Uniwersytet SWPS

Neuronalne i psychologiczne korelaty dysfunkcji poznawczych w prokrastynacji akademickiej

Neural and psychological correlates of cognitive dysfunctions in academic procrastination

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Praca doktorska napisana pod kierunkiem

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Warszawa, 2023

Niniejsza rozprawa doktorska składa się z cyklu publikacji pod wspólnym tytułem: „Neuronalne i psychologiczne korelaty dysfunkcji poznawczych w prokrastynacji akademickiej”, na który składają się trzy artykuły opublikowane w czasopismach uwzględnionych w ministerialnym wykazie punktowanych czasopism naukowych. Wszystkie artykuły zostały przygotowane w oparciu o dane zgromadzone w ramach projektu naukowego OPUS nr 2014/13/D/HS6/03015, finansowanego z grantu Narodowego Centrum Nauki i realizowanego na Uniwersytecie SWPS pod kierownictwem dr. hab. Jarosława Michałowskiego, prof. Uniwersytetu SWPS.

Podziękowania

Niniejsza praca doktorska powstała dzięki wsparciu wielu osób, którym chciałam złożyć serdeczne podziękowania.

Promotorowi niniejszej pracy – Jarosławowi Michałowskiemu – za nieocenione wsparcie merytoryczne, mentoring, poświęcony czas i uwagę. Za wzbudzanie fascynacji neuronauką i psychologią oraz podtrzymywanie motywacji do rozwoju kariery badawczej. Za zrozumienie dla niezrozumienia i błędów.

Markowi Wypychowi za owocną współpracę, ciekawe dyskusje i wartościowe rady.

Julii Bączek i Stanisławowi Karkoszowi za wzajemne wsparcie na drodze do doktoratu i tworzenie przyjaznej atmosfery pracy naukowej.

Magdzie Pietruch i wszystkim stażystom Laboratorium Neuronauki Emocji za cenną pomoc w realizacji badań.

Moim rodzicom, Jasiowi, Oli i innym bliskim mi osobom, które cierpliwie znosiły mój brak czasu, skutecznie podnosiły na duchu i nieustannie stymulowały mój układ nagrody.

Streszczenie

Prokrastynację definiuje się jako irracjonalne odkładanie realizacji zadań, przy zachowaniu świadomości negatywnych konsekwencji tego zachowania. Wśród potencjalnych czynników mogących zwiększać tendencję do prokrastynowania często wymienia się m.in. dysfunkcje wykonawcze, trudności w regulacji emocji i lęk przed porażką.

Celem niniejszych badań było poznanie neuronalnych korelatów dysfunkcji poznawczych u studentów z wysoką tendencją do prokrastynacji oraz zweryfikowanie wpływu informacji zwrotnej na ujawnianie się tych dysfunkcji. W przedstawionych artykułach zostały opisane badania porównujące studentów z wysoką (vs niską) tendencją do prokrastynowania pod względem: odporności na zewnętrzne dystraktory; angażowania kontroli proaktywnej i reaktywnej; oraz kontroli uwagowej i przetwarzania błędów pod wpływem pozytywnej lub negatywnej informacji zwrotnej uzyskanej w zadaniu.

Przedstawione badania wykazały, że osoby z wysoką (vs niską) prokrastynacją prezentują większą zmienność czasu reakcji oraz słabszą aktywność neuronalną związaną z alokacją zasobów uwagowych na prezentowanych bodźcach. Ponadto, wysoka tendencja do odwlekania związana była ze wzorcem aktywacji mózgu i sposobem reagowania sugerującym słabsze zaangażowanie kontroli proaktywnej. Nie zaobserwowano jednak związku pomiędzy prokrastynacją a stopniem zaangażowania kontroli reaktywnej oraz odporności na zewnętrzne dystraktory. Co więcej, wyniki ostatniego z przedstawionych badań wskazują na to, że informacja zwrotna o uzyskanych wynikach w zadaniu może wpływać na aktywność poznawczą studentów z wysoką tendencją do prokrastynacji.

Uzyskane wyniki pozwalają na lepsze zrozumienie mechanizmu prokrastynacji, co może przyczynić się do rozwoju interwencji ukierunkowanych na radzenie sobie z tym problemem.

Abstract

Procrastination is defined as an irrational task delay, while being aware of negative consequences of this behavior. Factors which are often indicated as potential sources of increased tendency to procrastinate include executive dysfunctions, difficulties in emotion regulation and fear of failure.

The aim of the present study was to identify the neural correlates of cognitive dysfunctions among highly procrastinating students and verify the influence of feedback on the manifestation of these dysfunctions. The presented articles describe studies that compare students with high (vs. low) tendency to procrastinate in terms of: resistance to external distractors; proactive and reactive control engagement; as well as attentional control and error processing under the influence of positive or negative feedback received in the task.

The presented studies showed that high (vs. low) procrastinating individuals present higher reaction time variability as well as lower neural activity reflecting allocation of attentional resources engaged to process presented stimuli. In addition, high procrastination was related to the pattern of brain activity and behavioral responses suggesting lower engagement of proactive control. However, we did not observe the relationship between procrastination and reactive control or resistance to external distractions. Moreover, the results of the last presented study indicate that negative (vs. positive) feedback reflecting one's performance in the task might negatively influence cognitive functioning among high procrastinating students.

Obtained results allow for better understanding of the mechanism of procrastination, which might contribute to the development of interventions aimed at dealing with this issue.

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Autoreferat

Prokrastynacja określa irracjonalne odwlekanie wcześniej zaplanowanej realizacji zadania, pomimo świadomości, że późniejsze wykonanie pracy może pociągnąć za sobą negatywne konsekwencje, co często prowadzi do poczucia winy i innych negatywnych reakcji emocjonalnych (Klingsieck, 2013). Choć chroniczna prokrastynacja może przejawiać się w różnych obszarach życia, jest to problem, który często występuje w środowisku edukacyjnym, szczególnie wśród studentów (Steel, 2007). W związku z tym, wyróżniony został termin prokrastynacji akademickiej, określający irracjonalne odwlekanie takich zadań, jak pisanie prac zaliczeniowych, czy przygotowywanie się do egzaminów (Steel Klingsieck, 2016). Oprócz niższych osiągnięć akademickich (Goda i in., 2015), prokrastynacja wśród studentów pociąga za sobą negatywne konsekwencje również w innych sferach funkcjonowania. Wyższa tendencja do odwlekania związana jest chociażby z wyższym poziomem stresu i depresji oraz z ogólnym obniżeniem satysfakcji z życia (Beutel i in., 2016). W związku z tym, wielu badaczy podejmuje próbę znalezienia odpowiedzi na pytanie o potencjalne przyczyny tego problemu.

Choć do tej pory nie udało się jednoznacznie zidentyfikować źródeł prokrastynacji, według jednej z najbardziej wpływowych teorii - *Temporal Motivation Theory* (TMT) - sformułowanej przez Steela i König (2006), należą do nich zarówno zmienne sytuacyjne, jak i osobowościowe. Zgodnie z TMT, częściej odwlekane są zadania, których realizacja ma niską subiektywną wartość oraz daje niewielkie szanse uzyskania pożądanych efektów (odniesienia sukcesu). Prawdopodobieństwo prokrastynacji rośnie również wraz z odroczeniem otrzymania spodziewanej nagrody za wykonane zadanie oraz z indywidualną wrażliwością na odraczanie gratyfikacji, co w TMT utożsamiane jest z impulsywnością - pochopnym działaniem i podejmowaniem nieprzemyślanych decyzji pod wpływem aktualnie dominujących potrzeb. Autorzy teorii podkreślają, że osoby impulsywne są mniej wytrwałe w realizacji celów, co może wynikać m.in. z niskiej kontroli uwagowej, rozumianej jako zdolność do utrzymywania uwagi na celu wykonywanego zadania przy jednoczesnym ignorowaniu pojawiających się w otoczeniu dystraktorów (Steel, 2007; Steel i in., 2018). Deficyty w tym zakresie, poza tym, że zwiększają postrzeganą trudność zadania (a więc zmniejszają jego wartość i postrzegane szanse na sukces), mogą przyczyniać się również do łatwiejszego przekierowywania uwagi z celu zadania na cele alternatywne (np. sprzątanie mieszkania lub spotkanie ze znajomymi zamiast pisania pracy magisterskiej).

Choć hipoteza odnośnie związku pomiędzy prokrastynacją a słabszą kontrolą uwagi znalazła potwierdzenie w wielu badaniach kwestionariuszowych (Fernie i in., 2016; Moon i in., 2020; Steel i in., 2018), badań w tym zakresie, wykorzystujących bardziej obiektywne miary jest znacznie mniej. Jednym z nich jest opublikowane przez nas badanie z 2020 roku (Michałowski i in., 2020; choć artykuł ten nie należy do zbioru publikacji składających się na niniejszą pracę doktorską), w którym zaobserwowaliśmy, że w porównaniu do osób rzadko prokrastynujących, osoby z wysoką tendencją do prokrastynacji prezentują słabszą aktywność mózgu odzwierciedlającą alokację zasobów uwagowych w kierunku bodźca oraz większą zmienność czasu reakcji, świadczącą o niestabilności procesów związanych z koncentracją uwagi. Jednak wspomniana praca, ani żadna inna (zgodnie z moim stanem wiedzy), nie weryfikowała tego, czy zaobserwowane trudności w utrzymywaniu uwagi związane są z niską odpornością na dystrakcję zewnętrzną, co było sugerowane we wcześniejszych badaniach wykorzystujących miary samoopisowe. W związku z tym, celem badania opisanego w pierwszej z załączonych publikacji było uzupełnienie tej luki i porównanie osób z wysoką oraz niską tendencją do prokrastynacji pod względem aktywności mózgu oraz sposobu reagowania podczas wykonywania zadania wymagającego ignorowania pojawiających się w otoczeniu dystraktorów. Uzyskane wyniki nie potwierdziły wcześniej obserwowanego związku pomiędzy wysoką prokrastynacją a deklarowaną podatnością na dystrakcję zewnętrzną. Badane grupy nie różniły się istotnie pod względem aktywności mózgu w odpowiedzi na pojawiające się dystraktory oraz ich wpływu na czas reakcji i poprawność odpowiedzi. Niemniej, udało nam się zreplikować wyniki wcześniejszych badań (Michałowski i in., 2020) wskazujące na to, że osoby z wysoką (vs niską) tendencją do prokrastynacji prezentują większą zmienność czasu reakcji oraz niższą aktywność mózgu związaną z alokacją zasobów uwagowych w kierunku bodźców istotnych z perspektywy celu zadania. Możliwe więc, że zaobserwowane deficyty w kontroli uwagowej u osób prokrastynujących odzwierciedlają większą podatność na dystrakcję wewnętrzną (np. błądzenie myślami), a deklarowana rozpraszalność pod wpływem zewnętrznych dystraktorów jest formą racjonalizacji postrzeganych trudności w realizacji zadań.

Poza kontrolą uwagową, również inne dysfunkcje wykonawcze związane z impulsywnością wskazywane są często jako potencjalne przyczyny prokrastynacji. Na przykład, w badaniu Gustavsona i współpracowników (2015) zaobserwowano negatywną korelację pomiędzy prokrastynacją a wspólnym czynnikiem funkcji wykonawczych, który w teorii Miyake i Friedman (2012) odzwierciedla zdolność do utrzymywania i aktualizowania celu zadania. Wspólny czynnik funkcji wykonawczych jest więc konceptualnie zbliżony do wyróżnionej w modelu Bravera (2012) kontroli proaktywnej, która związana jest z podtrzymującą się, wzmożoną kontrolą poznawczą oraz aktywnością przygotowawczą polegającą na utrzymywaniu i bieżącym aktualizowaniu celu zadania w umyśle. Oprócz kontroli proaktywnej, model Bravera wyróżnia także kontrolę reaktywną, która odzwierciedla przemijającą aktywację kontroli poznawczej bezpośrednio w odpowiedzi na bodziec wymagający reakcji. W drugim z przedstawionych artykułów składających się na niniejszą pracę opisane jest badanie nad związkiem pomiędzy prokrastynacją a wspomnianymi dwoma rodzajami kontroli poznawczej. Biorąc pod uwagę wyżej opisane wyniki badań Gustavsona i współpracowników (2015), przewidywaliśmy, że w porównaniu do studentów rzadko prokrastynujących, studenci z wysoką tendencją do prokrastynacji będą przejawiali niższy stopień aktywacji kontroli proaktywnej, co mogłoby wyjaśniać ich trudności w realizacji celów. W przeprowadzonym badaniu zaobserwowaliśmy częściowe potwierdzenie tej hipotezy: w porównaniu do studentów z niskim poziomem prokrastynacji, osoby z wysoką tendencją do odwlekania prezentowały niższe wartości neurofizjologicznych wskaźników kontroli proaktywnej oraz niektórych wskaźników behawioralnych świadczących o słabszym zaangażowaniu tego rodzaju kontroli poznawczej. Nie zaobserwowano jednak różnic w żadnym ze wskaźników kontroli reaktywnej. Możliwe zatem, że osoby często prokrastynujące są w stanie odpowiednio zaangażować kontrolę poznawczą w odpowiedzi na bodźce wymagające reakcji, choć kontrola ta jest krótkotrwała i przemijająca, co może przyczyniać się do trudności w aktywnym utrzymywaniu celu zadania w umyśle, a tym samym sprzyjać realizacji celów alternatywnych.

Choć wyżej opisane prace wskazują na to, że osłabienie funkcji wykonawczych przejawia się u osób z wysoką prokrastynacją w różnych zadaniach eksperymentalnych, niektórzy badacze sugerują, że istotna w tym zakresie może być rola procesów emocjonalno-motywacyjnych (Wypych i Potenza, 2021). W licznych badaniach kwestionariuszowych wysoka prokrastynacja związana była z wyższą wrażliwością na kary (Przetacka i in., 2021; Wypych i in., 2019), nieadaptacyjnym perfekcjonizmem (Xie i in., 2018) oraz lękiem przed porażką (Schouwenburg, 1992). Co więcej, badania eksperymentalne wykazały, że perspektywa kary finansowej za błędy popełnione w zadaniu (w porównaniu do nagrody za prawidłowe reakcje) powodowała, że osoby z wysoką (vs niską) tendencją do prokrastynacji reagowały wolniej (Michałowski i in., 2017) oraz w mniej elastyczny sposób (Przetacka i in., 2021), jak również prezentowały słabszą aktywność obszarów mózgu odpowiedzialnych za kontrolę poznawczą (Wypych i in., 2019). Potencjalny mechanizm wpływu tego rodzaju motywacji na funkcjonowanie poznawcze obejmuje trudności w regulacji emocji, które często występują u osób z wysoką tendencją do prokrastynacji (Wartberg i in., 2021; Wypych i in., 2018). Według koncepcji Sirois i Pychyl (2013), prokrastynacja postrzegana jest jako nieadaptacyjna strategia radzenia sobie z negatywnymi stanami emocjonalnymi, wywołanymi przez awersyjne zadanie. Z kolei Wypych i Potenza (2021) argumentują, że deficyty w regulacji emocji mogą skutkować osłabieniem kontroli poznawczej w awersyjnych kontekstach, co mogłoby się przekładać na niższy poziom wykonania zadań i trudności w utrzymywaniu uwagi na celu zadania, któremu towarzyszy lęk lub inne negatywne reakcje emocjonalne.

Warto zaznaczyć, że moderacyjna rola kary i nagrody finansowej w związku pomiędzy prokrastynacją a funkcjonowaniem poznawczym nie ujawniła się we wszystkich wskaźnikach analizowanych w wyżej przytoczonych badaniach. Co więcej, efekt ten nie został zreplikowany w badaniu z 2020 roku (Michałowski i in., 2020), w którym perspektywa utraty pieniędzy za błędy nie miała żadnego wpływu na różnice w wykonaniu zadania oraz aktywności mózgu pomiędzy osobami często i rzadko prokrastynującymi. Możliwe więc, że motywacja finansowa nie jest wystarczająco silna, aby w znaczący sposób wpłynąć na funkcjonowanie osób z wysoką tendencją do odwlekania. Co więcej, w środowisku akademickim bardziej powszechne są kary i nagrody w postaci ocen, często wskazujące na poziom uzyskanych osiągnięć w porównaniu do członków grupy rówieśniczej. Biorąc to pod uwagę, w trzecim z przedstawionych badań chcieliśmy sprawdzić wpływ tego rodzaju motywacji społecznej na funkcjonowanie poznawcze i aktywność mózgu studentów z wysokim oraz niskim poziomem prokrastynacji. Wykorzystaliśmy w tym celu manipulację eksperymentalną w postaci informacji zwrotnej, która wskazywała na poziom wykonania zadania uczestników w porównaniu do innych osób badanych. Informacja ta (pozytywna vs negatywna, wskazująca odpowiednio na wynik wyższy lub niższy niż przeciętny) była z góry ustalona i nie miała rzeczywistego związku z wynikami uczestników. Okazało się, że w warunku negatywnej informacji zwrotnej, studenci z wysoką tendencją do odwlekania prezentowali słabszą aktywność mózgu związaną z koncentracją uwagi na prezentowanych bodźcach oraz z przetwarzaniem błędów popełnionych w zadaniu, w porównaniu do studentów rzadko prokrastynujących. Zaś w warunku pozytywnej informacji zwrotnej nie wystąpiły podobne różnice między grupami. Możliwe zatem, że występujące u osób prokrastynujących lęk przed porażką oraz trudności w regulacji emocji sprawiają, że informacja o niskim poziomie wykonania zadań indukuje ruminacje lub inne formy dystrakcji wewnętrznej, która angażuje zasoby poznawcze. Niemniej, pozytywny wpływ sukcesu (w porównaniu do porażki) na funkcjonowanie poznawcze prokrastynujących studentów nie ujawnił się we wszystkich analizowanych wskaźnikach behawioralnych, co wskazuje na możliwość występowania pewnych deficytów poznawczych związanych z prokrastynacją, które są niezależne od czynników motywacyjnych.

Podsumowując, badania opisane w niniejszym zbiorze publikacji wskazują na istnienie związku pomiędzy wysoką prokrastynacją a słabszą kontrolą uwagową oraz niższym zaangażowaniem kontroli proaktywnej, co jest zgodne z założeniami modelu TMT oraz stanowi potencjalne wyjaśnienie trudności w realizacji celów u studentów zmagających się z chroniczną prokrastynacją (choć należy wziąć pod uwagę korelacyjny charakter przeprowadzonych badań). Niemniej, nie udało się znaleźć potwierdzenia dla obserwowanego w badaniach kwestionariuszowych związku pomiędzy wysoką prokrastynacją a niską odpornością na dystrakcję zewnętrzną, co wskazuje na inne źródła postrzeganych trudności w funkcjonowaniu poznawczym. Co więcej, ostatnie z przedstawionych badań wykazało, że dysfunkcje wykonawcze u osób często prokrastynujących mogą być modulowane przez kontekst motywacyjny: nasilać się pod wpływem niekorzystnych porównań społecznych i/lub osłabiać w wyniku odniesienia sukcesu. Wyniki te wpisują się w postrzeganie prokrastynacji i związanych z nią deficytów poznawczych przez pryzmat trudności w regulacji emocji, które mogą pogarszać funkcjonowanie w awersyjnych kontekstach (Sirois i Pychyl, 2013; Wypych i Potenza, 2021). Badania przeprowadzone w niniejszej pracy przyczyniły się do lepszego zrozumienia problemu chronicznego odwlekania realizacji zadań. Uzyskane wyniki mogą wpłynąć na rozwój strategii ukierunkowanych na zminimalizowanie prokrastynacji w środowisku akademickim.

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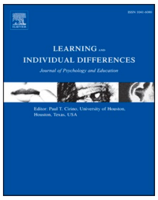
Załącznik nr 1 – Publikacja badań nad związkiem pomiędzy prokrastynacją i podatnością na dystrakcję

Learning and Individual Differences 107 (2023) 102364

Contents lists available at ScienceDirect

Learning and Individual Differences

journal homepage: www.elsevier.com/locate/lindif



“I can’t focus now, I will study tomorrow” - The link between academic procrastination and resistance to distraction

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ARTICLE INFO

Keywords:
Procrastination
Attention
Distraction
Event-related potentials

ABSTRACT

Procrastination is a tendency to delay tasks, despite being aware of the negative consequences of doing so. Previous studies have shown that students who frequently procrastinate, present difficulties with maintaining attention during task completion. These problems might be related to decreased resistance to distraction caused by task-irrelevant stimuli appearing in the surrounding environment. In the present study we verified this hypothesis by investigating the relationship between procrastination and susceptibility to distraction with the use of behavioral and neurophysiological measures. We recruited high (HP) and low (LP) procrastinating students and asked them to perform an Auditory Visual Distraction task which required participants to respond to visual stimuli and ignore the preceding sounds. Although HP (vs. LP) did not show increased orientation of attention towards distracting sounds, they were still less attentive to task-relevant stimuli. These results indicate that procrastination-related attentional deficits might be linked to other sources of distraction, such as mind-wandering episodes.

Educational relevance statement: According to our knowledge, the presented study was the first to use objective measures in order to investigate the link between procrastination and the ability to ignore external distractors. Although we did not confirm the expected relationship, we observed that students who frequently procrastinate still present certain attentional dysfunctions, which might be related to other sources of distraction, such as mind-wandering episodes. We believe that observed deficits might partially explain higher propensity to delay completion of different assignments, as inability to maintain sustained attention can increase the perceived aversiveness and difficulty of the performing tasks and/or facilitate attentional shift towards alternative goals. Obtained findings might contribute to the development of therapeutic interventions or guidelines for psychologists, managers, team leaders or teachers on how to manage the problem of procrastination in the workplace or school settings.

