donchin & Coles, 1988), the P3 from a Go/NoGo task, specifically the NoGo task, is thought to reflect inhibitory control (Kamarajan et al., 2005). In contrast with the work of Polich and Martin (1992) this study identified no relationship between P3 latency (measured as the average across electrodes C1, Cz, C2, CP1, CPz, CP2, P1, Pz, and P2) and academic performance. A significant positive correlation was identified between the amplitude of the Go task target condition P3 and performance in reading, as well as the amplitude of the NoGo nontarget condition P3 and performance in reading and arithmetic. However, when controlling for factors such as IQ and school grade level, the relationship between the amplitude of the NoGo nontarget condition P3 and reading performance was no longer significant. These findings suggest that reading is perhaps more influenced by working memory, while mathematics is more dependent on inhibitory control. It is worth noting that previous work has identified that both these abilities are influential in reading and mathematics (Bull & Scerif, 2001; Cortés Pascual et al., 2019; St Clair-Thompson & Gathercole, 2006).

Although Amin and colleagues (2015) did not explicitly define their memory recall measure as academic performance, this variable represents a common way that academic performance is operationalized in education. That is, a student is asked to complete a test or quiz based on a lesson or series of lessons in an academic discipline. This group identified a significant positive correlation between P3 amplitude at electrode Pz and performance on a quiz based on a computer-delivered biology lesson. Additionally, a negative correlation between P3 latency and quiz performance was identified. Considering that the P3 in this study was generated using a visual oddball task, it is possible that this effect was related more to differences in working memory. This study is noteworthy for being the first to look at the link between the P3 and academic performance in an academic discipline that was not mathematics or language.

The most recent study on the relationship between the P3 and academic performance was that of Luo & Zhou (2020). In this study, the authors investigated whether the P3 could be used to predict academic performance as defined as the combined total score on Chinese and mathematics exams. They found that students designated as high ability based on performance on Raven's Advanced Progressive Matrices tended to have higher amplitude P3s at electrode Cz than those designated as low ability. Furthermore, multiple linear regression analysis revealed that the amplitude of this P3 component accounted for a significant amount of variance in academic performance. These results provide additional support for the previously reported positive correlation between P3 amplitude and academic performance, but may have limited generalization due to how academic performance was operationalized.

To summarize, P3 amplitude has been the most reliably reported neuromarker of academic performance in the limited previous research. Positive correlations between the amplitude of the P3 component generated using Go/NoGo (Hillman et al., 2012), visual oddball (Amin et al., 2015), and 2-back tasks (Luo & Zhou, 2020) were all significantly associated with academic performance, broadly operationalized. While P3 latency was negatively associated with academic performance, this finding was less robust. It is unclear why significant associations between P3 component latency and academic performance are not more commonly reported, especially in light of evidence supporting this negative association under conditions of impaired cognitive function (e.g., Zhong et al., 2019).

5. DISCUSSION AND CONSIDERATIONS FOR FUTURE INVESTIGATIONS

Considerable effort is needed in order to build on the limited yet promising early work investigating the P3 as a potential neuromarker of academic performance. While a number of consistent findings have been reported, methodological heterogeneity and an exclusive focus on temporal characteristics has led to some mixed results and an incomplete characterization of the P3's ability to support prediction. One possible explanation for these mixed results could be related to how academic performance is operationally defined. Depending on the study, academic performance has been operationalized as performance on the WRAT3 (Hillman et al., 2012), overall GPA (Polich & Martin, 1992), performance on summative exams in Chinese and mathematics (Luo & Zhou, 2020), or performance on a multiple-choice quiz based on a computer-delivered biology lesson (Amin et al., 2015). Adoption of standardized academic assessments for use in future investigations can address these issues, supporting comparisons to be made between separate studies.