1. Introduction

Procrastination describes an irrational delay of important tasks despite being aware of its potential negative outcomes, which often triggers feelings of guilt and regret (Blunt & Pychyl, 2005; Klingsieck et al., 2013). This problem is particularly common in educational settings (Steel, 2007), being linked to poor learning outcomes (e.g. worse understanding of study material) and lower academic achievements (e.g. lower grades; Goda et al., 2015; Lubbers et al., 2010; Wäschle et al., 2014; Scheunemann et al., 2022).

Different environmental and situational factors might impact the frequency of procrastinatory behaviors (Corkin et al., 2014; Wieland et al., 2022). For example, the probability that a task will be procrastinated depends on its characteristics (e.g., difficulty; Blunt & Pychyl, 2000) as well as on one’s current internal state (e.g., mood; Tice et al., 2001). However, procrastination varies across individuals, showing partial heritability (Gustavson et al., 2014) and substantial stability over time (e.g., 10-years test-retest reliability = 0.77, Steel, 2007; see also Rice et al., 2012 for a short-term longitudinal study). Because of that, a plethora of studies investigates procrastination as a trait-like phenomenon (e.g., Gadosey et al., 2021; Koppenborg & Klingsieck, 2022; Steel, 2007), although Sirois and Pychyl (2016) suggested that it might be

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https://doi.org/10.1016/j.lindif.2023.102364
Received 22 October 2022; Received in revised form 1 August 2023; Accepted 7 September 2023

better described as a characteristic adaptation, which in the Big Five Theory of Personality (McCrae & Costa, 2008) refers to patterns of behavior shaped by both foundational, biologically determined traits (e.g., conscientiousness) and certain external factors (e.g., social norms). Either way, the stability of tendency to procrastinate along with its significant costs motivate researchers to identify neuronal and psychological mechanisms that might determine this maladaptive disposition.

The influence of situational and dispositional factors on procrastinatory behaviors has been elaborated within the Temporal Motivation Theory (TMT) coined by Steel and König (2006). In its simplified version, it states that motivation to complete a task is increasing with higher subjective task value and greater probability of achieving the desired outcomes as well as with decreasing delay in gratification and lower individual sensitivity to delayed gratification or impulsivity (Steel & König, 2006). However, this theory also emphasizes the importance of goal setting processes, including goal striving. According to authors, this process can be disrupted leading to procrastination due to several factors, among which is poor control over one's attention (Steel, 2007; Steel et al., 2018). Problems in attentional control manifest in lower ability to stay focused on task-related goals and ignore distractions at the same time. These difficulties can facilitate attentional shift towards alternative activities or temptations, and as a consequence, promote engaging in them, hindering task completion.

In line with TMT, previous questionnaire studies have shown that individuals who often delay tasks declare enhanced lower attentional control, which is frequently manifested in enhanced distractibility (e.g. Fernie et al., 2016; Moon et al., 2020; Steel et al., 2018). Furthermore, the relationship between high procrastination and decreased attentional control has also been confirmed in studies using different cognitive tasks, which allow for conducting more objective measurements than questionnaires. For example, our past research (Michałowski et al., 2020; Wiwatowska et al., 2022) has shown that high, as compared to low procrastinating students, present increased reaction time variability (RTV). This measure reflects instability within reaction times, presumably linked to difficulties in maintaining sustained attention on the performed task (MacDonald et al., 2009; Weissman et al., 2006). In these past studies, we also used the event-related potentials (ERPs) method, which is based on averaging the electrical brain activity in response to certain stimuli or reactions. This results in the ERP wave, in which different potentials (components) can be identified. The amplitude of these potentials is often interpreted as reflecting neural activity underlying specific cognitive processes (Luck, 2014). In support of the found differences in RTV, we observed that high (vs. low) procrastination is associated with smaller amplitudes of the P3b component, which reflects reduced neural activity linked to allocating attentional resources to process task-relevant stimuli (Ghani et al., 2020; Polich, 2007). Both increased RTV and reduced P3b have been found in disorders previously linked to attentional deficits, such as ADHD (Kofler et al., 2013; Szuromi et al., 2011) or depression (Kaiser et al., 2008; Röschke & Wagner, 2003), as well as during states of reduced attentional control induced by sleep deprivation (Dan et al., 2021; Floros et al., 2021; Lee et al., 2003) or alcohol consumption (Fairbairn et al., 2021; Jelen et al., 2011). One of the symptoms of poor attentional control is low resistance to external distraction, which can absorb cognitive resources and diminish the brain's capacity to process goal-related information (e.g. Berry et al., 2014; Derryberry & Reed, 2002). Therefore, we have speculated that the increase in RTV and reduction in P3b among high procrastinators could be related to their increased susceptibility to distraction. This hypothesis can be further supported by research using functional and structural neuroimaging, which has indicated that higher procrastination is related to lower activity and decreased volume of dorsolateral prefrontal cortex (DLPFC; Chen et al., 2020; Hu et al., 2018; Wypych et al., 2019), both being linked to resistance to external distractions (e.g. (Denkova et al., 2019; Gisselgård et al., 2003; Woods & Knight, 1986).

Although numerous self-report, behavioral and neuroimaging studies indicate that an increased tendency to delay tasks might be related to higher distractibility, to our knowledge, none of the previously conducted research has used behavioral and neurophysiological measures to verify whether high procrastinators are more vulnerable specifically to external distractors, such as noises in the surrounding environment. It is of particular relevance, as it seems that this source of distraction differs from other sources, such as mind-wandering episodes, which represent orienting attention towards one's internal states, i.e. thoughts and feelings (Kam & Handy, 2013; Unsworth & McMillan, 2014). Clarifying this issue might help to better understand the underlying mechanisms of attentional deficits in procrastination, and as a result, contribute to the development of different interventions and strategies aimed at reducing the risk of procrastinatory behaviors, for example by choosing a distraction-free environment for learning or working.

The present study aimed to fill the above-mentioned gap in the literature and investigate the link between procrastination and resistance to external distraction. To achieve this goal, we recruited high (HP) and low (LP) procrastinating students, who performed the Audio-Visual Distraction Paradigm (AVD; Cid-Fernández et al., 2014; Escera et al., 2000), which has often been used to study resistance to distraction across different age groups (Cid-Fernández et al., 2014), clinical populations (including children with ADHD; e.g. van Mourik et al., 2007), and experimental conditions (e.g. Garcia-Garcia et al., 2010). In this task participants have to react to visual stimuli, which are preceded by three types of sounds that need to be ignored: standards - short 1 kHz tones, presented in 70 % of trials; deviants - short 2 kHz tones, presented in 15 % of trials; and novels - different environmental sounds, presented in 15 % of trials. The presentation of novel sounds has a distracting effect on subjects' performance, prolonging their reaction times in response to task-relevant visual stimuli (Escera et al., 1998, 2001; Wetzel et al., 2019). As we predicted that HP, as compared to LP, would be less resistant to distraction, we expected that the prolongation of reaction times after novel (distracting) sounds would be more pronounced in this group of participants.

The AVD has also been used to measure the neurophysiological correlates of distraction. One of such measures is P3a - a component scored from frontal areas around 300 ms after the sound onset. Higher amplitudes of this component reflect stronger involuntary orientation of attention towards novel, distracting sounds (Berti et al., 2004; Yago et al., 2001). Increased amplitudes of this potential have been observed in different disorders associated with attention deficits, including higher distractibility, for example in ADHD (Gumenyuk et al., 2005; Oja et al., 2016; van Mourik et al., 2007), depression (Lepistö et al., 2004) or alcoholism (Polo et al., 2003). Along with these findings, we expected that in HP, as compared to LP individuals, distracting sounds would elicit increased P3a.

Apart from P3a, AVD has previously been used to evaluate another potential - reorienting negativity (RON). This component is evoked at frontal regions around 400–500 ms after the appearance of distracting sounds and reflects the neural response linked to shifting attention away from distractors, back to task-relevant stimuli (Berti et al., 2004; Kluska et al., 2013; Yago et al., 2001). We hypothesized that HP would present smaller RON than LP subjects, as in our previous study (Michałowski et al., 2020) we found that HP might present some difficulties in shifting attention between different events. Namely, this group of participants, as compared to LP, presented higher post-error slowing (PES; computed as a difference in reaction times in trials preceding vs. following a mistake) and according to some scholars, this measure reflects difficulties in reorienting attention back to task-relevant stimuli (Notebaert et al., 2009; see Danielmeier & Ullsperger, 2011 for a review).

In addition to the above-mentioned expectations that HP would show increased automatic attention towards auditory distractors (higher P3a than LP) and difficulties in shifting attention away from these distractors (less negative RON and longer reaction times than LP), we also aimed to measure RTV and P3b in response to visual stimuli, expecting to replicate our previous findings of larger RTV and smaller P3b among HP, as compared to LP individuals (Michałowski et al., 2020; Wiwatowska et al., 2022). Also, we predicted that the differences in P3b between groups would be higher in response to visual stimuli preceded by novel, as compared to standard sounds, which would be associated with an increased distraction effect.

Moreover, taking into account that deficits in attentional control are one of the core symptoms in attention deficit hyperactivity disorder (ADHD) and that past research found a positive relationship between procrastination and the severity of ADHD-related behaviors (Altgassen et al., 2019; Bolden & Fillauer, 2020; Zhen et al., 2020), we decided to use the self-report scale of ADHD symptoms in the presented study, expecting to observe higher results among HP vs. LP participants. Although this tool is insufficient for clinical diagnosis, we wanted to replicate previous findings of the relationship between high procrastination and ADHD as well as verify whether the potential differences between groups in the objective measures of distraction would be accompanied by differences in subjective perception of distractibility and hyperactivity.

To sum up, we have formulated the following hypotheses:

1. RTs will be longer in response to visual stimuli preceded by novel (vs. standard) sounds and this difference will be bigger among HP (vs. LP) subjects.
2. HP (vs. LP) participants will show higher P3a, but smaller (less negative) RON in response to novel sounds.
3. HP (vs. LP) participants will show higher RTV and lower P3b in response to visual stimuli.

2. Methods

2.1. Participants

A total of 484 students from various universities and colleges in Poznań completed the Polish version of the Aitken Procrastination Inventory (API; Aitken, 1982; Wiwatowska et al., 2022). Out of the collected sample, 100 students were selected based on their scores in the scale. They were divided into two groups of 50 participants: HP (scores in API above 1 SD of the mean result: API $\geq$ 74) and LP (scores in API below 1 SD of the mean result: API $\leq$ 47). The values used to distinguish groups were based on the standard deviation of the mean result in API obtained in our previous study, in which the scale was completed by 1968 students (Wiwatowska et al., 2022). We decided to follow this approach in order to compare groups, as the available resources did not allow for conducting correlational studies, which require higher sample size to obtain sufficient power. Because there are no specified, universal criteria to diagnose procrastination, we could not determine it based on specific cut-off, similarly to the diagnosis of different mental disorders.

We excluded participants who declared being diagnosed psychiatric or neurological disorders as well as having vision or hearing impairments that precluded successful task completion. The sample size was determined based on the limitations of available resources.

Out of the sample of 100 students, we had to exclude 7 participants due to technical issues, 8 subjects because of poor EEG signal quality (>25 % excluded epochs, see the next section) and 1 subject who achieved too low response accuracy (lower than 50 % in response to Go signals). The final sample included 84 participants −42 in each HP (23 women; $M_{age} = 22.74$, $SD_{age} = 2.01$; $M_{API} = 80.24$, $SD_{API} = 5.29$) and LP group (22 women; $M_{age} = 22.24$, $SD_{age} = 2.44$; $M_{API} = 37.90$, $SD_{API} = 5.06$). There were no significant differences between groups in mean age ($t(82) = 1.03$; $p = .308$) or gender ($X^2(1) = 0.49$, $p = .827$).

2.2. Questionnaires

To assess subjects' procrastination levels, we used the Polish version of the API (Aitken, 1982; Wiwatowska et al., 2022), which contains 19 items regarding difficulties in completing or initiating academic tasks (e.g. "I delay starting things so long I don't get them done by the deadline" or "I am often frantically rushing to meet deadlines"). Participants answered on a 5-point Likert scale, with responses ranging from 1 (false) to 5 (true). The Polish version of the scale demonstrated high internal consistency (Cronbach's alpha = 0.89; Wiwatowska et al., 2022).

To measure participants' inattention and hyperactivity symptoms, we used the Polish version of Adult ADHD Self-Report Scale (ASRS; WHO; Kessler et al., 2005), which is a screening scale for ADHD in adults. The scale includes 18 items (e.g. "How often do you fidget or squirm with your hands or feet when you have to sit down for a long time?" or "How often are you distracted by activity or noise around you?"), to which participants answer on a 5-point Likert scale ranging from 0 (never) to 4 (very often). The scale demonstrated high internal consistency (Cronbach's alpha = 0.87).

2.3. Task and procedure

In sum, participants completed four tasks: Audio-Visual Distraction Paradigm (AVD; Cid-Fernández et al., 2014; Escera et al., 2000), Delayed Gratification Task (Schmidt et al., 2017), Iowa Gambling Task (Bechara et al., 1994) and Reaction Time Task with Feedback. The last three tasks are not described in this paper. The order of task completion was pseudorandomized and counterbalanced across groups (e.g. the first and fifth subjects from HP and LP group completed AVD as the first task, the second and sixth subjects completed AVD as the second task, the third and seventh subjects as the third task, etc.) After completing the tasks (ca. 1 h) participants filled out questionnaires. Subjects received between 50 PLN (~\$12) to 80 PLN (~\$19) at the end of the study (the amount of money depended on performance in other tasks, not on the performance in AVD).

Tasks were completed in a sound-attenuated and electrically-shielded room. Participants were seated in front of a 17-in. monitor located approximately 70 cm from their eyes. In the AVD (see Fig. 1) three types of visual stimuli were displayed: letters (a, e, c, u), digits (2, 4, 6, 8), and triangles (pointing up, down, right, or left). The subjects' task was to press the left or right shift on the keyboard whenever a digit or a letter (Go signals, presented in 66 % of trials) appeared on the screen. Half of the subjects pressed the left button to digits and the right button to letters, while the other half responded in the opposite manner – the button choice was pseudorandomized and counterbalanced across groups in the same manner as the order of tasks completion (see previous paragraph). The reactions had to be suppressed when a triangle (No-Go signal) was displayed (in 34 % of trials). Visual stimuli were preceded by three types of auditory stimuli that had to be ignored: standards (1 kHz tone; presented in 70 % of trials), deviants (2 kHz tones; presented in 15 % of trials), and novels (unique environmental sounds, e.g. drilling or breaking glass; presented in 15 % of trials). The task was divided into two equal blocks separated by a short break. In each block, there were 250 pairs of auditory-visual stimuli (500 pairs in total). Each auditory and visual stimulus was presented for 150 ms and 200 ms accordingly. There was a 150 ms interval between the offset of the sound and the onset of the visual stimulus. The intertrial interval was equal to 1500 ms. Before the main part of the task, participants performed a short practice session.

The study was reviewed and approved by the Ethics Committee at the SWPS University of Social Sciences and Humanities. It was conducted in accordance with the Declaration of Helsinki. All subjects signed an informed consent before participating in the study.

2.4. Electrophysiological recordings and signal processing

Brain activity was recorded with the BrainVision recorder and BrainAmpDC amplifier (Brain Products GmbH, Gilching, Germany). Sixty-four electrodes were used, which were placed according to the international 10–20 system. Data was digitized at a rate of 500 Hz and impedances were maintained below 50 kΩ (for most of the channels,

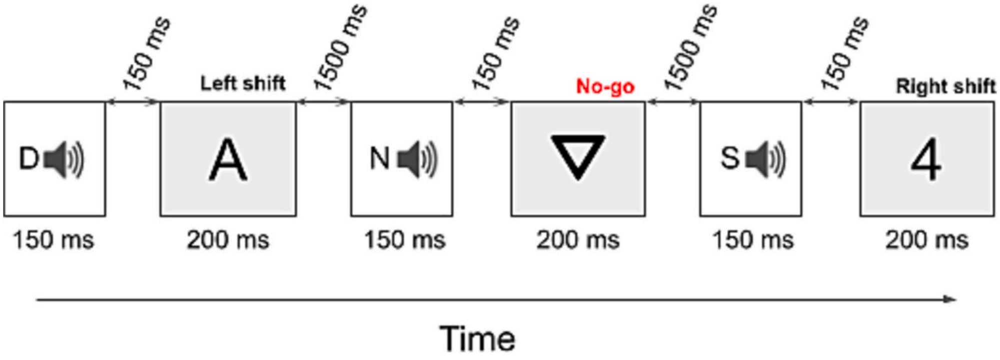

Fig. 1. Audio-visual distraction task (AVD). Each visual stimulus was preceded by one of three kinds of sounds that needed to be ignored: standards (S, 1 kH tones, presented in 70 % of trials), deviants (D; 2 kH tones, presented in 15 % of trials), or novels (N; environmental sounds, presented in 70 % of trials). Participants had to press either left or right shift in response to digits and letters (Go stimuli; 66 % of trials). They had to suppress their responses when they saw a triangle (No-Go stimuli; 34 % of trials).

impedances were below 20 kΩ).

Data was analyzed offline using EEGLAB and the ERPLAB toolboxes (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014) for MATLAB (The Mathworks, Inc., Natick, MA). Initially, the signal was filtered with 0.1 Hz high-pass and 30 Hz low-pass filters in order to remove very low and high frequencies that might have resulted from factors not related to neural activity (e.g. skin-electrode contact or muscle activity). Later, we visually inspected the signal in order to detect and interpolate noisy channels. Also, at this stage, large artifacts were manually removed from the signal and the average reference was set. Following these steps, the independent component analysis was performed in EEGLAB using the *extended runica* algorithm, which distinguishes independent sources that comprise the EEG signal. Consequently, it allows for removing non-brain-related activity from the signal without the loss of relevant data. To detect and reject components representing muscle and eye movements, cardiac activity, or channel noise, visual inspection was performed in addition to the automatic classifier ICLabel (Pion-Tonachini et al., 2019). In order to average the neural activity related to stimuli presentation, data was divided into epochs 200 ms before and 800 ms around the stimuli onset, with 200 ms pre-stimulus baseline correction. The artifactual epochs with voltages exceeding +/− 75 μV were automatically removed from the signal and the signal from the rest of the segments was averaged in order to obtain ERP waves for each subject. Participants with >25 % artifactual epochs (8 subjects) were excluded from further analyses.

The selection of time windows and electrodes for the components analyses was based on the visual inspection of the grand-averaged data from all participants (see Fig. 2). P3b was measured from Pz as a mean amplitude in the 250–450 ms time window after the onset of visual stimuli. P3a and RON were measured as the mean amplitudes of the difference waves between potentials in response to novel and standard auditory stimuli (novel minus standard). P3a was measured between 215 and 415 ms after stimuli onset from FCz. RON was analyzed between 450 and 550 ms after stimuli onset from Fz. To confirm the single-channel analyses, we also measured the amplitudes of all components from the following electrode clusters: parietal cluster for P3b measurements (channels Pz, P1, P2, POz, PO3, PO4), central-frontal cluster for P3a measurements (channels FCz, FC1, FC2, Cz, C1, C2), and frontal cluster for RON analyses (channels Fz, F1, F2, FCz, FC1, FC2).

2.5. *Statistical analysis*

IBM SPSS Statistics 27 was used for statistical analysis. A two-factor analysis of variance with repeated measures was performed to compare P3b amplitudes and most behavioral indices: reaction times (RTs) for correct responses to Go stimuli and error rates (omission errors and wrong reactions to Go stimuli as well as commission errors to No-Go stimuli). The between-group factor was procrastination (high vs. low) and the within-group factor was the sound (standard, deviant, or novel). P3b analyses also included visual stimulus (Go vs. No-Go) as an additional within-group factor. Bonferroni and Greenhouse-Geisser corrections were used to account for multiple comparisons and violations of the sphericity assumption respectively.

t-tests were conducted to compare the ASRS results, RTV as well as P3a and RON amplitudes. We decided to analyze RTV only in response to visual stimuli preceded by standard sounds to evaluate participants` ability to maintain attention during repetitive sensory stimulation, as we did in our previous studies (Michałowski et al., 2020; Wiwatowska et al., 2022). Measuring RTV in deviant and novel trials might have introduced some additional variability, not necessarily related to participants' problems with maintaining sustained attention. For example, less frequent sounds (such as deviant and novel stimuli) might temporarily

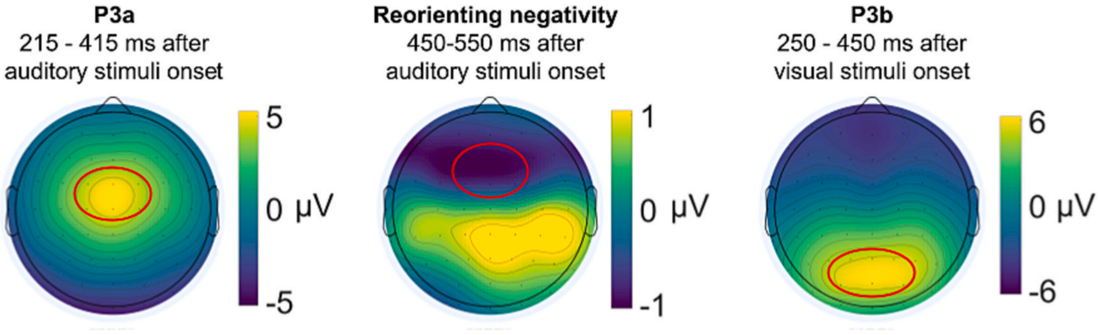

Fig. 2. Scalp maps representing event-related potentials averaged from all participants that were included in the final analyses. Left and middle figures represent the topography of the difference waves computed by subtracting the potentials in response to standard sounds (1 kH tones, presented in 70 % of trials) from the potentials evoked by novel sounds (environmental sounds, presented in 15 % of trials) in the Audio-Visual Distraction task. In the task, participants had to react to visual stimuli and ignore preceding sounds. Right figure represents the topography of the potentials evoked by visual stimuli. The potentials were averaged in the time windows provided above the scalp maps. The red circles include channels that were chosen for cluster analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

raise vigilance levels and it has been shown that increasing preparatory states via task modifications have a significant impact on RTV both in healthy adults (Wodka et al., 2009) and children with ADHD (Ryan et al., 2010).

In case of observing insignificant differences between groups in the variables of interest, we performed the Bayesian analyses in JASP (Version 0.17.1), as unlike the frequentist approach, they allow for evaluating the strength of evidence in favor of null over alternative hypotheses (Wagenmakers, 2007). The width of the prior distribution for *t*-tests was set to 0.707 by default in JASP. We interpreted the obtained Bayes factors according to the following criteria: factors within the range of 1–3 were interpreted as "weak"; 3–10 as "moderate"; 10–30 as "substantial"; 30–100 as "strong"; and over 100 as "decisive" (Maneejuk & Yamaka, 2021).

In the final analyses of all variables, we excluded observations that were above or below the three standard deviations of the group's mean.

3. Results

3.1. Behavioral results

Mean reaction times and error rates are presented in Table 1.

The results of RTs showed the expected effect of distraction (main effect of trial type; $F(1.50,121.71) = 42.88$; $p < .001$; $\eta_p^2 = 0.346$; see Fig. 3). Paired comparisons revealed that participants reacted slower in response to visual Go stimuli that were preceded by novel sounds, as compared to Go stimuli preceded by standards ($p < .001$) or deviants ($p < .001$). There were neither differences in RT between standard and deviant trials ($p > .1$), nor significant main effects of sound for error rates (omission errors or wrong reactions) in response to Go stimuli (*Fs* < 2; *ps* > 0.1).

The analyses of commission error rates in response to No-Go signals showed the main effect of sound ($F(1.80,134.97) = 10.19$; $p < .001$; $\eta_p^2 = 0.120$). Paired comparisons indicated that fewer errors were committed in response to No-Go stimuli preceded by novel, as compared to standard ($p < .001$) and deviant sounds ($p = .011$), but error rates in standard and deviant trials did not differ significantly ($p > .1$).

Regardless of the presented sound, HP (vs. LP) presented higher percentage of omission ($F(1,77) = 7.00$; $p = .010$; $\eta_p^2 = 0.083$) and commission errors ($F(1,75) = 7.00$; $p = .010$; $\eta_p^2 = 0.083$). However, it is important to interpret these results with caution, as there was clearly a ceiling effect in the data, which might have resulted from low difficulty level of the task. We did not observe any differences between groups in RTs or wrong reactions to Go stimuli (*Fs* < 2; *ps* > 0.1). Opposite to what we expected, none of the obtained behavioral results showed procrastination x sound interactions (*Fs* < 2; *ps* > 0.1).

Table 1
Mean values (*SDs*) for high (HP) and low (LP) procrastinating students performing Audio-Visual Distraction task, in which participants reacted to visual (Go and No-Go) stimuli preceded by three types of sounds that needed to be ignored.

Presented sound	Group	Reaction times to Go [ms]	Omission errors to Go [%]	Wrong reactions to Go [%]	Commission errors to No-Go [%]
Standard	LP	478.66 (50.33)	0.18 (0.33)	4.42 (3.80)	0.36 (0.76)
	HP	475.14 (52.62)	0.38 (0.68)	5.49 (3.35)	0.90 (1.32)
Deviant	LP	476.70 (49.14)	0.10 (0.45)	5.12 (4.41)	0.21 (0.90)
	HP	477.54 (58.97)	0.25 (0.67)	5.00 (4.96)	0.63 (1.48)
Novel	LP	497.78 (49.41)	0.05 (0.31)	4.40 (3.39)	0.00 (0.00)
	HP	498.33 73.64)(	0.44 (0.94)	5.15 (3.76)	0.00 (0.00)

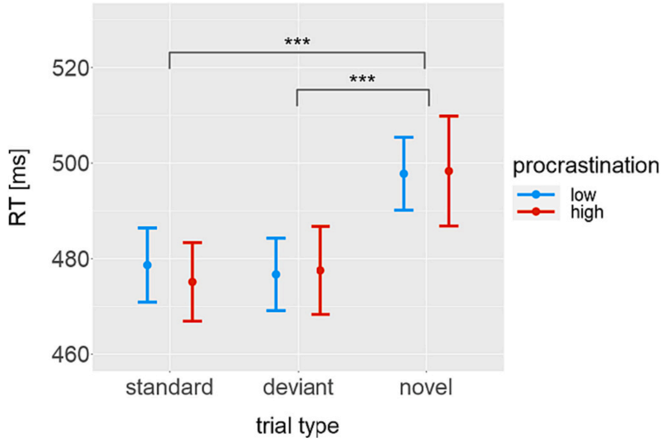

Fig. 3. Mean reaction times (RTs) in response to visual stimuli preceded by three kinds of sounds that needed to be ignored: standards (short 1 kH tones, presented in 70 % of trials), deviants (short 2 kH tones, presented in 15 % of trials) and novels (environmental sounds, presented in 15 % of trials). Error bars represent one standard error.
*** $p < .001$.

As our hypothesis stated that HP (vs. LP) would present a greater difference in RTs between novel and standard trials, in order to further confirm the results obtained in previous analyses showing the lack of significant interaction between sound and group, we computed the differences scores (RTs in novel minus standard trials) and performed Bayesian independent sample *t*-tests to compare these scores between the groups. The Bayes factor (BF_{01}) showed that the data was 4.10 times more likely under the null than the alternative (non-directional) hypothesis.

The comparison of RTV in standard trials revealed that in line with our hypothesis, HP showed higher variability in reaction times than LP students ($M_{LP} = 0.19$, $SD_{LP} = 0.04$; $M_{HP} = 0.21$, $SD_{HP} = 0.06$; $t(82) = 2.23$; $p = .029$; $d = 0.486$).

3.2. Electrophysiological results

Opposite to what we hypothesized, t-tests did not show any significant differences between HP and LP subjects in P3a and RON neither in single-channel analyses, nor in comparisons within clusters (*ts* < 2; *ps* > 0.1; see Fig. 4). Therefore, we performed Bayesian t-tests to evaluate the strength of the evidence in favor of null vs. alternative hypothesis. The comparisons of P3a yielded only weak evidence ($BF_{01} = 2.62$ for FCz; $BF_{01} = 1.91$ for cluster) in favor of null over non-directional hypothesis.

The Bayesians comparisons of RON yielded weak evidence in favor of a null over alternative hypothesis ($BF_{01} = 2.94$ for Fz; $BF_{01} = 1.98$ for cluster)

P3b analyses yielded main effect of sound, indicating that the amplitudes of this component were the smallest in response to visual stimuli preceded by standards, as compared to novels ($p < .001$) or deviants ($p < .001$), but P3b in novel and deviant trials did not differ significantly ($p = .075$).

HP (vs. LP) showed lower amplitudes of P3b regardless of presented sound or visual stimuli (main effect of procrastination: ($F(1,79) = 5.36$; $p = .023$; $\eta_p^2 = 0.064$; see Fig. 5). However, opposite to our expectations, we did not observe an interaction between procrastination and sound (*Fs* < 1; *ps* > 0.1). These single-channel analyses were confirmed by the analyses of the parietal cluster ($F(1,81) = 5.71$; $p = .023$; $\eta_p^2 = 0.064$ for the main effect of procrastination; $F < 1$; $p > .1$ for sound x procrastination interaction).

Because we had predicted that the differences between groups in P3b would be larger in response to stimuli presented after novel vs. standard sounds, and the analyses did not yielded significant interaction between

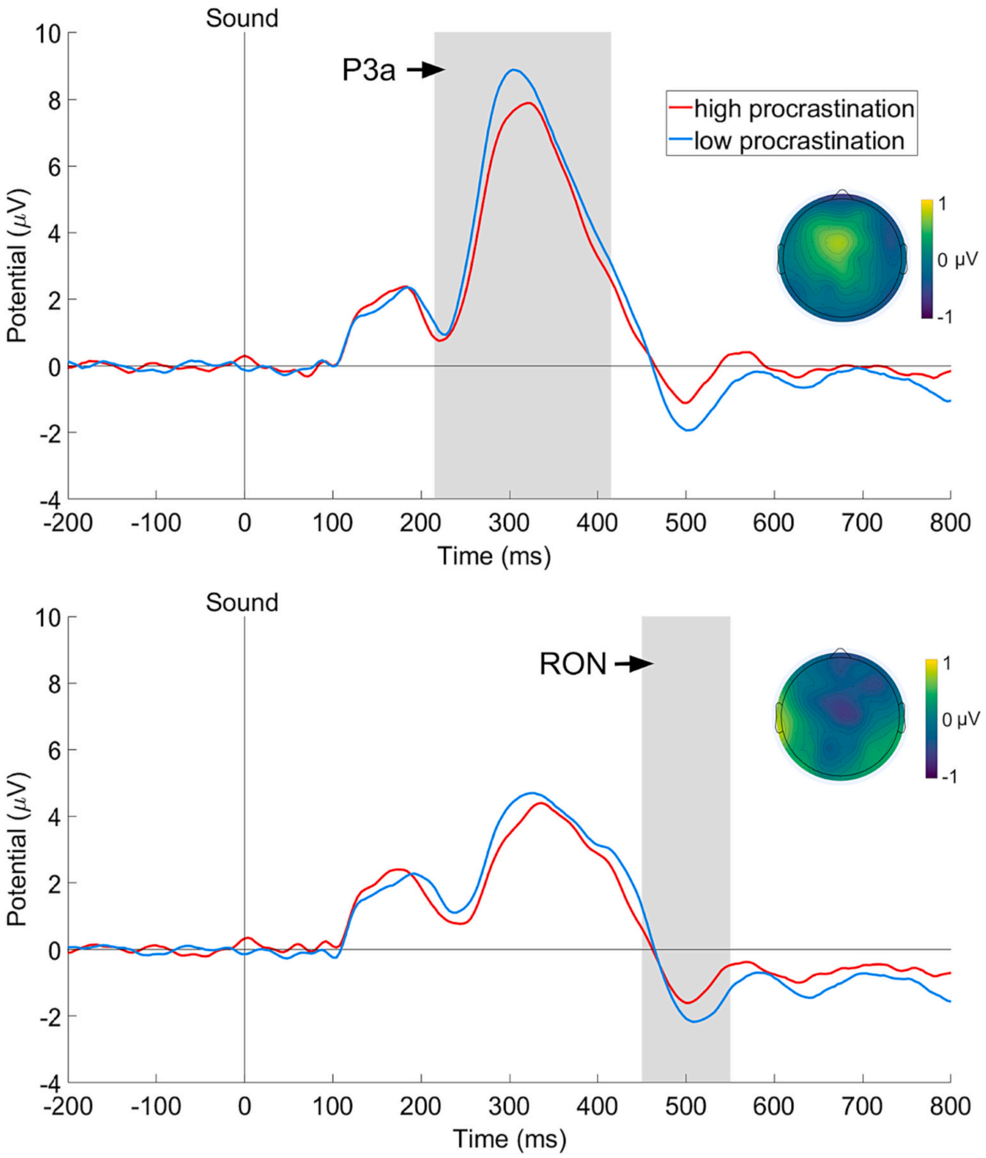

Fig. 4. Difference waves of the event-related potentials, computed by subtracting the potentials in response to standard sounds (1 kH tones, presented in 70 % of trials) from the potentials evoked by novel sounds (environmental sounds, presented in 15 % of trials) in the Audio-Visual Distraction task, in which. Participants had to react to visual stimuli and ignore preceding sounds. Shaded areas represent the time-windows chosen for the analyses of P3a and reorienting negativity (RON), which were scored accordingly from channels FCz (upper figure) and Fz (lower figure). Scalp maps represent the differences in event-related potentials between low and high procrastination groups within the time windows corresponding to components analyses. The analyses showed no significant differences between high and low procrastination groups either in P3a or RON (see the Results section for details).

sound and procrastination, we performed additional Bayesian mixed factor ANOVA with procrastination (HP vs. LP) as a between-group factor and sound (standard vs. novel) as a within-group factor. The results indicated that the data was best represented by the main effect of sound and that this model explained the data better than procrastination x sound interaction. The evidence was weak for potentials scored from Pz ($BF_{01} = 1.70$) and moderate for cluster analyses ($BF_{01} = 3.28$).

3.3. *ASRS results*

HP scored higher in ASRS than low procrastinating participants ($M_{LP} = 27.52$, $SD_{LP} = 8.15$; $M_{HP} = 43.79$, $SD_{HP} = 9.49$; $t(82) = 8.43$; $p < .001$; $d = 1.84$; see Fig. 6).

4. Discussion

In the present study we investigated the differences between HP and LP in resistance to external distraction. Taking into account previous studies indicating reduced attentional control among HP students (e.g. Michałowski et al., 2020; Wiwatowska et al., 2022), we expected that this group of participants would be more distracted by short task-irrelevant environmental sounds than non-procrastinating individuals. However, opposite to our hypotheses, we found no differences between groups in behavioral and neurophysiological indices reflecting attentional orientation towards distracting stimuli. Although the analyses of RTs showed the expected effect of distraction - participants reacted slower in response to visual stimuli preceded by novel, as compared to standard or deviant sounds - this increase in RT was similar in both groups. Also, procrastinators did not respond with increased P3a and RON, reflecting accordingly attentional capture by novel sounds and reorientation of attention back to task-relevant stimuli. Moreover, by conducting Bayesian analyses, we found positive evidence for the lack of group differences in all these indices (RTs, P3a, and RON), which undermines the assumption that procrastination is related to lower resistance to external distraction. However, the evidence indicated by Bayes factors was weak to moderate, which should prevent from drawing strong conclusions based on these findings.

Nevertheless, in line with our predictions and previous findings (e.g. Michałowski et al., 2020; Wiwatowska et al., 2022), we observed that HP, as compared to LP, presented increased RTV in standard trials as well as lower amplitudes of P3b to visual stimuli. Higher RTV reflects instability of cognitive processes, often related to fluctuations within attentional control (MacDonald et al., 2009; Weissman et al., 2006), while lower P3b indicates reduced amount of cognitive resources used to

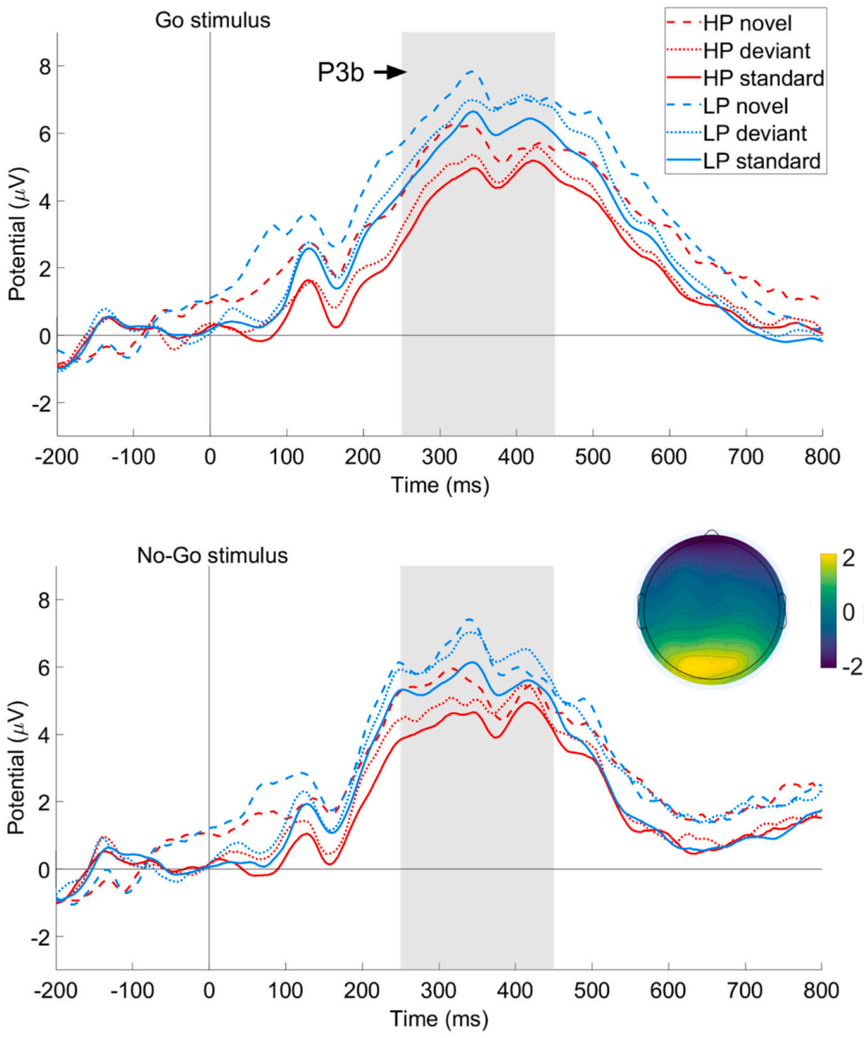

Fig. 5. The event-related potentials scored from the Pz channel in response to Go (upper figure) and No-Go (lower figure) visual stimuli preceded by three types of sound in the Audio-Visual Distraction task among high (HP) and low (LP) procrastination groups. In the task, participants had to respond to visual stimuli preceded by three kinds of sounds that needed to be ignored: standard (1 kH tones, presented in 70 % of trials), deviants (2 kH tones, presented in 15 % of trials), and novels (environmental sounds, presented in 15 % of trials). Shaded areas represent the time window chosen for the P3b analyses, which showed main effects of sound and procrastination (see the Results section for details). The scalp map represents the difference in event-related potentials between low and high procrastination groups (mean for Go and No-Go stimuli) within the time window corresponding to component's analyses.

process task-relevant stimuli (Ghani et al., 2020; Polich, 2007). Both increased RTV and reduced P3b have been systematically found in ADHD (see Kaiser et al., 2020; Kofler et al., 2013; Szuromi et al., 2011 for metaanalyses) as well as in other disorders associated with deficits in attentional control (Bora et al., 2006; Kaiser et al., 2008; Klawohn et al., 2020; Röschke & Wagner, 2003). Further, higher RTV and lower P3b have been found during mind-wandering episodes, as compared to states of focused attention during task completion (Barron et al., 2011; Maillet et al., 2020; Smallwood et al., 2008). Taking into account that procrastination is related to a higher declared tendency to experience intrusive thoughts, like rumination or daydreaming (Rebetez et al., 2018), it might be that this internally-oriented distraction underlies the observed differences in RTV and P3b between groups. Although both internal and external distraction are displays of attentional control failure, it seems that they are distinct processes (Unsworth & McMillan, 2014; Ziegler et al., 2018). Actually, it has been suggested that mind-wandering represents the decoupling of attention from the external environment towards one's thoughts and feelings (Kam & Handy, 2013). In support of this view, Barron et al. (2011) showed that higher frequency of mind-wandering episodes was related to reduced neural response to both task-relevant and distracting stimuli. Therefore, the relationship between procrastination and lower attentional control indicated by previous theories and studies (e.g. Steel et al., 2018) might stem from the inability to control the content of one's thoughts, and not distraction sourced from the surrounding environment. Thus, the previously reported link between procrastination and declared susceptibility to external distraction might reflect perceived, rather than actual causes for delayed task completion. Further, beliefs about lower ability to ignore distractions can decrease perceived self-efficacy and contribute to the development of self-handicapping strategies, which have been previously related to higher tendency to procrastinate (e.g. Strunk & Steele, 2011).

Although in our study we did not observe significant differences between groups in their behavioral and neural reactions to distraction, it might be related to the characteristics of presented distractors, which could have drawn participants' attention in a bottom-up manner. Indeed, it has been suggested that P3a reflects more automatic attentional orienting, while P3b amplitude is more dependent on top-down cognitive control processes (Kaunhoven & Dorjee, 2017). It has been frequently suggested that bottom-up and top-down attentional functions are distinct processes, related to activation within different brain networks (e.g. Corbetta & Shulman, 2002; Power & Petersen, 2013). This distinction indicates that reduced activity of a network responsible for top-down attentional control might not necessarily lead to deficits in bottom-up orienting. Also, the findings of this study are in line with our previous research, which indicated that although HP (vs. LP) showed reduced neural activity (lower P3b and contingent negative variation) associated with proactive cognitive control (linked to goal maintenance), the groups did not differ in reactive control engagement (as shown by similar N2 and P3a; Wiwatowska et al., 2022), which is more dependent upon bottom-up processes (Braver, 2012).

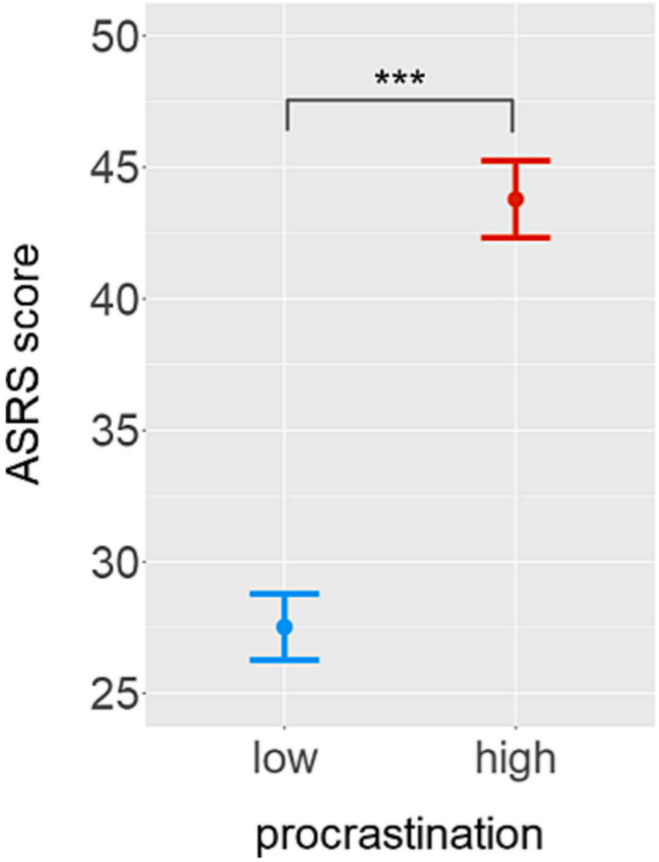

Fig. 6. Mean scores of the Adult ADHD Self-Report Scale (ASRS; WHO; Kessler et al., 2005). Error bars represent one standard error.
*** $p < .001$.