Use of sensor-space measures of the P3 may also contribute to these mixed results. EEG sensor data are "noisy" and reflect the volume conduction of signals from throughout the entire brain (Luck, 2014). To date, all studies investigating the relationship between the P3 and academic performance have relied on sensor space measures of amplitude and latency. The poor signal to noise ratio of sensor data could result in the inability to identify meaningful changes in the P3 associated with differences in academic performance. The use of blind source separation (BSS) algorithms, including InfoMax ICA (Bell & Sejnowski, 1995), fast ICA (Hyvärinen & Oja, 1997), and SOBI (Belouchrani, Abed-Meraim, Cardoso, & Moulines, 1993, 1997), on EEG data have improved signal to noise ratio, allowing for detection of weak activations not reliably reported using sensor space data (e.g., Sutherland & Tang, 2006). Application of linear mixed-effects models during data analysis may further address these issues by accounting for subject-level variability which may otherwise obscure effects of interest (e.g., Privitera, Momenian, & Weekes, 2022). Issues with signal quality, especially related to P3 habituation, may also be addressed through future exploration of neuromarkers from resting-state data (Damoiseaux et al., 2006). In a recent set of studies, a resting-state network with a scalp topography similar to the P3 was characterized (Privitera, Sun, & Tang 2022; Tang, Privitera, Fung, & Hua, 2021). Further work is needed in order to explore the utility of this measure as a possible substitute for the P3 component.

While most research using the P3 as a neuromarker has focused on the temporal characteristics of this component, there has been recent interest in investigating differences in underlying neural generators. Converging evidence supports that the P3 is generated by a broadly distributed network of structures spanning the brain's four lobes (Linden, 2005; Privitera & Tang, 2022). Interestingly, this network shows significant overlap with structures innervated by neuromodulatory cholinergic and noradrenergic projections, systems implicated in the processing of novelty (Ranganath & Rainer, 2003). In psychiatry, some evidence supports that an understanding of the spatial characteristics of the P3 component may be important for better detecting, differentiating, and understanding disorders, especially those that are comorbid or highly similar in their symptomology (Sauve, Morand-Beaulieu, O'Connor, Blanchet, & Lavoie, 2017). P3 spatial neuromarkers have been explored for psychosis in epilepsy (Canuet et al., 2011), depression (Zhou et al., 2019), and schizophrenia (Bachiller et al., 2015; Molina et al., 2019; Winterer et al., 2001). Meaningful differences in P3 spatial configuration have also been reported in samples of healthy participants, associated with differences in performance on a behavioral task (Privitera & Tang, 2022). Inconsistent findings from studies exclusively focused on the P3 component's temporal characteristics may be remedied through investigation of its spatial components in future investigations.

Finally, while academic performance is directly related to the events and experiences a student has in an educational environment, research exploring its relationship with the P3 component has been exclusively conducted in laboratory settings. Whether findings from laboratory research can apply to real-world situations remains an open question. While it is typically the case that EEG data are collected in a shielded room under tightly controlled conditions, the availability of portable EEG systems has allowed for questions related to education to be asked in real classroom settings (e.g., Dikker et al., 2017; Gong & Xu, 2019; Ko, Komarov, Hairston, Jung, & Lin, 2017; Poulsen, Kamronn, Dmochowski, Parra, & Hansen, 2017). Given the non-invasive nature of EEG, future studies can likely be conducted in students at any age, a trend already evidenced in the previous investigations described above. Interest in these classroom-based investigations may be growing in some parts of the world, with a somewhat recent trend towards the adoption consumer-grade EEG in schools in China, albeit on a small scale (Wang, Hong, & Tai, 2019). Moving these studies from the laboratory to the classroom may also open additional avenues for inquiry, potentially illuminating our understanding of the learning brain in a way that can inform how educators are trained (Privitera, 2021).

6. CONCLUSION

Much can be gained in the fields of education and neuroscience from the development of robust neuromarkers of academic performance. While limited previous research has identified the P3 component as a promising candidate, additional work is needed in order to further validate its utility. Future work should extend this line of inquiry beyond the traditionally studied temporal domain characteristics to explore the potentially rich source of information found in the spatial domain. Efforts should also be made to leverage advances in mobile EEG technology in the interest of increasing the ecological validity of future studies. Neuromarkers in education can provide a more direct assessment of the organ underlying learning, circumventing the limits of current instruments in support of student success.

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