4.1. Limitations and future directions

The presented study is not free from limitations, which can be addressed in future studies. First of all, in this research we used distractors that were presented in a different sensory modality (auditory) than task-relevant stimuli (visual) and it has been acknowledged that unimodal and cross-modal selective attention might rely on partially distinct mechanisms and therefore, yield differential distraction effects (e.g. Guerreiro et al., 2010). That said, it would be interesting for future research to further verify the obtained findings and investigate whether HPs' performance would be impacted to a higher extent by other distractors presented in the same sensory modality as task-relevant stimuli. Further, although the external distraction elongated RTs and resulted in higher amplitudes of selected ERPs, the error rates were not increased after the appearance of distracting stimuli. We hypothesize that this could have been caused by a ceiling effect for response accuracy (which was also observed in other studies using this kind of paradigm, e.g., Cid-Fernández et al., 2014, 2016). Therefore, in the future, it might be beneficial to utilize a more difficult task than the one that was used in this study, as it might be that procrastination-related susceptibility to external distractors would be manifested to a higher extent in more demanding conditions.

Future studies might also examine the influence of distractors with varying motivational significance, such as the sounds of incoming messages or social-media notifications. As previously shown, financial or social motivators can have a different impact on cognitive performance and brain activity among HP, as compared to individuals with a lower tendency to delay tasks (e.g. Michałowski et al., 2017; Przetacka et al., 2021; see Wypych & Potenza, 2021 for a discussion on this topic). Therefore, HP students might be more sensitive to personally meaningful distractions than non-procrastinators. It is also possible that these motivationally significant distractors would draw attention to a similar extent among students regardless of their procrastination tendencies, but HP might find it harder to resist temptations to check their phones or answer their emails. Also, some external distractors might induce internal distraction. For example, the sound of a facebook/twitter notification might trigger thoughts about recent social-media activities or upcoming events and ignoring these thoughts may be more dependent upon top-down control. These issues should be addressed in future investigations. In addition, it would be valuable to verify whether the attentional dysfunctions among HP students are indeed associated with higher frequency of internally-oriented thoughts and to what extent observed deficits directly contribute to the exacerbation of procrastinatory behaviors.

It is also worth noting that the studied sample of HP and LP differed significantly in reported ADHD symptoms, which is in line with previous studies (Altgassen et al., 2019; Bolden & Fillauer, 2020; Zhen et al., 2020). Despite the fact that we excluded participants with diagnosed mental health disorders, it is possible that the HP group was comprised of individuals with subclinical or yet undiagnosed ADHD or other mental health issues, which are related to procrastination (e.g. depression; Constantin et al., 2018). Although it might be perceived as a confounding factor, this result indicates that the conclusions from this study might be to some extent extrapolated to other populations suffering from attention deficits. It might be the case that chronic procrastination is merely the symptom of ADHD, or that these two conditions share certain similar neural underpinnings which impacts their frequent concomitance. Nonetheless, it should be kept in mind that we used only a self-evaluation method of ADHD, which does not allow for reliable diagnosis. Future studies might try to control for this factor by conducting clinical evaluation in order to exclude participants who fulfill criteria for these disorders and verify if under such conditions increased procrastination would still be associated with lower P3b or higher RTV.

It should also be acknowledged that even though P3a and RON have been frequently related to orienting attention towards and away from distracting stimuli, some studies indicate that other processes might be reflected by these components, such as an increase in arousal elicited by novelty (e.g. Masson & Bidet-Caulet, 2019; SanMiguel et al., 2010; Widmann et al., 2018). Although this interpretation does not exclude the possibility of attentional shift towards arousing stimuli, it should be recognized that there might be alternative interpretations for the lack of differences between groups in the amplitudes of these components. Even though insignificant effects of procrastination on P3a and RON were accompanied by the lack of differences between groups in behavioral data, other indices of external distraction in the future studies would be desirable in order to further confirm the findings of this study.

Moreover, it should be kept in mind that in our research, participants performed multiple tasks during one session. The order of task completion was counterbalanced across groups, so the risk that it could have affected the obtained differences (or lack of them) was minimized, but it might be completely avoided in the future investigations by including only one task per study session.

Another important limitation of the presented study is that HP and LP groups were distinguished solely on the self-report measure of procrastination. While this is a frequently adopted method to identify the general tendency to delay tasks, it might reflect the subjective beliefs that might not always reflect actual behaviors. Yet, observer-report measures are not free from errors either and some studies show that in comparison to questionnaires, they are worse predictors of procrastination outcomes (e.g. Krause & Freund, 2014). For example, evaluating the time of finishing certain assignments might be better suited for capturing state procrastination, as opposed to general disposition. Moreover, this type of measures might be more sensitive to other kinds of delay, such as strategic delay or those caused by unforeseen circumstances. Nevertheless, in the future, multiple different measures might be used in the same study in order to minimize the measurement error. Also, given the fact that procrastination is more common in certain contexts (e.g. education; Steel, 2007) and states (negative mood; Blunt & Pychyl, 2000), it would be interesting to investigate the influence of external distraction on situational procrastination.

4.2. *Concluding remarks*

To sum up, the presented study did not support the hypothesis of the link between an increased tendency to delay tasks and reduced resistance to external distraction. However, we confirmed our previous findings of procrastinators' attentional control deficits (Michałowski et al., 2020; Wiwatowska et al., 2022), which in this population are potentially related to other sources of distractibility, e.g. an increased tendency to experience mind-wandering or rumination. The conclusions from the presented study provide potential directions for the development of interventions aimed at reducing procrastination, for example by training top-down attentional control. This is of particular importance, as some of the psychotherapeutic protocols for treating procrastination emphasize the need for training resistance to external distraction (e.g. Höcker et al., 2022), which in reality might not be that relevant. However, the efficacy of methods concentrated on enhancing attentional control should be further evaluated in future studies. As procrastination is a very prevalent problem among students (Steel, 2007), substantially decreasing their quality of life and academic achievements (Beutel et al., 2016; Kim & Seo, 2015; Morris & Fritz, 2015), it is important that this issue receives proper attention.

CRediT authorship contribution statement

Ewa Wiwatowska: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Magdalena Pietruch:** Formal analysis, Investigation, Writing – review & editing. **Przemysław Katafoni:** Formal analysis, Investigation, Writing – review & editing. **Jarosław M. Michałowski:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Data availability

The data and code are available to download from a public repository at the following link: https://repod.icm.edu.pl/privateurl.xhtml?token=d7cf9422-4286-40ee-9f5e-1c5a28139070.

Acknowledgments

This research was supported by grants from the National Science Center (Narodowe Centrum Nauki, NCN) to the first author Ewa Wiwatowska (decision number: DEC-2021/41/N/HS6/02832) and to the senior author Jarosław M. Michałowski (decision number: DEC-2017/27/B/HS6/03065). The authors are grateful to the students and interns of Poznan Laboratory of Affective Neuroscience for their assistance in data collection.

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Załącznik nr 1A – Oświadczenia współautorów o wkładzie pracy w realizację i publikację badań nad związkiem pomiędzy prokrastynacją i podatnością na dystrakcję

Warszawa, dnia 18.09.2023

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Niniejszym oświadczam, że w pracy Wiwatowska, E., Pietruch, M., Katafoni, P., Michałowski, J.M. (2023). “I can’t focus now, I will study tomorrow” - The link between academic procrastination and resistance to distraction. *Learning and Individual Differences*, *107*, 102364. mój udział polegał na pomocy w przeprowadzaniu badań, analizie danych oraz korekcie przygotowanego manuskryptu. Mój udział w powstaniu pracy wynosi 10%.

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Niniejszym oświadczam, że w pracy Wiwatowska, E., Pietruch, M., Katafoni, P., Michałowski, J., M. (2023). "I can't focus now, I will study tomorrow" - The link between academic procrastination and resistance to distraction. *Learning and Individual Differences, 107*, 102364. mój udział polegał na pracy koncepcyjnej, rekrutacji uczestników, zbieraniu i analizowaniu danych, interpretacji uzyskanych wyników, przygotowaniu pierwszej wersji manuskryptu oraz jego późniejszej korekcie, złożeniu artykułu do czasopisma i odpowiedzi na uwagi recenzentów. Mój udział w powstaniu pracy wynosi 50%.

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Podpis

Załącznik nr 2 – Publikacja badań nad związkiem pomiędzy prokrastynacją i kontrolą poznawczą

Cognitive, Affective, & Behavioral Neuroscience (2022) 22:171–186
https://doi.org/10.3758/s13415-021-00945-2

RESEARCH ARTICLE

Decreased preparatory activation and inattention to cues suggest lower activation of proactive cognitive control among high procrastinating students

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Accepted: 10 August 2021 / Published online: 8 September 2021

Abstract

Procrastination is a voluntary delay in completing an important task while being aware that this behavior may lead to negative outcomes. It has been shown that an increased tendency to procrastinate is associated with deficits in some aspects of cognitive control. However, none of the previous studies investigated these dysfunctions through the lenses of the Dual Mechanisms Framework, which differentiates proactive and reactive modes of control. The present study was designed to fill this gap, using behavioral and neurophysiological assessment during the completion of the AX-Continuous Performance Task (AX-CPT) by high (HP) and low (LP) procrastinating students ($N = 139$). Behavioral results indicated that HP (vs. LP) were characterized by increased attentional fluctuations (higher reaction time variability) and reduction in some indices of proactive cognitive control (lower *d*'-context and A-cue bias, but similar PBIs). Furthermore, the neurophysiological data showed that HP, compared with LP, allocated less attentional resources (lower P3b) to cues that help to predict the correct responses to upcoming probes. They also responded with reduced preparatory activity (smaller CNV) after cues presentation. The two groups did not differ in neural responses linked to conflict detection and inhibition (similar N2 and P3a). Obtained findings indicate that HP might present deficits in some cognitive functions that are essential for effective proactive control engagement, along with preserved levels of reactive cognitive control. In the present paper, we discuss the potential neural and cognitive mechanisms responsible for the observed effects.

Keywords Attention · Cognitive control · Procrastination · Event-related potentials

Introduction

Procrastination describes the behavior of delaying tasks despite knowing that it may bring negative consequences. Increased tendency to procrastinate affects approximately 15-20% of the total population (Klingsieck, 2013) and is especially common among students (Steel, 2007). It significantly reduces their academic performance (for meta-analysis see Kim & Seo, 2015) and quality of life (Beutel et al., 2016). Although different emotional and motivational factors have been proposed as potential causes for procrastinatory behaviors, growing evidence indicates that cognitive control deficits also might contribute to the exacerbation of this problem. For example, our recent study showed that high procrastinating students present difficulties with monitoring their performance and maintaining focused attention during task completion (Michałowski et al., 2020). Moreover, Gustavson and collaborators (2015) found that procrastination is linked to lower scores in the common executive functions factor that was suggested to reflect the ability to actively maintain goal-relevant information in order to guide and control behavior (Miyake & Friedman, 2012). These procrastination-related goal management failures also have been reflected in self-report data, which showed that the tendency to delay tasks is linked to a higher frequency of cognitive slips, such as forgetting simple things or frequently making mistakes (Gustavson et al., 2014; Gustavson et al., 2015).

Overall, these findings lead to the conclusion that procrastination is associated with deficits in some aspects of cognitive

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control. However, this issue has not been fully explored and calls for further investigation. For example, it is unclear whether the cognitive control dysfunctions related to procrastination are more reactive or proactive, as it is defined by the Dual Mechanisms Framework (Braver, 2012). According to this concept, two distinct modes of cognitive control can be engaged during task completion: proactive control, which is associated with global, tonic activation of the cognitive system in order to anticipate upcoming events; and reactive control, which serves as a late-correction mechanism, linked to transient response to targets. Some research has shown that these two mechanisms of control might be at the ends of one dimension, with a shift towards higher proactive control resulting in lower reactive control deployment and vice versa (Boudewyn et al., 2019; Braver et al., 2009). However, some preliminary studies have indicated a possibility that proactive and reactive control might represent independent processes, which can be simultaneously applied (Gonthier et al., 2016; Mäki-Marttunen et al., 2019).

At the neural level, proactive control is associated with sustained activation in the lateral prefrontal cortex (lPFC; Jimura et al., 2010), which plays an important role in maintaining focus on task-relevant information (MacDonald et al., 2000) and anticipating incoming stimuli (Sohn et al., 2007). Reactive control is linked to transient activation of lPFC and anterior cingulate cortex (ACC; Burgess & Braver, 2010; Marini et al., 2016), which is especially active during conflict detection and inhibition of impulsive responses (Borst et al., 2014; Braver et al., 2001). Furthermore, proactive control has been suggested to be associated with the higher activity of lPFC areas to cues that help to prepare appropriate reactions to probes, while reactive control was proposed to be linked to higher lPFC activation in response to probes (Braver et al., 2009).

Proactive and reactive mechanisms of cognitive control are often studied with the use of the AX - Continuous Performance Task (AX-CPT; Cudo et al., 2018; Locke & Braver, 2008). In this task, pairs of letters appear on the screen in a cue-probe sequence. There are two types of cues (A and B) and probes (X and Y) resulting in four types of trials: AX, AY, BX, and BY (see *Methods* section for details). Trials AX are the most frequent (70%) and require a target response that is different than the response to other trials (i.e., nontarget response). Slower reactions and lower response accuracy in AY trials indicate increased proactive control engagement, as the appearance of the A-cue increases expectations and response preparation for the X-probe. Accordingly, slower and more erroneous responses in BX trials are linked to higher reactive control engagement, due to transient activation of response representation associated with the most common AX trial. Also, several other behavioral indices related to proactive control have been previously distinguished in the AX-CPT paradigm: *d*'-context, A-cue bias, and Proactive Behavioral Index (PBI). The *d*'-context and A-cue bias are measures derived from the signal detection theory (Stanislaw & Todorov, 1999); the first index reflects the ability to apply contextual information from a cue in response execution (Barch et al., 2001), and the second indicates to what extent the A cue biases individuals to execute a target response (as in AX trials) independently of the probe type (Gonthier et al., 2016). The PBI reflects the shift from the reactive to proactive mode of control from the perspective of the unidimensional approach, with higher values indicating increased proactive but decreased reactive control engagement and vice versa (Braver et al., 2009).

The AX-CPT also allows for investigating the neural correlates of reactive and proactive control processes with the use of different neuroimaging tools. One of such techniques is the event-related potential (ERP) method, which allows for the measurement of brain responses to different stimuli with high temporal precision. Several components have been identified as cognitive control indices in the AX-CPT. Increased proactive control engagement is assumed to be associated with higher amplitudes of the P3b component in response to cues (Cudo et al., 2018; Morales et al., 2015). This is a parietally distributed, positive potential, linked to allocating attentional resources to salient stimuli and updating contextual information in working memory (Kok, 2001; Lenartowicz et al., 2010; Polich, 2007). Therefore, higher amplitudes of this component might indicate greater utilization of cues in order to respond quickly and correctly to the upcoming probes (Frömer et al., 2021).

Proactive control also is reflected by more negative amplitudes of Contingent Negative Variation (CNV) preceding probe presentation (Chaillou et al., 2017; Cudo et al., 2018; Morales et al., 2015). CNV is a slowly decreasing, negative wave, which appears between cue and probe presentation and indicates both cognitive and motor response preparation as well as context maintenance (Falkenstein et al., 2003). Larger (i.e., more negative) amplitudes of this component are (similarly to P3b) linked to faster and more accurate responses (Frömer et al., 2021; Hohnsbein et al., 1998; Van Den Berg et al., 2014). Although multiple brain areas have been identified as the potential sources of CNV, numerous studies indicate the significant contribution of dorsolateral PFC (dlPFC) and ACC (Bareš et al., 2007; Gómez et al., 2003; Gómez et al., 2007; Mannarelli et al., 2015; Onoda et al., 2004; Rosahl & Knight, 1995).

Regarding reactive control engagement, it is often assumed to be reflected by more pronounced amplitudes of N2 and P3a in response to probes in AY trials (Chaillou et al., 2017; Li et al., 2018). These are frontally distributed components, which have been previously associated with ACC activity (Nieuwenhuis et al., 2003; Volpe et al., 2007). N2 is related to the detection of incongruence or conflict, for example as a result of expectations violation or competing choice alternatives (Donkers & Van Boxtel, 2004; Groom & Cragg, 2015; Nieuwenhuis et al., 2003). P3a reflects inhibition of motor response and attentional orienting towards unexpected stimuli (Enriquez-Geppert et al., 2010;

Polich, 2007). Thus, larger amplitudes of these components are associated with efficient response inhibition and cognitive control in the face of conflict.

The present study aimed to investigate differences in proactive and reactive control engagement between high and low procrastinating students. We predicted that high, compared with low procrastinators, would be less effective in applying proactive control, which would be reflected by quicker and more accurate responses specifically in AY trials, decreased values of behavioral proactive control indices (*d*'-context, A-cue bias and PBI) as well as lower amplitudes of P3b and CNV after cues presentation.

We have based our hypotheses on several premises. First, procrastination has been previously linked with low goal-management skills and deficits in the common executive functions factor (Gustavson et al., 2014, 2015)—a concept that is closely related to proactive control, as it encompasses the maintenance and implementation of task-related goals (Friedman & Miyake, 2017).

Second, procrastination has been associated with decreased grey matter volume and weaker activation of dlPFC (Chen et al., 2020; Liu & Feng, 2017), as well as decreased dlPFC and ACC activity throughout longer periods in the Go/No-Go task, which measures different aspects of cognitive control (Wypych et al., 2019). The sustained character of these ACC and dlPFC functional changes, along with the structural differences within dlPFC is another argument for the possibility of lower proactive control engagement among high procrastinating individuals.

Finally, in our previous ERP study, we observed that high (vs. low) procrastinating students presented overall lower P3b amplitudes in the parametric Go/No-Go task (Michałowski et al., 2020), an effect that we suggested to reflect lower levels of sustained attention, which is essential for effective proactive control engagement. Moreover, lower P3b amplitudes in high procrastinating students were accompanied by higher reaction time variability (RTV), which might indicate fluctuations in attentional control, resulting in momentary lapses of attention and disengagement from the performing task (Esterman et al., 2013; MacDonald et al., 2009; Weissman et al., 2006). It has been suggested that increased RTV might be associated with failures in proactive cognitive control (Fassbender et al., 2014). However, this relationship has not been fully investigated yet, which is why we decided to conduct additional, correlational analyses between this measure and proactive cognitive control indices (behavioral and neurophysiological). We speculated that higher RTV would be related to lower proactive control engagement.

Regarding reactive cognitive control, we did not expect to find any differences between high and low procrastinating students, as the neural and behavioral data collected in previous studies have shown that high procrastinators have rather preserved abilities to inhibit prepotent responses and detect incongruity in the external environment (Michałowski et al., 2017; Wypych et al., 2019).

Methods

Questionnaires

To measure the level of academic procrastination, we used the Polish version of Aitken Procrastination Inventory (API: Aitken, 1982), which consists of 19 items with a 5-point Likert scale response format and answers ranging from 1 (False) to 5 (True). The details of the Polish adaptation procedure and its results are provided in the supplementary materials.

Participants

Students ($N = 1968$) from different universities and colleges in Poznań completed the Polish version of API (Aitken, 1982). Of this sample, based on the standard deviation of the mean result in API, we selected 80 participants for high (scores 1 SD above the mean or higher; API ≥74; HP) and 80 subjects for low (scores 1 SD below the mean or lower; API ≤47; LP) procrastination groups. We excluded participants with psychiatric or neurological disorders as well as uncorrected vision. Of this sample, we had to exclude 21 participants: 2 participants turned out to be under psychotropic medications, 2 subjects misunderstood the instructions, 5 participants responded with too low accuracy (≥50% in AX or BY trials), 11 subjects had poor quality of EEG signal (more than 25% excluded epochs), and 1 participant prematurely ended the task. The final sample consisted of 69 participants (36 females) in the LP and 70 participants (36 females) in the HP group. The descriptive statistics of the API results for both groups are provided in the supplementary materials (see Table S1).

The study was approved by the local Ethics Committee at the SWPS University of Social Sciences and Humanities and performed in accordance with the Declaration of Helsinki. All participants signed informed consent of participation and received 80 PLN (~22 USD) at the end of the study.

Task and procedure

Participants completed the AX-CPT task (Figure 1) presented on a 17” monitor placed approximately 70 cm from participants' eyes. In the AX-CPT pairs of letters appeared on the screen in a cue-probe sequence. The letter A served as a target cue, the letter X as a target probe and letters other than A or X as nontarget cues or probes. There were four possible trial types: AX with a target cue (A) followed by a target probe (X); AY with a target cue followed by a nontarget probe (letter other than X); BX with a nontarget cue (letter other than A) followed by a target probe; and BY with a nontarget cue followed by a non-target probe.

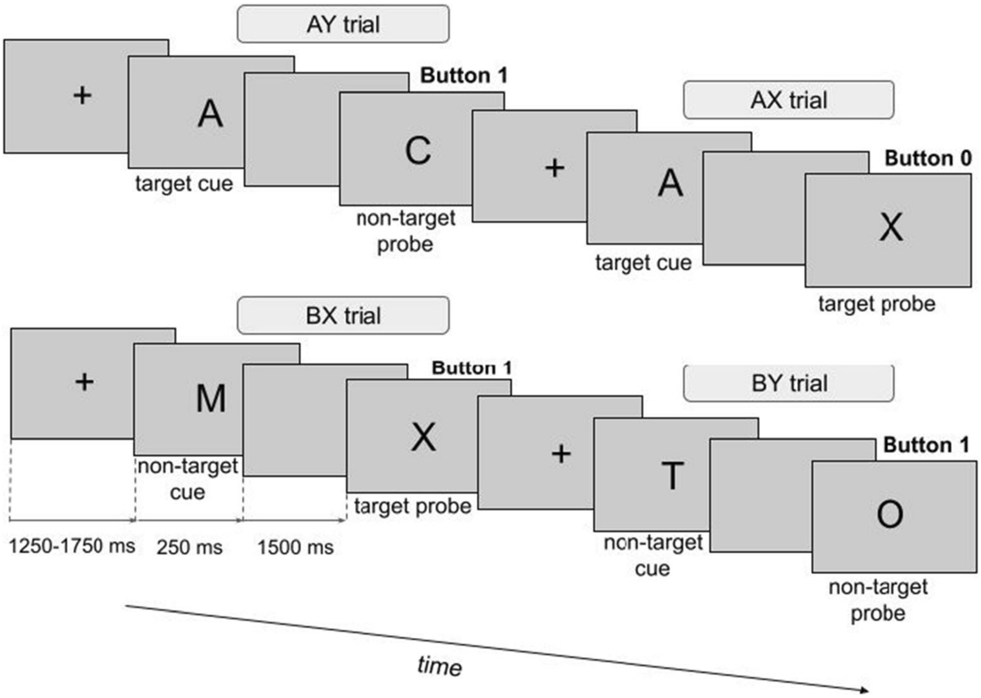

Fig. 1 The AX - Continuous Performance Task. Pairs of letters appeared on the screen in cue-probe sequences. The letter A served as a target cue, the letter X as a target probe and letters other than A or X as nontarget probes or cues. There were four possible trial types: AX: a target cue followed by a target probe; AY: a target cue followed by a nontarget probe; BX: a nontarget cue followed by a target probe; BY: a nontarget cue followed by a nontarget probe. Participants responded to probes by pressing one of two buttons (1 or 0) on the keyboard. Trials AX occurred with 70% probability and required the response with a different button than other three trial types (each presented with 10% probability). Increased proactive control is thought to be reflected by more errors and longer reaction times in AY trials, while reactive control is linked with worse performance in BX trials.

Participants had to respond to probes by pressing buttons 0 or 1 on the top row of the keyboard (with their left and right hand accordingly). Half of the participants in each group responded with 1 to probes in AX trials and with 0 to probes in other trial types, while the other half responded in the reversed manner. The response deadline was until the onset of the next cue presentation (1250-1750 ms after probes). There were 4 blocks of 100 trials with the following number of trial types in each block: AX – 70; AY – 10; BX – 10; and BY – 10. Trials were presented in a randomized order within each block. Letters were presented in black font on a grey background. The intertrial interval was randomized between 1250, 1500 and 1750 ms. Before each trial, a fixation cross appeared on the screen. A cue and a probe were presented for 250 ms. There was a 1500-ms interval between the cue offset and the onset of a probe. At the beginning of the task, there was a short training session, which could have been repeated in the case of instructions misunderstanding.

Electrophysiological recordings and signal processing

Continuous brain activity was recorded using BrainVision Recorder and BrainAmpDC amplifier (Brain Products GmbH, Gilching, Germany) with 64 electrodes placed according to the 10-20 system. Impedances were kept below 50 kΩ and the sampling rate was 500 Hz. Data was processed offline with EEGLAB and ERPLAB toolbox (Delorme & Makeig, 2004; Lopez-Calderon & Luck, 2014) for MATLAB (The Mathworks, Inc., Natick, MA). First, the signal was filtered with 0.1-Hz high-pass and 30-Hz low-pass filters. Then, via visual inspection, we detected and interpolated noisy channels as well as manually rejected large artifacts from the signal. After that, the average reference was set and the independent component analysis was performed using the *extended runica* algorithm in EEGLAB. Visual inspection, in addition to the automatic classifier - ICLabel (Pion-Tonachini et al., 2019), was used to detect and reject components reflecting muscle and eye movements, heart activity or channel noise.

For the P3a, P3b, and N2 analyses, the data was segmented into epochs 200 ms before and 800 ms after cue or probe onset with prestimulus baseline correction. For the CNV analyses epochs were extracted from −1950- to 200-ms time window relative to probes[1] with 200-ms precue baseline. Segments with

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[1] In some studies, using experimental tasks with sufficiently long intertrial intervals (ISIs), early and late CNV can be distinguished (Bender et al., 2012; Funderud et al., 2012; Hart et al., 2012). However, in AX-CPT paradigms with shorter ISIs, CNV is usually scored shortly before the probe presentation (−200 or even −100 to 0 ms before probes), even though it starts to develop much earlier (Beste et al., 2011; Chaillou et al., 2017; van Wouwe et al., 2011).

voltages exceeding ±75 µV were rejected from averaging and participants with more than 25% artifactual epochs (11 subjects) were excluded from further analyses.

Electrodes and time windows for ERPs analyses were chosen based on previous studies (Cudo et al., 2018; Incagli et al., 2020; Morales et al., 2015) as well as the visual inspection of electrical brain activity maps (see Figure S1 in the supplementary materials) and ERP waves grand-averaged from all subjects. As a result, the following electrodes and time windows were chosen for further analyses: P3a was scored from 300 to 400 ms after the probe onset at FCz; P3b was analyzed in the time window between 400 and 600 ms after the cue onset at Pz; N2 was calculated from 200 to 300 ms after the probe presentation at FCz; CNV was scored from −200 to 0 ms before the probe onset at FCz.

Statistical analysis

Statistical analyses were conducted with IBM SPSS Statistics 25. For each trial type, we compared rates of commission errors (incorrect button presses), omission errors (missed responses) as well as mean reaction times (RTs) for correct reactions only. RTV was calculated only for AX trials, as it was shown that this measure requires a relatively high trial number to achieve sufficient reliability (Saville et al., 2011). Other trial types were much less frequent and might have introduced some response variability resulting from other processes than failures in sustained attention. RTV was indexed as the coefficient of variation (CV), computed by dividing the standard deviation of RT by mean RT for each participant individually (Saville et al., 2011).

Regarding the behavioral indices linked to proactive control: PBI was calculated according to the formula (AY - BX)/(AY + BX) for both error rates (commission errors) and RTs in AY and BX trials; the *d*'-context was measured as the difference between z-transformed values of AX hit rate and BX commission error rate: $Z(AX_{hits}) - Z(BX_{ER})$; while the A-cue bias was calculated as the mean of z-transformed values of AX hit rate and AY commission error rate: $½*(Z[AX_{hits}] + Z[AY_{ER}])$. The log-linear transformation was applied to all error rate and hit rate data used in the calculation of all three proactive indices in order to correct for trials with error or hit rates equal to 0 or 1 (Gonthier et al., 2016; Hautus, 1995). The transformation was applied according to the formula: error/hit rate = (number of hits/errors + 0.5) / (number of trials + 1).

To compare RTs and error rates two-way mixed ANOVAs were conducted with a group (HP vs. LP) as the between-subject factor and a trial type (AX, AY, BX, BY) as the within-group variable. Independent sample *t*-tests were conducted to measure differences between procrastination groups in RTV and proactive control indices.

For ERPs analyses, two-way mixed ANOVAs were conducted including the between-subject factor group (HP vs. LP) and the within-subject factor cue (A vs. B) for CNV and P3b analyses or a trial type (AX, AY, BX, BY) for P3a and N2 analyses. For both behavioral and electrophysiological analyses, Bonferroni and Greenhouse-Geisser corrections were applied to account for multiple comparisons and violation of sphericity assumption accordingly. Additionally, independent sample *t*-tests were run to test the differences between groups in case of a significant interaction. Two-tailed Pearson correlation analyses were performed in order to assess the relations between RTV (in AX trials) and neurophysiological and behavioral indices of proactive control.

Participants, who achieved too low accuracy (≥50%) in AX or BY trials were excluded from analyses (5 subjects).

Results

Behavioral data

RTs and error rates are presented in Table 1 and Figure 2.

Reaction times

There were significant main effects of trial type for RTs ($F(2.07; 282.85) = 502.59$; $p < 0.001$; $\eta_p^2 = 0.79$). Paired comparisons revealed higher RTs for AY as compared with other trial types and increased RTs for AX in comparison to BX and BY trials ($ps < 0.001$). No differences in RT were observed between BX and BY trials ($p > 0.1$). HP responded slower than LP in all trial types ($F(1,137) = 5.27$; $p = 0.023$; $\eta p^2 = 0.04$) throughout the task.

Response accuracy

There were main effects of trial type for both types of error rates ($F(1.11; 152.36) = 126.37$; $p < 0.001$; $\eta p^2 = 0.48$ for commission errors; $F(1.71; 234.86) = 39.87$; $p < 0.001$; $\eta p^2 = 0.23$ for omission errors). Significant differences in commission error rates were observed between all trial pairs ($ps < 0.05$). The highest number of commission error rates was observed for AY trials, then in BX, AX, and BY trials.

The highest rate of omission rates was observed for BX and BY trials, then for AY trials and the lowest were for AX trials ($ps < 0.05$). There were no differences in omission rates between BX and BY trials ($p > 0.1$).

Regarding both omission and commission error rates, no significant group differences nor interactions were obtained ($Fs < 1$; $ps > 0.1$). Therefore, we did not confirm our hypotheses that compared with LP, HP would present decreased RTs and error rates specifically in AY trials, which would indicate lower proactive control engagement.

Table 1 Mean values (SDs) of reaction times, response accuracy and reaction-time variability (RTV) for high (HP) and low (LP) procrastinators and four trial types

Trial type	Reaction times [ms]			Commission errors [%]			Omission errors [%]		
	HP	LP	Mean	HP	LP	Mean	HP	LP	Mean
AX	379,34 (96,24)	357,57 (88,13)	368,53 (92,61)	1.35 (0.21)	1.25 (0.21)	1.30 (0.15)	2.47 (0.45)	1.67 (0.49)	2.07 (0.32)
AY	538,16 (94,93)	492,75 (94,86)	515,62 (97,26)	14.57 (1.67)	15.33 (1.68)	14.95 (1.18)	3.29 (0.58)	2.10 (0.58)	2.69 (0.41)
BX	349,35 (146,06)	301,20 (120,89)	325,45 (135,84)	2.82 (0.44)	2.03 (0.45)	2.43 (0.31)	6.36 (0.93)	6.12 (0.93)	6.24 (0.66)
BY	353,03 (129,39)	303,23 (123,81)	328,31 (128,64)	1.07 (0.23)	0.73 (0.23)	0.90 (0.16)	6.82 (1.05)	6.59 (1.06)	6.71 (0.74)

Reaction time variability

In accordance with our predictions, RTV in AX trials was higher in HP (M = 0.347; SD = 0.104) than in LP (M = 0.298; SD = 0.089) group (t(137) = 2.94; p = 0.004; d = 0.51). This suggests that HP show larger fluctuations in attentional control than LP.

Behavioral indices linked to proactive cognitive control

We predicted that HP would present lower values of behavioral indices linked to proactive control engagement. In line with our predictions, d'-context was lower in HP than in LP group (t(137) = 2.08; p = 0.039; d = 0.35; Figure 3), which indicates a reduced ability to use contextual information in response execution among HP. There also was a trend-level difference in A-cue bias between groups with lower values in HP (t(137) = 1.84; p = 0.068; d = 0.31; Figure 3), showing that this group of participants have lower tendency to make a target response after A cues (as in AX trials) regardless of the probe type. Opposite to what we expected, there were no significant differences in PBIs between groups (t(137) = 1.56; p = 0.121; d = 0.26 for commission error rates; t(129,65) = 1.26; p = 0.211; d = 0.21 for RTs).

The results of these behavioral indices show that HP (vs. LP) present a reduced ability to use contextual information from the cues in response to probes and are less biased to make a target response (as in AX trials) after A cues, regardless of the following probe type. However, the PBI results indicate that the decreased effectiveness of proactive control in HP is not accompanied by increased reactive control.

Electrophysiological data

Cue-related components

The results of P3b and CNV are presented in Table 2 and Figure 4.

P3b amplitudes were smaller in response to A vs. B cues (F(1,137) = 279.72; p < 0.001; η_p^2 = 0.67) and in HP than in LP group (F(1,137) = 10.10; p = .002; η_p^2 = 0.07) which is in accordance with our hypothesis and can be interpreted as lower attention to cues, linked with decreased proactive control employment. We also observed the significant group x cue interaction (F(1,137) = 4.41; p = .038; η_p^2 = 0.03). Post-hoc independent sample t-tests revealed that the differences between groups were larger in response to B cues (t(137) = 2.99; p = 0.003; MD = 1.17; SE = 0.39) compared with A cues (t(137) = 2.17; p = 0.032; MD = 0.41; SE = 0.19). As B cues are always followed by the same response irrespective of the upcoming probe, they allow for the proactive preparation of motor responses. Therefore, these results further confirm that HP present lower attention towards salient cues, which is essential for effective proactive control engagement. These findings are in line with behavioral data, which indicated lower d'-context among HP (see the above section).

CNV analyses confirmed our hypothesis, revealing that HP (vs. LP) presented smaller (less negative) amplitudes for both A and B cues (F(1,137) = 5.20; p = 0.024; η_p^2 = 0.04) with no significant main effect of cue or group x cue interaction (Fs < 1; ps > 0.1). This means that HP present lower preparatory activity before probes presentation. Lower CNV among HP also might contribute to reported above slower reactions to probes and lower A-cue bias, as higher preparatory activity might hinder the ability to withdraw the target response that is usually executed after A cues (see the behavioral data section).

Probe-related components

The results of N2 and P3a are presented in Table 3 and Figure 5.

N2 comparisons yielded the main effect of trial type (F(2.18; 298.47) = 21.70; p < 0.001; η_p^2 = 0.14). *Post hoc* tests showed more negative amplitudes evoked by Y probes (both in AY and BY trials) compared with those elicited by X probes (in AX and BX trials; ps < 0.001). There also was a trend toward bigger N2 in AY than in BY trials (p = 0.058). There were no significant differences in probe-related N2 amplitudes between AX and BX trials (p > 0.1).

P3a analyses showed the main effect of trial type (F(1.92; 262.58) = 48.02; p < 0.001; η_p^2 = 0.26). *Post hoc* tests revealed higher P3a to probes in AY trials compared with those occurring in other trial types and increased P3a to probes in AX trials

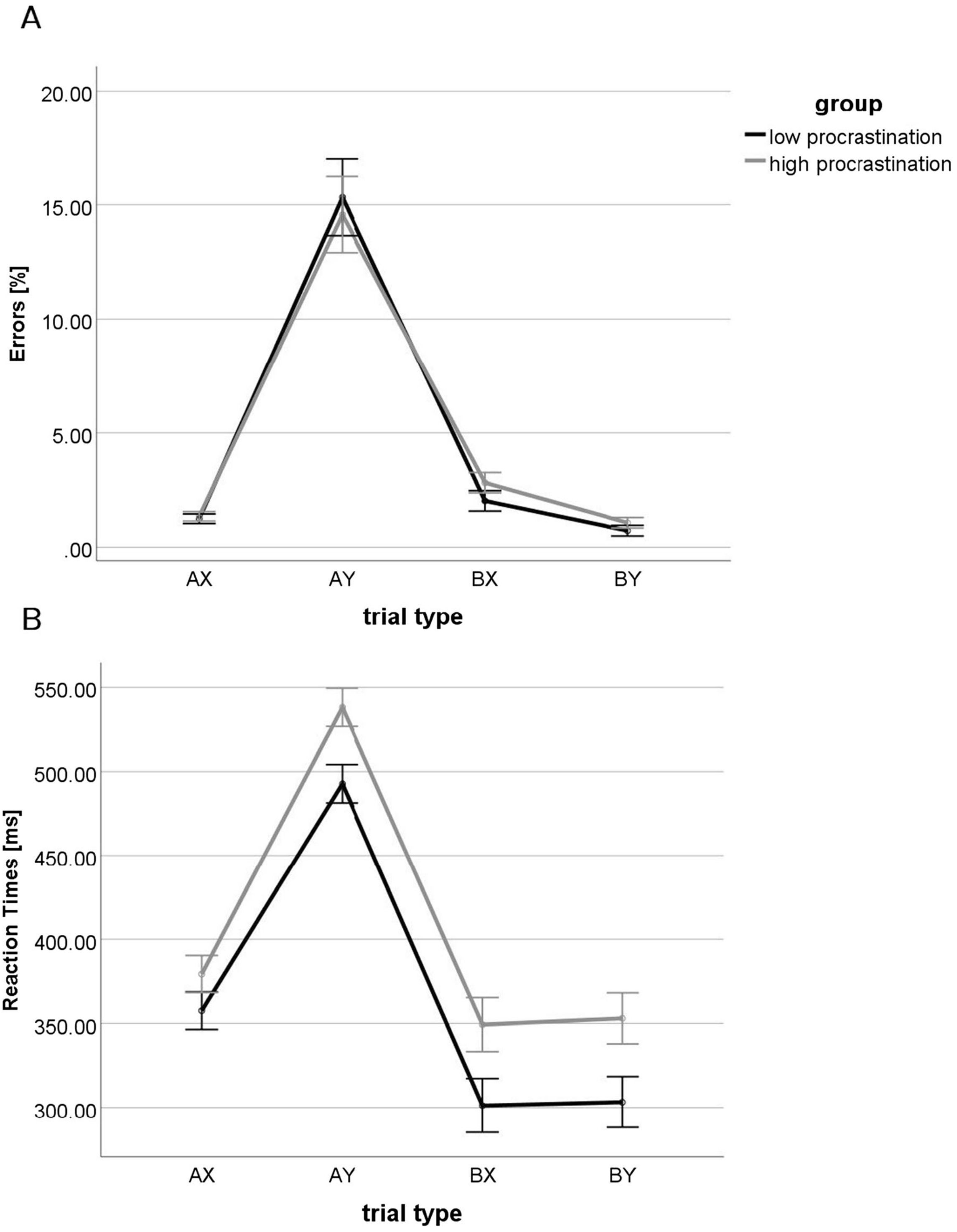

Fig. 2 Commission error rates (**A**) and reaction times (**B**) for high and low procrastinating participants in four types of trials. Each trial consisted of a cue: type A (letter A) or B (letters other than A); and a probe: type X (letter X) or Y (letters other than X). Participants had to press one button to X probes occurring after A (i.e., AX trials) and another button in other trial types (AY or BX or BY). The AX trials were the most frequent (70% of all trials). Error bars represent one standard error

when compared with those presented in BX and BY trial types (*ps* < 0.05), with no differences between BX-BY ($p > 0.1$).

We observed no main effect of group nor group x trial type interaction for both N2 and P3a (*Fs* < 2; *ps* > 0.1), which shows that there are no statistically significant differences between HP and LP in neurophysiological indices of reactive cognitive control, linked to conflict detection and inhibition.

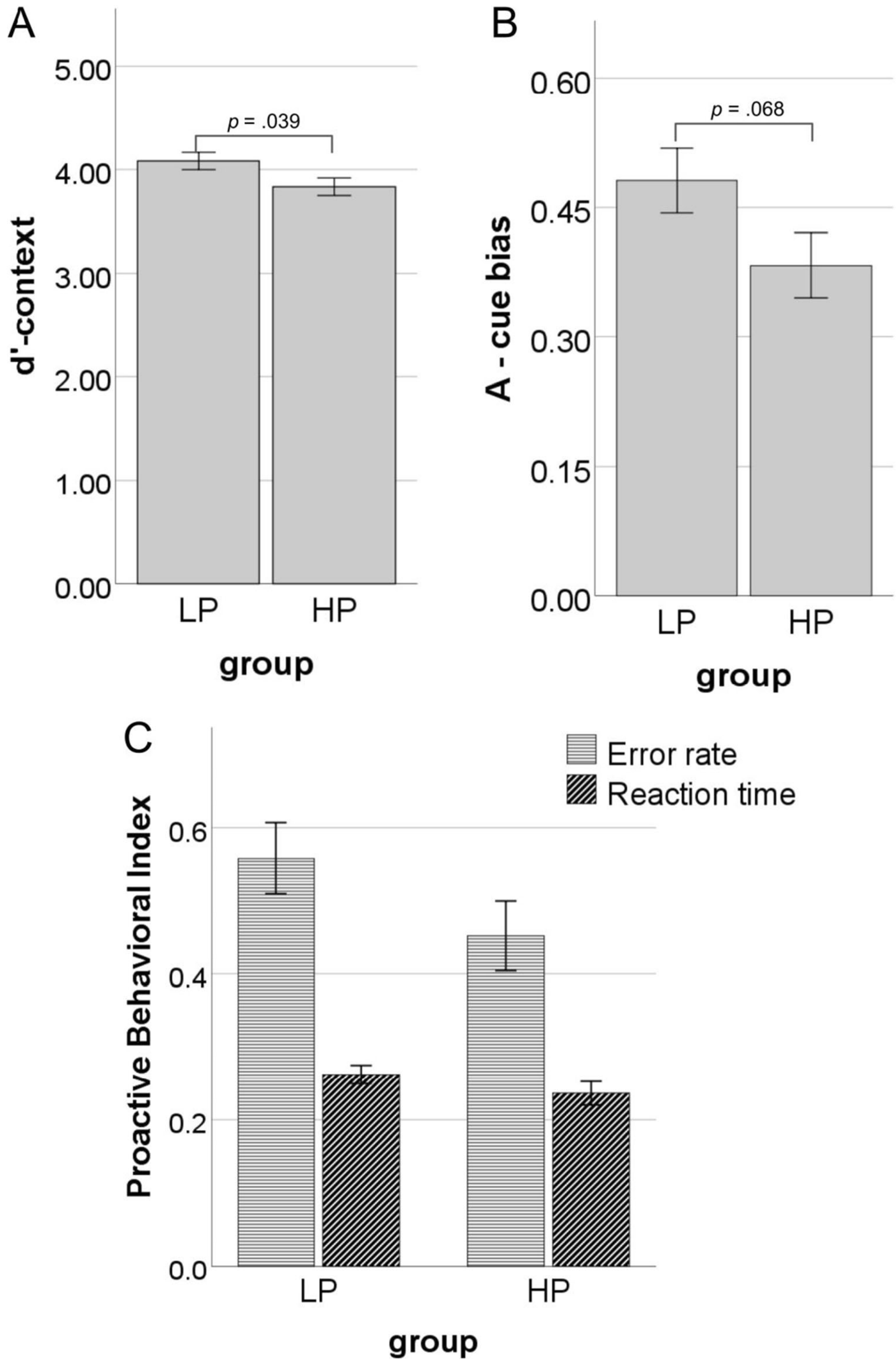

Fig. 3 Differences between high (HP) and low (LP) procrastination groups in proactive control indices: *d*'-context (**A**), A-cue bias (**B**), Proactive Behavioral Index calculated for error rates (commission errors) and reaction times (**C**). Higher values indicate increased proactive control engagement. Error bars represent one standard error

Table 2 Mean values (SDs) of P3b and CNV amplitudes elicited by A and B cues in high (HP) and low (LP) procrastinators

Cue type	P3b amplitudes [μV]		CNV amplitudes [μV]	
	HP	LP	HP	LP
A	0.88 (0.13)	1.29 (0.13)	−2.97 (0.30)	−3.94 (0.30)
B	3.53 (0.28)	4.70 (0.28)	−3.25 (0.27)	−3.94 (0.27)

Table 3 Mean values (SDs) of P3a and N2 amplitudes elicited by probes in high (HP) and low (LP) procrastinators in the four trial types

Trial type	P3a amplitudes [μV]		N2 amplitudes [μV]	
	HP	LP	HP	LP
AX	0.39 (2.58)	0.72 (3.48)	-0.47 (2.17)	-0.78 (2.35)
AY	1.97 (4.04)	2.29 (4.30)	-1.91 (2.68)	-1.61 (3.10)
BX	-0.25 (2.47)	-0.07 (2.87)	-0.50 (2.26)	-0.43 (2.50)
BY	-0.35 (2.61)	-0.38 (2.74)	-1.36 (2.31)	-1.05 (2.29)

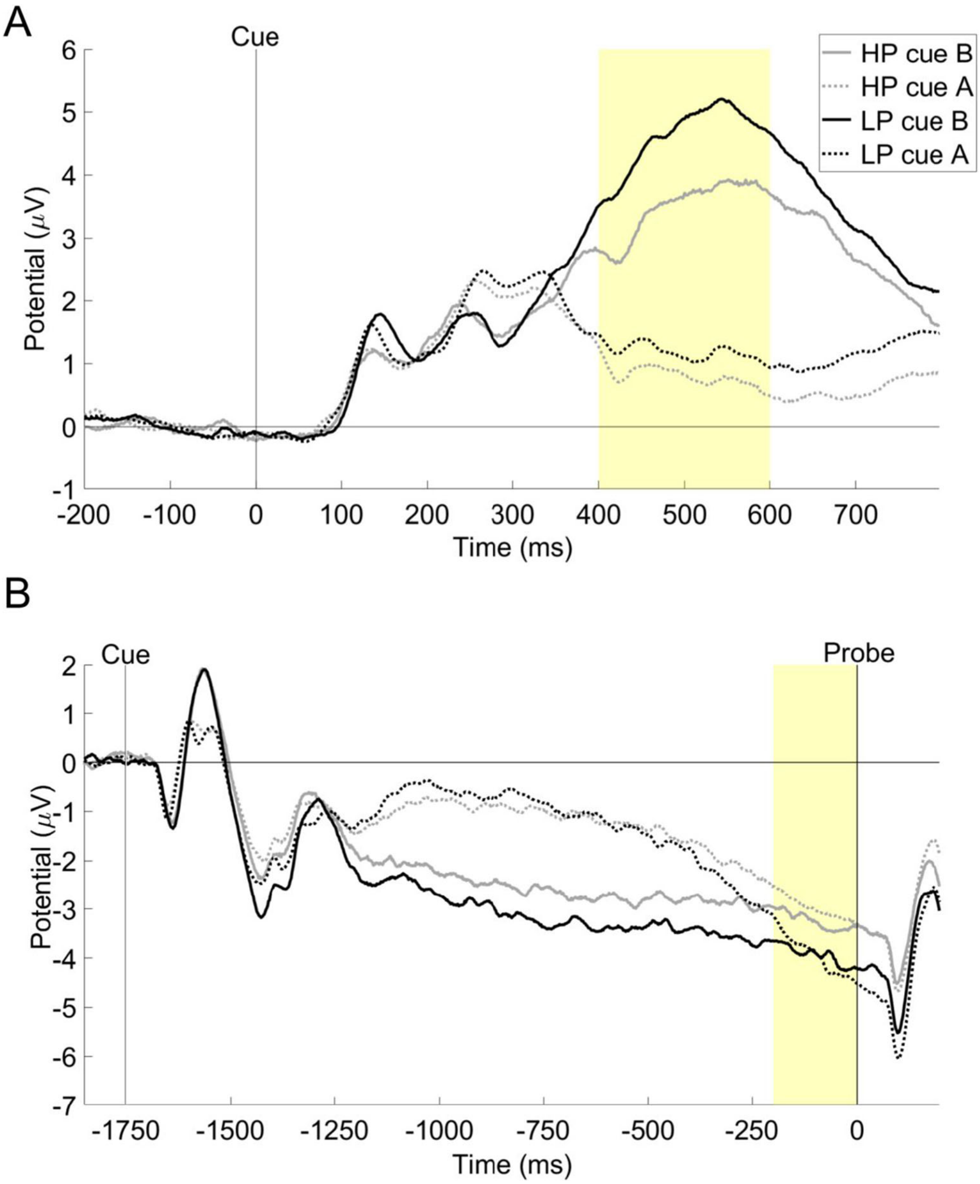

Fig. 4 Event-related potentials (ERPs) elicited by A and B cues in the AX-Continuous Performance Task among high (HP) and low (LP) procrastination groups. (**A**) ERPs averaged over Pz with a highlighted window chosen for P3b analyses; (**B**) ERPs averaged over FCz with a highlighted window chosen for CNV analyses

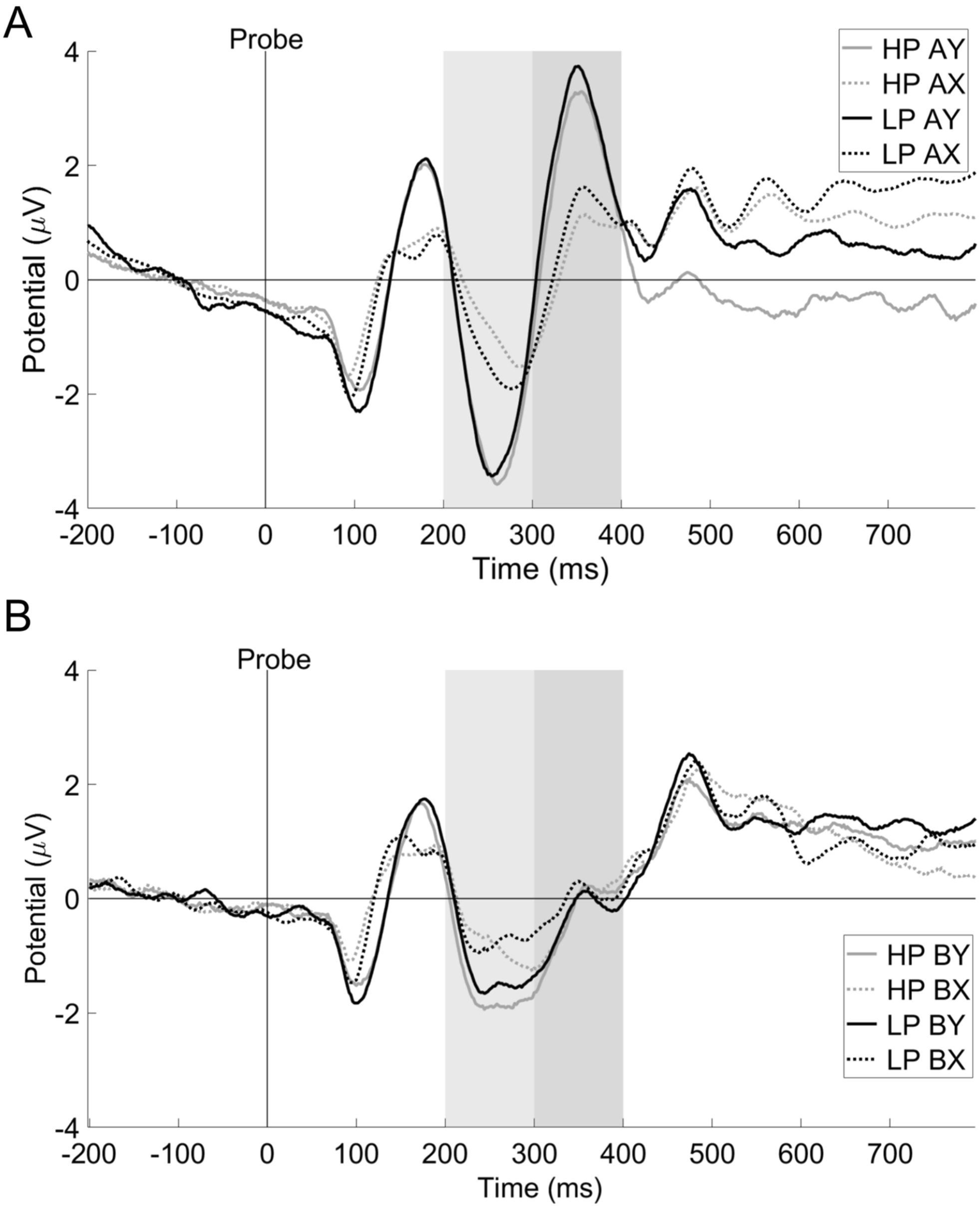

Fig. 5 ERPs averaged over FCz, elicited by the probes in four types of trials of the AX-Continuous Performance Task high (HP) and low (LP) procrastinating participants. (**A**) ERPs in trials AX and AY. (**B**) ERPs evoked in trials BX and BY. Highlighted areas represent the time windows chosen for N2 (light grey) and P3a (dark grey) analyses

Correlations with reaction time variability and proactive indices

Because RTV is supposed to reflect difficulties with sustained attention, we wanted to verify the link between this measure and proactive control indices. Confirming our predictions, increased RTV was correlated with lower *d*-context and A-cue bias as well as less pronounced P3b to B cues and CNV amplitudes. There were no significant correlations between RTV and PBIs as well as P3b in response to A cues (Table 4). This means that decreased ability to sustain attention is linked with lower utilization of cues, smaller preparatory activity before probes presentation and reduced tendency to execute a target response after A cue appearance, irrespective of the probe type. However, attentional fluctuations seem not to relate to the trade-off between performance in AY and BX trials.

Discussion

We investigated the differences in proactive and reactive control between students with high and low levels of procrastination. Based on the previous research on deficits in sustained

Table 4 Correlations between reaction time variability (RTV) as well as behavioral and neurophysiological indices of proactive control

	PBI-error	PBI-RT	*d*'-context	A-cue bias	CNV-A	CNV-B	P3b-A	P3b-B
RTV	−0.092	−0.116	−0.505**	−0.254**	0.317**	0.204*	0.006	−0.269**
PBI-error		0.575**	0.308**	0.670**	−0.286**	−0.211*	0.123	0.304**
PBI-RT			0.206*	0.557**	−0.387**	−0.340**	0.013	0.365**
d'-context				0.443**	−0.305**	−0.236*	−0.190*	0.210*
A-cue bias					−0.374**	−0.209*	−0.058	0.271**
CNV-A						0.649**	0.058	−0.267**
CNV-B							−0.067	−0.217*
P3b-A								0.420**

$^{**}p < 0.01$; $^{*}p < 0.05$; RTV = reaction time variability; PBI = Proactive Behavioral Index calculated for error rate (PBI-error) or reaction times (PBI-RT); CNV = Contingent Negative Variation (higher values represent smaller - less negative - CNV); A, B - cue types.

attention and goal-management failures in procrastination (Gustavson et al., 2014, 2015; Michałowski et al., 2020), we predicted that high procrastinating participants would present lower activation of proactive cognitive control than low procrastinating students. To test this hypothesis, we applied the AX-CPT paradigm along with electrophysiological measurements. Obtained results partially confirmed our predictions. Although the mean RTs, as well as error rates, in different trial types did not show a reduced proactive control pattern in high, as compared with low procrastinating participants, some of the proactive control indices were indeed lower in the high procrastination group. We also observed lower amplitudes of P3b and CNV in response to cues in high (vs. low) procrastinators, which further points out the possibility of decreased recruitment of proactive cognitive control among this group of participants. Also, we did not observe any significant differences between groups in probes-locked N2 and P3a, which indicates potentially similar reactive control engagement among high and low procrastinating subjects.

P3b reflects allocating attentional resources and updating contextual information in working memory (Polich, 2007). Smaller amplitudes of this component among high procrastinating participants might indicate lower proactive control engagement, as proper utilization of cues directs attention, reduces the number of alternative goal representations and in the end allows for more effective response preparation. Observed P3b differences between groups reached significance in response to both types of cues but were larger in response to B cues. In the AX-CPT paradigm B cues allow for the proactive preparation of the motor response, as reactions to the following probes are always the same, in contrast to A-cue trials, in which response choice is largely dependent on the following probe type (MacDonald & Carter, 2003; Mäki-Marttunen et al., 2019; Qiao et al., 2018). Therefore, larger between-group differences in P3b to B cues might indicate that high procrastinating participants allocate less attentional resources to task-relevant information, which allows for optimizing response strategy.

Along with lower P3b amplitudes, high procrastinators also showed less pronounced CNV between cue and probe presentation. Smaller amplitudes of this component might be associated with previously reported lower grey matter volume and decreased activation within dlPFC among high procrastinators (Chen et al., 2020; Liu & Feng, 2017), as this brain structure plays a significant role in behavioral control and response preparation (MacDonald et al., 2000). These structural and functional changes may significantly reduce procrastinators' ability to maintain focus on task-relevant information and contribute to an increased tendency to reorient attention towards external or internal distractors, reducing the amount of available cognitive resources. Indeed, in previous research higher procrastination has been linked to more frequent daydreaming and intrusive thoughts (Constantin et al., 2018; Rebetez et al., 2018). Therefore, it would be interesting for future studies to further explore the associations between proactive control deficits and proneness to mind-wandering in procrastination.

Apart from lower neurophysiological indices of proactive cognitive control in high procrastinating participants, we observed no differences between groups in the probes-locked N2 and P3a amplitudes, which are the indicators of reactive cognitive control engagement. It has been shown that these components are related to inhibition abilities with larger amplitudes reflecting higher inhibitory control (Donkers & Van Boxtel, 2004; Falkenstein et al., 1999; Van Boxtel et al., 2001). N2 reflects conflict detection, while P3a is an effect of conflict resolution and motor inhibition (Enriquez-Geppert et al., 2010; Groom & Cragg, 2015). Observed results are in line with previous studies that did not demonstrate deficits in inhibitory control among high procrastinating participants (Michałowski et al., 2017; Rebetez et al., 2016; Wypych et al., 2019). However, we cannot entirely rule out the possibility of the differences between groups in reactive control engagement. It might be that the AX-CPT is better suited for investigating individual differences in proactive than reactive cognitive control. Therefore, it would be beneficial if prospective studies used different paradigms to evaluate the link between procrastination and reactive control.

Also, some researchers emphasize the role of N2 and P3a components in orienting response towards novelty and expectation violation (Nieuwenhuis et al., 2003; Schomaker & Meeter, 2014). Unfortunately, it is impossible to disentangle these processes in AX-CPT, as the appearance of a non-target probe after an A-cue both violates expectations and requires inhibition of the most frequent response associated with a target cue. Therefore, it would be interesting for future studies to further elaborate on this topic and verify whether high procrastinating participants show an attenuated response to novel stimuli that do not require motor inhibition.

Regarding behavioral measures, high procrastinators showed lower means of proactive control indices than low procrastinating subjects. However, these differences between groups reached significance only in *d*'-context along with a tendency in A-cue bias. Lower *d*'-context might reflect a decreased ability of high procrastinating subjects to use contextual information in order to adjust their behavior. This index has been previously proven to be the most reliable measure among all behavioral indices of proactive control that have been analyzed in this study (Cooper et al., 2017; Kubota et al., 2020). However, different factors can influence the *d*'-context, such as better memory for the cue or less impulsive responding. Therefore, it might indicate that high procrastinators present deficits in only some aspects of cognitive functioning that are essential for effective proactive control engagement.

Decreased A-cue bias among high procrastinators might be considered as the more direct measure of lower proactive control engagement than *d*'-context, as it measures the tendency to execute target responses for A cues independently of the probe type (Gonthier et al., 2016). Moreover, this index is a more advantageous measure than simple comparisons of error rates in AY trials, as it also takes into account the accuracy in AX trials. However, as the differences between groups in A-cue bias were at the tendency level, we should interpret this result with caution. It would certainly be beneficial to replicate this effect on a bigger sample of participants.

Although we found lower *d*'-context and A-cue bias among high (vs. low) procrastinating participants, the differences in PBIs did not reach statistical significance in the present study. The possible explanation for this pattern of results is that PBIs capture the shift from the reactive to proactive style of responding, assuming that these two modes of cognitive control are at the opposite poles of one dimension (Braver et al., 2009). Accordingly, lower PBIs would indicate smaller proactive control, but at the same time higher reactive control and vice versa. However, our findings indicate the possibility of distinct nature of these two mechanisms, as high and low procrastinating subjects differed only in some indices of proactive control engagement, with no observed differences in reactive control. These results are in line with other studies showing that these two modes of cognitive control are independent of each other and can be simultaneously applied (Gonthier et al., 2016; Mäki-Marttunen et al., 2019). In such a case, PBIs might be less sensitive to capture proactive control problems when there are no differences between groups in reactive control engagement. Nevertheless, the lack of differences between groups in PBIs is an issue worth further investigation and signals the need to interpret the obtained results with caution.

Apart from lower values of some of the proactive control indices, high procrastinators also showed slower reactions throughout the task, which might result from inattention to cues and decreased preparatory activation before probe presentation. Indeed, previous studies have shown that greater cue utilization and larger CNV amplitudes are associated with faster reactions (Brouwers et al., 2017; Hillyard, 1969; Werre et al., 2001). We also replicated our previous results regarding increased RTV among high procrastinators, which indicates difficulties in sustained attention in this group of participants (Michałowski et al., 2020). Moreover, this measure turned out to be negatively correlated with most behavioral and neurophysiological indices of proactive control, such as A-cue bias, *d*'-context, CNV and P3b to B cues. It is in line with previous findings showing that higher RTV is linked with lower proactive responding (Mäki-Marttunen et al., 2018) and reduced CNV (Doehnert et al., 2013) and indicates that this measure might be considered as another index of proactive control engagement, reflecting processes involved in sustained attention. On the contrary, we did not observe significant correlations between RTV and PBIs. The potential explanation for this effect is that the ability to sustain attention is relatively equally relevant for fast and accurate responses in both AY and BX trials. Thus, RTV might be negatively related not only to proactive but also to reactive control engagement.

Contrary to our predictions, we did not find effects of high procrastination on faster reactions or lower error rates specifically in AY trials, which would further confirm decreased proactive control engagement. However, comparing the performance on AY trials independent of other trial types might not be sensitive enough to capture more subtle differences in proactive control between groups. Although RTs should be more sensitive to between-group differences of proactive control engagement than error rate data in such easy tasks as AX-CPT, it might not be the case for comparisons of subjects that generally differ in mean RTs. For example, Locke and Braver (2008) showed that the activation of proactive control during the introduction of reward incentives was associated with more errors in AY trials but the overall faster reactions, without any specific RTs effects for AY trials. Similar findings were obtained by Mäki-Marttunen and collaborators' (2018), who compared proactive and reactive groups of participants. Reactive subjects presented generally increased RTs, regardless of trial type, along with higher RTV. Therefore, it might be that frequent lapses of attention and slower responding are themselves indicative of reduced proactive control, despite the lack of a specific response pattern. However, these findings call for caution in drawing any definitive conclusions from this study. Future research might provide more insight into this issue, by applying different experimental paradigms to measure differences in proactive and reactive modes of control between high and low procrastinators.

According to our knowledge, this is the first study that investigated differences in proactive and reactive cognitive control activation among high and low procrastinating students. Obtained results revealed that high and low procrastinators present a similar neural response to inhibitory control and automatic conflict detection, which might indicate comparable reactive control engagement. We also observed that high as compared to low procrastinators show reduced neural activity linked to response preparation and allocation of attentional resources to task-relevant, contextual information. These neurophysiological results indicate that high procrastinators might present lower proactive control engagement than low procrastinating individuals. This is partially supported by the behavioral data, although some ambiguity in the behavioral results signals the need for caution in drawing any definitive conclusions. It would be desirable to replicate the presented findings in a correlational design study to verify whether there is a linear relationship between procrastination and proactive control recruitment. Although the comparison of extreme groups allows for capturing subtle effects in studies with a relatively small sample size, this kind of design poses some limitations. For example, it might overlook the possibility that the observed differences in cognitive control are manifested only in individuals with extreme procrastination tendencies.

Despite its limitations, the presented study provides some evidence of lower proactive control engagement in high, as compared to low procrastinating individuals. However, the associations between cognitive control recruitment and procrastination tendencies require further exploration. Future studies might take a closer look at different psychological and neuronal mechanisms that impair high procrastinators' cognitive performance and possible solutions to overcome these problems.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13415-021-00945-2.

Acknowledgments This research was supported by a grant from the National Science Centre (Narodowe Centrum Nauki, NCN) to the senior author Jarosław M. Michałowski, decision number: DEC-2017/27/B/HS6/03065. The authors are grateful to the students and interns of Poznan Laboratory of Affective Neuroscience for their assistance in data collection.

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SUPPLEMENTARY METHODS

Table S1. Aitken Procrastination Inventory - descriptive statistics for high and low procrastination groups

Group	Mean (SD)	Skewness (SE)	Kurtosis (SE)	Minimum - Maximum
Low procrastination (N = 69)	39.67 (5.48)	-0.75 (0.29)	-0.02 (0.57)	23.00 - 47.00
High procrastination (N = 70)	78.97 (3.64)	1.11 (0.29)	1.10 (0.57)	75.00 - 91.00

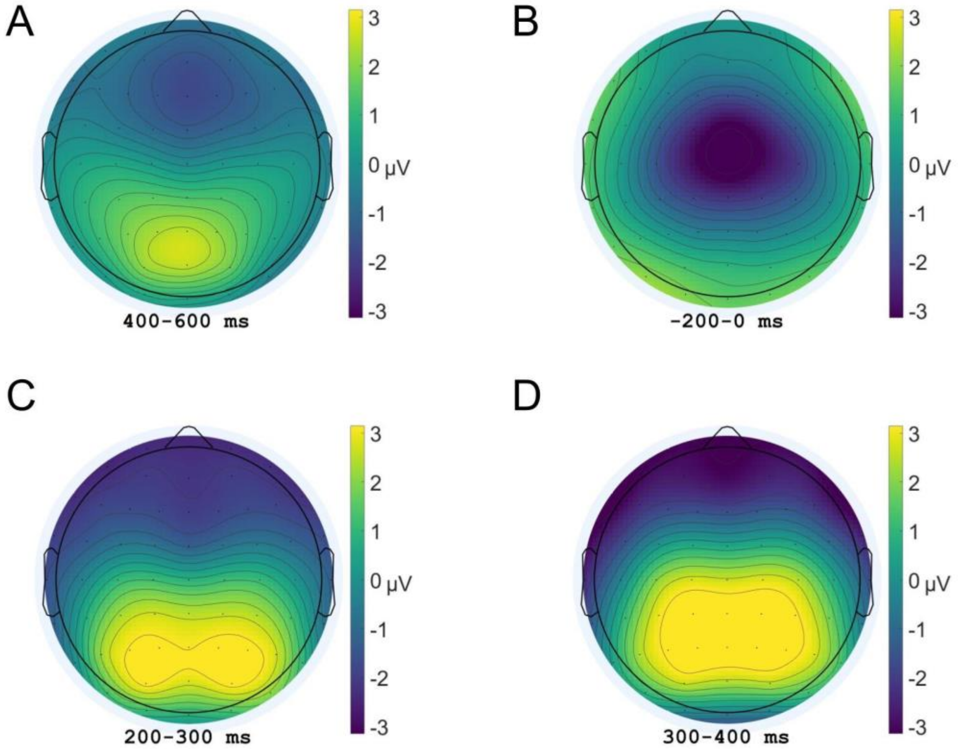

Figure S1. The maps of neurophysiological activity averaged from all subjects and trial types of the AX - Continuous Performance Task. The pictures represent the activity averaged in the following time windows chosen for the ERPs analyses: A) 400 to 600 ms after cue presentation (for P3b analysis); B) 200 to 0 ms before a probe onset (for CNV analysis); C) 200 to 300 ms after probe presentation (for N2 analysis); D) 300 to 400 ms after probe presentation (for P3a analysis)

VALIDATION OF AITKEN PROCRASTINATION INVENTORY

Participants and measures

The original version of the Aitken Procrastination Inventory (API; Aitken, 1982) was translated into Polish and then back-translated into English by two independent translators. Then, the back-translated version was compared with the original by another researcher. English translation was accepted as an equivalent of the original scale. Subsequently, the Polish questionnaire was completed by students from different universities and colleges (N = 347; 82% women) to assess the reliability and validity of the scale. The age of participants varied between 18 to 40 years old (*M* = 21.44; *SD* = 2.41).

Validity of the scale was assessed by comparing the results of API with the Polish adaptation of the Study Problem Questionnaire (SPQ; Schouwenburg, 1995; Wichrowski, 2008), which consists of 23 items organized into 3 subscales: low work discipline, fear of failure and low study interest. The scale response format is a 5-point Likert scale ranging from 1 (*highly agree*) to 5 (*highly disagree*). This questionnaire was chosen for API validation, as it encompasses three well-known correlates of procrastination: fear of failure (e.g. (Schouwenburg, 1992)), low conscientiousness (e.g. Scher & Osterman, 2002; Schouwenburg & Lay, 1995) and task aversiveness (Blunt & Pychyl, 2000; Milgram, Marshevsky, & Sadeh, 1995).

Results

Descriptive statistics of the API and SPQ results are presented in Table S3.

Reliability measurement showed high internal consistency of the API (Cronbach’s alpha = .89). As the original API questionnaire provides only the general result with no subscales, we assessed a single-factor model by conducting the Confirmatory Factor Analysis with AMOS 25 software. According to the modification indices, correlations were introduced between errors of items that shared variance due to similar wording (5 pairs of errors, between items: 1 and 3; 6 and 17; 6 and 18; 11 and 12; 17 and 18). The model ($X^2 = 339.3$, $p < .001$; $df = 147$) had acceptable fit indices (CFI = .93; RMSEA = .061; SRMR = .057).

Table S2. Standardized factor loadings for single-factor structure of Aitken Procrastination Inventory (API)

Item number	Standardized factor loading
1	.74
2	.41
3	.79
4	.71
5	.29
6	.43
7	.59
8	.64
9	.44
10	.74
11	.68
12	.70
13	.62
14	.61
15	.61
16	.32
17	.32
18	.33
19	.34

We observed significant correlations between API and general SPQ result ($r = .543$; $p <.001$) as well as between API and all SPQ subscales (fear of failure: $r = .256$; $p <.001$; low work discipline: $r = .713$; $p <.001$; low study interest: $r = .264$; $p <.001$).

Table S3. Descriptive statistics of Aitken Procrastination Inventory (API) and Study Problem Questionnaire (SPQ) with three subscales.

	Mean (SD)	Skewness (SE)	Kurtosis (SE)	Minimum - Maximum
API	61.37 (13.36)	-0.38 (0.13)	-0.58 (0.27)	28 - 88
SPQ	71.20 (14.14)	-0.15 (0.13)	-0.51 (0.26)	32 - 102
SPQ: fear of failure	31.76 (8.16)	-0.04 (0.13)	-0.69 (0.26)	13 - 49
SPQ: low work discipline	24.27 (6.07)	-0.52 (0.13)	-0.45 (0.26)	8 - 35
SPQ: low study interest	15.18 (4.82)	0.32 (0.13)	-0.47 (0.26)	6 - 29

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Załącznik nr 2A – Oświadczenia współautorów o wkładzie pracy w realizację i publikację badań nad związkiem pomiędzy prokrastynacją i kontrolą poznawczą

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Wiwatowska, E., Czajeczny, D., Michałowski, J.M. (2021). Decreased preparatory activation and inattention to cues suggest lower activation of proactive cognitive control among high procrastinating students. *Cognitive, Affective, & Behavioral Neuroscience, 22,* 171–186. mój udział polegał na pracy koncepcyjnej, rekrutacji uczestników, zbieraniu i analizowaniu danych, interpretacji uzyskanych wyników, przygotowaniu pierwszej wersji manuskryptu oraz jego późniejszej korekcie, złożeniu artykułu do czasopisma i odpowiedzi na uwagi recenzentów. Mój udział w powstaniu pracy wynosi 55%.

PODPIS ZAUFANY
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Dominik Czajeczny
....
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Niniejszym oświadczam, że w pracy Wiwatowska, E., Czajeczny, D., Michałowski, J.M. (2021). Decreased preparatory activation and inattention to cues suggest lower activation of proactive cognitive control among high procrastinating students. *Cognitive, Affective, & Behavioral Neuroscience, 22,* 171–186. mój udział polegał na pozyskiwaniu środków na realizację badań, współpracy koncepcyjnej, wsparciu merytorycznym, monitorowaniu postępów realizacji badań, interpretacji uzyskanych wyników, korekty powstałego manuskryptu. Mój udział w powstaniu pracy wynosi 30%.

……………………………
Podpis

Załącznik nr 3 – Publikacja badań nad wpływem informacji zwrotnej na przetwarzanie błędów i kontrolę uwagową w prokrastynacji

International Journal of Psychophysiology 192 (2023) 1–12

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Improved attention and performance monitoring in high procrastinating students after positive relative to negative norm-referenced feedback

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ARTICLE INFO

Keywords:
Procrastination
Feedback
Attention
Performance monitoring
Event-related potentials

ABSTRACT

Procrastination is an irrational delay of task completion. Previous studies have demonstrated that individuals who often procrastinate present deficits in attentional control and performance monitoring and that these dysfunctions might be differentially manifested depending on the motivational context. Building upon these results, the present event-related potential (ERP) study aimed to investigate the impact of norm-referenced feedback on executive functions among students with high (HP; $N = 75$) or low (LP; $N = 77$) procrastination levels. Participants completed the parametric Go/No-Go task, while receiving either positive or negative false feedback indicating how well they performed in comparison to others. The results indicated that positive (as opposed to negative) feedback led to higher self-reported arousal and increased post-error slowing in HP (vs. LP) participants. Moreover, neurophysiological measures indicated lower neural activation linked to attentional control (P300) and performance monitoring (ERN, CRN and Pe) in HP than LP participants, while the groups did not differ in these indices during the positive feedback condition. Obtained findings indicate that HP might be more sensitive to the motivating effects of success and more vulnerable to the detrimental influence of failure.

1. Introduction

One of the challenges that students frequently have to face while pursuing their academic endeavors is to overcome procrastination. This phenomenon is described as an irrational delay of task initiation or completion, often leading to feelings of guilt and anxiety (Blunt and Pychyl, 2005; Klingsieck, 2013). Although different environmental factors can exacerbate students' procrastinatory behaviors, some individuals struggle with chronic task delay more than others, which is often linked to lower academic achievements (Kim and Seo, 2015) as well as increased levels of stress and anxiety (Beutel et al., 2016). Taking into account the high prevalence of this issue (Steel, 2007) and its negative consequences for education and mental health, it is important to identify potential cognitive and motivational factors that might exacerbate or reduce procrastination.

A plethora of research points out that high tendency to delay tasks is related to certain individual differences that negatively affect motivation. For example, different studies consistently show the positive relationship between procrastination and such traits as fear of failure, maladaptive perfectionism (associated with increased concern over one's mistakes and potential criticism from others) and sensitivity to punishments (Michałowski et al., 2017; Przetacka et al., 2021; Schouwenburg, 1992; Wypych et al., 2019). Along with poor emotion regulation skills (e.g. Wartberg et al., 2021; Wypych et al., 2018), this constellation of traits might hinder procrastinators' motivation to engage in difficult tasks in which they expect to fail. The perspective of potential failure might evoke negative emotions that are difficult to deal with. In consequence, high procrastinating individuals often lose their motivation to complete the task and choose alternative activities, which allow for short-term mood regulation, but hinder successful fulfillment of assigned duties and responsibilities (Sirois and Pychyl, 2013).

Another area of procrastination research focuses more on the cognitive domain of functioning and indicates that excessive task delay might result from deficits in executive functions. Executive functions (which also go under the name of executive or cognitive control) consist of processes that allow for successfully carrying out goal-directed behavior, such as controlling focus of attention (e.g. ignoring distractions), inhibiting automatic and impulsive reactions, as well as monitoring and correcting one's actions (performance monitoring; Diamond, 2013; Friedman and Miyake, 2017). The relationship between

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https://doi.org/10.1016/j.ijpsycho.2023.07.004
Received 28 March 2023; Received in revised form 30 June 2023; Accepted 25 July 2023
Available online 29 July 2023

procrastination and executive dysfunctions has been identified in multiple studies using both self-report (e.g. Harriott et al., 1996; Niermann and Scheres, 2014; Rabin et al., 2011; Sabri et al., 2016) and behavioral measures (e.g. Gustavson et al., 2015; Rebetez et al., 2016). For example, our previous studies have shown that high procrastinating (HP) students present reduced attentional control and performance monitoring, as compared to low procrastinating (LP) individuals (Michałowski et al., 2020; Wiwatowska et al., 2022; Wypych et al., 2019). Having difficulties with maintaining attentional control as well as noticing and correcting one's mistakes during task performance can surely interfere with its completion, which in consequence might increase perceived task aversiveness and further reduce motivation to work on it. Moreover, these deficits can facilitate redirection of attention towards alternative, task-unrelated goals, such as other, but less important duties or leisure activities.

It has been suggested that procrastination-related executive dysfunctions may increase in aversive contexts (Wypych and Potenza, 2021; Heatherton and Wagner, 2011), such as the threat of punishment. For example, Przetacka et al. (2021) observed that HP, as compared to LP individuals, were less cognitively flexible while performing the task that measured learning from errors, but the differences between groups were bigger when participants were financially punished for their mistakes, than when they were rewarded for correct reactions. Another study (Michałowski et al., 2017) showed that HP (vs. LP) students reacted generally slower in the financial punishment, but not in the monetary reward and neutral conditions of the Go/No-Go task. Moreover, in the punishment condition HP students reacted with less caution after making a mistake. Although the following research (Wypych et al., 2019) using a similar paradigm did not replicate these findings, it showed another interesting interaction between financial motivation and procrastination level: in a punishment (vs. neutral) context, LP participants presented increased activity within brain areas responsible for attentional control and performance monitoring (namely right dorsolateral prefrontal cortex and anterior cingulate cortex), but this effect was not present in HP subjects. On the contrary, in the subsequent study (Michałowski et al., 2020), we found no effect of motivation (financial punishment vs. reward) on the observed differences between HP and LP groups in neurophysiological and behavioral indices of attentional control and performance monitoring. Therefore, although individuals with higher tendency to delay tasks consistently report increased sensitivity to punishment as compared to LP subjects (Michałowski et al., 2017; Przetacka et al., 2021; Wypych et al., 2019), this difference does not always come up in tasks using different types of financial motivation. This indicates that the perspective of losing or winning a small amount of money might not be a sufficiently relevant motivator. Nevertheless, despite inconsistencies between different studies, there is some evidence that punishments might impair executive functions among HP individuals. In light of the above-mentioned findings, along with the notion of positive relationship between procrastination and fear of failure, it might be expected that unfavorable social comparison (e.g. as shown in Ilies et al., 2007; Unger et al., 2012) may be motivationally more relevant than the monetary punishment to disrupt procrastinators' executive functioning. However, to our knowledge, none of the previously conducted studies investigated this issue with the use of experimental methods, i.e. by direct manipulation of evaluative feedback based on social comparison. The present study aimed to fill this gap and examine how the executive functions among HP and LP students can be affected by positive and negative norm-referenced feedback, i.e. information that their performance is better or worse in comparison to others.

It has already been shown that different traits related to procrastination might moderate the influence of feedback on cognitive and affective processes. For example, Chester et al. (2015) showed that higher levels of maladaptive perfectionism are associated with lower mood after receiving negative performance evaluation. Further, Lerche et al. (2018) showed that individuals with increased fear of failure presented reduced speed of decision making process (i.e. slower information accumulation) in a color discrimination task, especially after receiving negative feedback. Taking into account that both maladaptive perfectionism and fear of failure are positively associated with trait procrastination (Haghbin et al., 2012; Schouwenburg, 1992; Xie et al., 2018), we predicted that previously observed executive dysfunctions among HP individuals would be more pronounced under negative (vs. positive) evaluation.

We decided to focus on the sample of university students, as procrastination is very prevalent in this group of individuals (Steel, 2007), who at the same time frequently have to deal with norm-referenced feedback during their academic endeavors. Because we intended to measure behavioral and neurophysiological indices of performance monitoring and attentional control, we used the same paradigm as in Michałowski et al. (2020), namely the Parametric Go/No-Go task, which consists of two difficulty levels (see the Methods section for details) and which has been frequently used to evaluate different executive functions in previous research (e.g. Piani et al., 2022; Plewnia et al., 2013; Weidacker et al., 2017). In the study from 2020, we observed that HP, as compared to LP students presented reduced attentional control and error processing, which was reflected both in neural and behavioral indices. Also, HP subjects' deficits in attention became even more apparent at the behavioral level when the task demands increased during the high difficulty level, which might indicate faster resource depletion in this group of participants. In the present study we expected to replicate these previous findings. We also predicted that the above-mentioned differences between groups would be more pronounced under the influence of failure (vs. success) induced by norm-referenced feedback.

To measure behavioral indices of attention and performance monitoring, we used reaction time variability (RTV) and post-error slowing (PES). Higher RTV reflects lapses in attentional control (MacDonald et al., 2009; West et al., 2002), while increased PES reflects difficulty with reorienting attention away from committed error (e.g. Danielmeier and Ullsperger, 2011; see Notebaert et al., 2009 for a review). We also used the event-related potentials (ERPs) method to examine the neural activity linked to performance monitoring and attention, as we believe that investigating the patterns of brain activity would help to better understand the mechanisms underlying procrastination-related cognitive deficits. ERPs method is based on averaging the electrical brain activity in response to certain stimuli or reactions. This results in the ERP wave, in which different components (potentials) can be identified. The amplitude of these potentials is often interpreted as indicating the strength of specific cognitive processes and their underlying neural activity in response to the events (Luck, 2014). In particular, we analyzed the P300 component, which reflects the amount of attentional resources engaged in processing incoming stimuli (Polich, 2007). Regarding neurophysiological indices of performance monitoring, we measured the amplitudes of error-related negativity (ERN), error positivity (Pe) and correct response negativity (CRN). ERN is linked to automatic error detection, resulting from increased activity of the anterior cingulate cortex (ACC; Luu et al., 2003; Miltner et al., 2003; Van Veen and Carter, 2002), whereas Pe reflects error awareness (Nieuwenhuis et al., 2001; Shalgi et al., 2009; Steinhauser and Yeung, 2010). CRN is elicited after correct reactions and appears in the similar time window and location as ERN (Bartholow et al., 2005; Weinberg and Hajcak, 2011). Therefore, we decided to include CRN in our analyses in order to investigate whether the predicted differences between feedback conditions and procrastination groups would be specific to error detection or reflect general issues in performance monitoring.

In light of the previous findings, we have formulated the following hypotheses:

1) HP (vs. LP) participants would present impaired performance monitoring, reflected by difficulties with reorienting attention after committing an error (higher PES) and by reduced neural response to errors (smaller amplitudes of ERN and Pe).

2) HP (vs. LP) subjects would show attention deficits, indicated by lower ability to maintain attentional control (higher RTV), especially during the difficult (vs. easy) part of the task; as well as reduced neural activity linked to focusing attention on presented stimuli (smaller amplitudes of P300).
3) The above-mentioned HP (vs. LP) students' deficits in performance monitoring (higher PES and smaller ERN/Pe) and maintaining attentional control (higher RTV and smaller P300) would be bigger under the influence of negative (vs. positive) norm-referenced feedback.
4) After receiving negative (vs. positive) evaluation, HP, as compared to LP students would report more negative emotions as well as higher arousal.

2. Methods

2.1. Participants

Students ($N = 1968$) from different universities and colleges in Poznań (Poland) completed an online survey including the Polish adaptation of the Aitken Procrastination Scale (APS: Aitken, 1982; Polish version in Wiwatowska et al., 2022), which is a common tool to assess procrastination in the academic context. It consists of 18 items (e.g. "I delay starting things so long I don't get them done by the deadline" or "I am often frantically rushing to meet deadlines") with a 5-point Likert scale response format. Out of this sample, 97 students whose APS score exceeded one standard deviation (SD) above the mean (APS $\geq$ 74) were invited to the HP group, and 99 students with score at least one SD below the mean (APS $\leq$ 47; LP) were invited to the LP group. Out of this sample, 43 subjects had to be excluded from all analyses: 29 participants did not believe in the feedback (see the following section), 7 subjects had low quality of the recorded EEG signal (over 25 % epochs excluded), 4 subjects misunderstood the instructions (e.g. clicked the wrong mouse button in response to Go signals), 1 participant was excluded due to technical problems during task completion, 1 participant resigned from taking part in the task; 2 subjects achieved too low accuracy to Go signals during the easy part of the task (<60 %). The final sample consisted of 77 participants in the LP group ($M_{age} = 21{,}55$; $SD_{age} = 2{,}20$; 40 women; 39 in the positive feedback condition) and 75 subjects in the HP group ($M_{age} = 22{,}04$; $SD_{age} = 2{,}89$; 44 women; 38 in the positive feedback condition). The HP and LP groups did not differ significantly in gender ($\chi^2(1, N = 152) = 0{,}69$; $p = .41$) or age ($t(150) = 1.36$; $p = .176$).

The study was approved by the local Ethics Committee at the SWPS University of Social Sciences and Humanities and performed in accordance with the Declaration of Helsinki. All participants signed informed consent of participation and received 80 PLN (~20 EUR) at the end of the study.

2.2. Procedure

Before completing the modified version of the Parametric Go/No-Go (PGNG; (Langenecker et al., 2007) task, participants performed the AX - Continuous Performance Task, which results are reported elsewhere (Wiwatowska et al., 2022). There was a 5-minute break between these two tasks.

Following the AX-CPT task participants completed the PGNG task in either positive or negative feedback condition. In the beginning of the PGNG task, subjects were informed that after each block of trials they would receive feedback regarding their performance in comparison to other students. After that, they completed the short training session, which included 20 trials and was structured in the same way as the main task. It was performed under the supervision of the experimenter. The training session could be repeated, if the experimenter noticed that the participant did not sufficiently understand the instructions and made too many mistakes.

The feedback was displayed in the form of two emojis: a smiling or a sad face indicating that the subject's performance was accordingly above or below the average result. Participants were told that after each block they would receive updated feedback on how they performed in comparison to other people and that this performance feedback would be based on their response times and response accuracy. In reality, feedback was fixed throughout the task (always positive or always negative) and independent of subjects' performance. The feedback was presented on the screen eleven times: after the training and after each block of trials. The first feedback emoji was presented after the training session and was accompanied by a verbal comment from the experimenter (the subsequent feedbacks did not include experimenter's presence):

"I can see that you did not do so well… Apparently, you responded slower or less correctly than others. You need to try a bit harder. Try to answer faster or more correctly in the main part of the task - maybe you will be able to get a better score." - this comment was provided in the negative feedback condition.

"I can see that you did quite well! Apparently, you responded faster or more accurately than others. You can maintain this result if you answer equally fast and correctly in the main part of the task." - this comment was provided in the positive feedback condition.

After completing the task, participants evaluated the subjective valence and arousal that they experienced during task completion using a scale from 0 to 10 (0 - very calm, 10 - very aroused, for arousal assessment; or 0 - very unpleasant, 10 - very pleasant, for emotional valence). They also estimated a perceived performance score, answering the question of how many points (from 0 to 100) they might have gained in the task. The purpose of these questions was to identify the influence of repeated positive or negative feedback on emotional reactions during task completion and on participants' beliefs about their performance.

Then, all participants completed a similar task with a procedure that was similar to the first task, but there was a change in the received feedback: from positive to negative or from negative to positive. However, we do not report the results of that part in this paper.

At the end of the study, participants completed a short form with the following question: "Do you agree that all the presented information regarding this task was true and that the experimenter conveyed it comprehensively?". If the negative answer was chosen, subjects were asked to provide an explanation. After that, all participants were debriefed about the real purpose of the study and introduced manipulation. We excluded participants who disagreed with the statement that all presented information in the study was true, claiming that the received feedback was false. However, some participants expressed their doubts about the reliability of the presented feedback despite answering "yes" to the question on the form[1]. Therefore, we decided to exclude also those participants who claimed that they did not believe in feedback, expressing their doubts before the debriefing.

At the end (or at the beginning) of the study participants filled out questionnaires which confirmed previous findings that procrastination is related to increased fear of failure, maladaptive perfectionism and sensitivity to punishment (Haghbin et al., 2012; Schouwenburg, 1992; Wypych et al., 2019; Xie et al., 2018). The order in which the questionnaires were completed (i.e. at the beginning or at the end of the study) was counterbalanced across groups and feedback conditions. Information about the questionnaires along with the results can be found in the supplementary materials.

2.3. Measures

2.3.1. Self-reported data

We evaluated the following self-reported data: emotional valence

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[1] We think that the potential reason for this discrepancy is that some participants focused more on the second part of the question regarding the way in which the experimenter conveyed the presented information.

and arousal experienced during the task, as well as perceived performance score.

2.3.2. *Behavioral data*

The following behavioral data is reported in the results section: post error slowing (PES) as the mean difference between RTs to Go signals in trials following versus those preceding each commission error; reaction time variability (RTV) measured as coefficient of variation, calculated by dividing each participant's standard deviation of reaction times (RT) by his/her mean RT. PES was interpreted as the index of performance monitoring and RTV was used as the measure of attentional control. Response accuracy, defined as the percentage of correct responses to No-Go stimuli (correct inhibitions) and mean RTs for hits are reported in the supplementary materials.

2.3.3. *Neurophysiological data*

The neurophysiological indices of performance monitoring included the mean amplitude of the early response-related ERP components (ERN and Pe in response to commission errors and CRN in response to hits) and the amplitude of the late response-related component (Pe in response to commission errors), while the mean amplitudes of the stimulus-related component (P300) triggered by Go and No-Go stimuli were used as the neurophysiological indices of attentional control.

2.4. *Task*

During the PGNG task participants were asked to respond to either digits or letters displayed on the 17-inch screen (see Fig. 1). Each stimulus was presented on the screen for 250 ms in the pseudo-randomized order, with the restriction that the No-Go stimuli would not be presented three times in a row. The inter-trial interval (ITI) was randomized and lasted 1 (62.5 % of ITIs), 1.5 (25 %) or 2 s (12.5 %). The selection of a stimuli type (letters vs. digits) was counterbalanced across groups and feedback conditions. The assignment of the stimuli type and feedback condition was selected based on the order of conducted examinations (e.g. the first person from the HP group completed the task with letters and positive feedback, the second person from the same group with letters and negative feedback, the third person with digits and positive feedback, etc.) There were two kinds of stimuli in the task: Go and No-Go signals (see below). Participants had to respond as quickly as possible by clicking the left mouse button whenever a Go signal appeared on the screen and they had to withhold their reaction to No-Go stimuli. The task consisted of two difficulty levels with 5 blocks of 70 trials each. In the easy level of difficulty two selected digits/letters served as No-Go signals (20 % of trials; the selection of the two No-Go signals changed from block to block), while Go signals were the remaining digits/letters. During the difficult part of the task, participants had to inhibit their responses to one selected digit/letter (10 % of trials; the selection of a No-Go signal changed every block) as well as to repeated Go stimuli (when the same Go stimulus appeared two or more times in a row; 10 % of trials). We used the Presentation software (Neurobehavioral Systems, Inc., Berkeley, CA, https://www.neurobs.com) for displaying stimuli and recording behavioral responses.

2.5. *Electrophysiological recording and processing*

Brain activity was recorded using BrainVision Recorder and BrainAmpDC amplifier (Brain Products GmbH, Gilching, Germany) with a 500 Hz sampling rate. The EEG cap included 64 electrodes placed according to the 10–20 system with impedances below 50 kΩ. Data processing was conducted in MATLAB (The Mathworks, Inc., Natick, MA, USA) with EEGLAB and ERPLAB toolboxes (Delorme and Makeig, 2004; Lopez-Calderon and Luck, 2014). The preprocessing steps included: filtering the signal with 0.1 Hz high-pass and 30 Hz low-pass filters; detecting noisy channels via visual inspection; interpolating artifactual channels; manually rejecting large artifacts from the continuous signal; re-referencing the data to the average of all channels; conducting independent component analysis with the *extended runica* algorithm in EEGLAB; detecting and rejecting (via visual inspection and automatic classifier ICLabel; Pion-Tonachini et al., 2019) components that

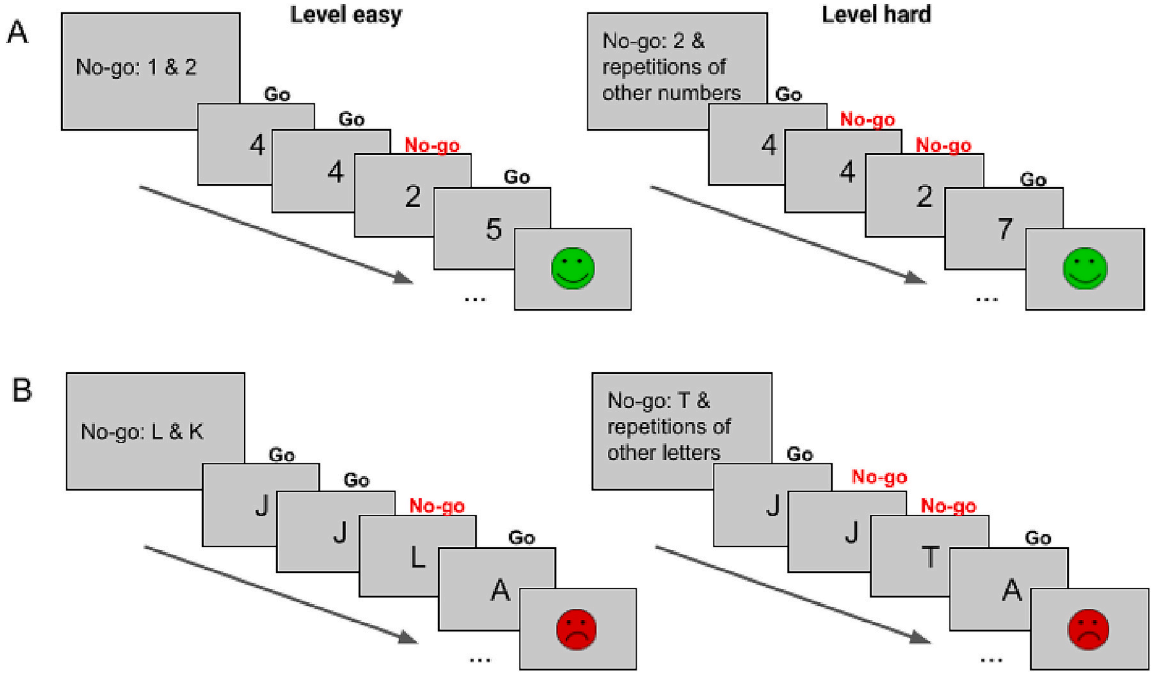

Fig. 1. The parametric Go/No-Go task. The task consisted of two difficulty levels. During the easy part of the task, participants had to inhibit their responses to No-Go stimuli (20 % of trials) and click a mouse button to other digits/letters (Go stimuli). During the difficult part, subjects had to withdraw their responses not only to No-Go stimuli but also to repetitions of other digits/letters (the same Go signal as the one in the subsequent Go trial). The Go and No-Go stimuli consisted of either numbers (panel A) or letters (panel B), counterbalanced across groups and feedback conditions. Participants completed the task in one of two possible experimental conditions: receiving either positive (panel A) or negative (panel B) performance feedback.

reflected eye movements, muscle and heart activity or channel noise.

For the ERN/CRN and Pe analyses, the data was segmented into epochs ranging from −400 to 800 ms around responses with baseline in the time range from −400 to −200 ms (Larson et al., 2013). For the P300 analyses, epochs were extracted from −400 to 800 ms around stimuli with 400 ms baseline correction before the stimulus onset (Skosnik et al., 2007). After the segmentation, epochs exceeding ±75 μV were automatically rejected. Participants with >25 % of artifactual epochs ($N = 7$) were excluded from further analyses.

Following previous work (e.g. Carrión and Bly, 2008; Michalowski et al., 2009, 2015; Sun and Harmon-Jones, 2021; Zheng et al., 2020) the channels and time-windows selected for the ERPs analyses were chosen based on visual inspection of grand-averaged data from all participants (regardless of procrastination or feedback condition). ERN/CRN was scored at Fz as the mean amplitude in the time window from −25 to 75 ms around commission errors (incorrect responses to No-Go) and hits (correct responses to Go). Pe was measured at CPz as the mean amplitude in the 150–350 ms time window after commission errors. The mean amplitude of P300 was calculated at Pz in the 400–600 ms time window after the stimulus onset.

2.6. *Statistical analyses*

Statistical analyses were performed with the use of MATLAB (The Mathworks, Inc., Natick, MA, USA) and IBM SPSS Statistics 25 software.

To test whether ratings of arousal, emotional valence and perceived performance scores differed as a function of group and feedback condition, we conducted two-way ANOVAs with procrastination (high vs. low) and feedback (positive vs. negative) as between-group factors. To analyze whether the behavioral data and Pe differed as a function of group, feedback condition and difficulty level, mixed ANOVAs were conducted with procrastination and feedback as between-group factors and difficulty level (easy vs. difficult) as a within-subject factor. To identify whether HP and LP differed in the early stages of performance monitoring across two experimental conditions, and whether these differences occurred during the processing of erroneous responses to No-Go stimuli (ERN for commission errors) and/or correct responses to Go stimuli (CRN for correct responses), we performed mixed ANOVA with procrastination (high vs. low) and feedback condition (positive vs. negative) as between-group factors as well as response type (ERN for commission errors vs. CRN for correct responses) and difficulty (easy vs. difficult) as within-group factors. P300 comparisons were similar to the ERN/CRN analyses, but instead of response type, they included stimulus type (Go vs. No-Go) as a within-group factor. In case of significant interactions with procrastination, HP and LP groups were compared with post hoc *t*-tests or ANOVAs conducted separately for each feedback condition (and/or difficulty level).

In the final analyses of all variables, we excluded observations that were above or below the three standard deviations of the group's mean.

2.7. *Transparency and openness*

We comprehensively report all manipulations applied in this study as well as data exclusions and software used for analyses. The data and code are available to download from a public repository at the following link:

https://repod.icm.edu.pl/privateurl.xhtml?token=77209a8f-cd85-41d6-a0d8-001d6a8050ae. This study's design and its analysis were not pre-registered.

3. Results

3.1. *Self-reported measures: valence, arousal and perceived performance score*

The results for the perceived performance score, emotional valence and arousal are presented in Fig. 2. There was a main effect of feedback: participants receiving positive (vs. negative) feedback estimated their performance as higher ($F(1,147) = 131.29$; $p < .001$; $\eta_p^2 = 0.472$) and rated the task experience as more pleasant ($F(1,148) = 74.94$; $p < .001$; $\eta_p^2 = 0.336$). Also, there was a trend towards a main effect of procrastination, with HP showing more negative emotional valence than LP ($F(1,148) = 3.18$; $p = .077$; $\eta_p^2 = 0.021$), which was independent of feedback condition ($F < 2$; $p > .1$ for feedback x procrastination interaction). However, we found a significant procrastination x feedback interaction for reported arousal ($F(1,148) = 10.03$; $p = .002$; $\eta_p^2 = 0.063$). The post-hoc t-tests showed that HP presented higher arousal than LP, but only in the positive feedback condition ($t(75) = 3.23$; $p = .002$; $d = 0.736$), but there were no group differences in the negative feedback condition ($t(65.05) = 1.14$; $p = .260$; $d = 0.263$).

Therefore, we did not confirm our hypotheses that HP (vs. LP) participants would show more negative emotions and higher arousal in the negative feedback condition.

3.2. *Behavioral results*

The results of response accuracy and reaction times are presented in the supplementary materials, which also include information about observed effects (in the analyses of the following variables) that were not directly related to the formulated hypotheses.

3.2.1. *Post-error slowing*

There was a significant procrastination x feedback interaction in PES ($F(1,146) = 4.18$; $p = .043$; $\eta_p^2 = 0.031$); additional ANOVAs (including difficulty and procrastination factors), separate for each feedback condition, indicated that there was a main effect of procrastination only in the analysis for the positive feedback condition, with HP showing higher PES than LP ($F(1,74) = 10.89$; $p = .001$; $\eta_p^2 = 0.128$). The main effect of procrastination was insignificant in the analysis for the negative feedback condition ($F(1,72) = 0.39$; $p = .535$; $\eta_p^2 = 0.005$; see Fig. 3A).

The obtained findings are incongruent with our hypotheses that the differences between HP and LP groups would be larger in the negative (vs. positive) feedback condition.

3.2.2. *Reaction time variability*

There was a main effect of procrastination, indicating that HP showed higher RTV than LP ($F(1,143) = 5.49$; $p = .021$; $\eta_p^2 = 0.037$; see Fig. 3B). However, this difference was irrespective of the feedback condition or difficulty level ($Fs < 1$; $ps > 0.1$ for interactions between procrastination and feedback or difficulty).

These findings confirmed our hypothesis of larger RTV among HP (vs. LP) participants. However, we did not confirm our predictions of increased differences between groups in the negative (vs. positive) feedback condition.

3.3. *Electrophysiological results*

3.3.1. *Early response-related components (ERN/CRN)*

Significant difficulty x procrastination x feedback interaction was observed ($F(1,147) = 5.58$; $p = .019$; $\eta_p^2 = 0.037$; see Figs. 4 & 6, left panel). Therefore, we conducted mixed ANOVA (with procrastination as between group factor and response type as a within-group factor) separately for each feedback condition and difficulty level. The analyses revealed main effect of procrastination in the easy part of the negative feedback condition, indicating that the early response-related neurophysiological activity was significantly lower in HP than LP ($F(1,72) = 6.54$; $p = .013$; $\eta_p^2 = 0.083$), an effect that was clearly weaker during the difficult part of the negative feedback condition ($F(1,72) = 2.82$; $p = .098$; $\eta_p^2 = 0.038$). There were no significant differences between groups in the positive feedback condition either during the easy or difficult part of the task ($Fs < 2$; $ps > 0.1$ for main effects or interactions with procrastination). Also, the above-mentioned interactions were similar for

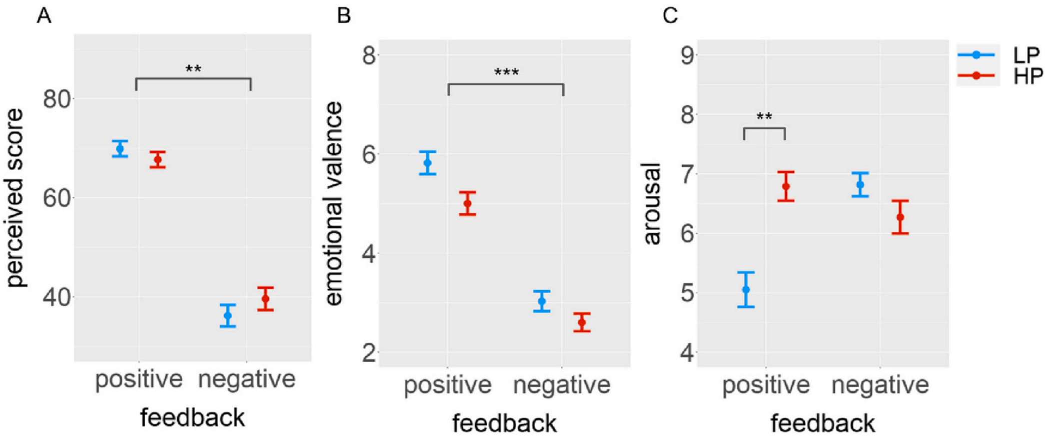

Fig. 2. Self-reported data. The mean results of the perceived performance score (A), emotional valence (B) and arousal (C) among low (LP) and high (HP) procrastinating participants performing the task in either positive or negative feedback condition. Error bars represent one standard error.
** $p < .01$; *** $p < .001$.

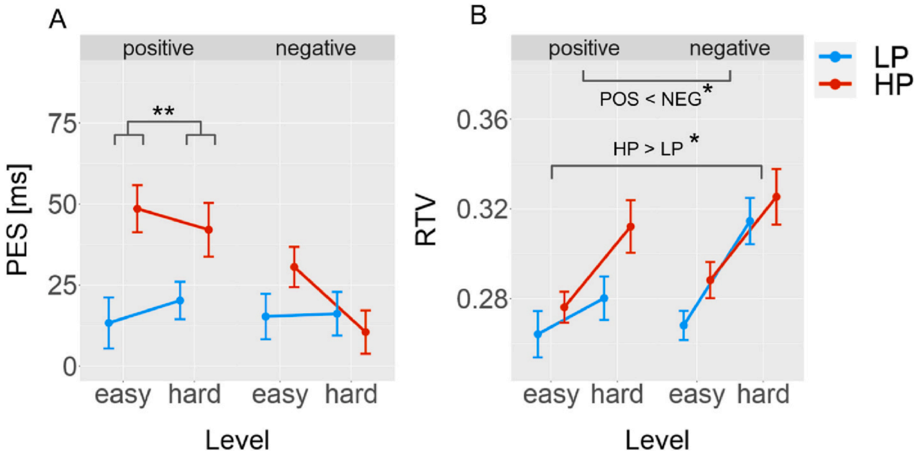

Fig. 3. Performance in the Parametric Go/No-Go task. The mean values of post-error slowing (PES; A) and reaction time variability (RTV; B) among low (LP) and high (HP) procrastinating participants. The task consisted of two difficulty levels. Subjects performed the task under two conditions: receiving either positive (POS) or negative (NEG) false feedback regarding their performance in comparison to others. Analyses revealed procrastination x feedback interaction for PES as well as the main effects of feedback and procrastination for RTV. Error bars represent one standard error.
* $p < .05$; ** $p < .01$.

ERN and CRN, that is, no procrastination x response type interactions were observed.

These findings are in accordance with our hypotheses that HP show weaker regarding early response-related brain activation than LP in the negative (vs. positive) feedback condition, although we did not expect the interaction with a difficulty level. Further, the observed differences were not specific to error processing, but they also occurred during the processing of correct responses, which was incongruent with our predictions.

3.3.2. Late response-related component (Pe)

A significant difficulty x procrastination x feedback interaction ($F(1,147) = 4.82$; $p = .03$; $\eta_p^2 = 0.032$) was observed (see Figs. 5 & 6, right panel). Therefore, we compared HP and LP with *t*-tests conducted separately for each feedback condition and difficulty level. The analyses revealed that in the negative feedback condition HP showed significantly smaller amplitudes than LP, but only during the easy part of the task ($t(73) = 3.64$; $p < .001$; $d = 0.842$), while the differences between groups (in the same direction) were at a tendency level during the difficult level ($t(73) = 1.70$; $p = .093$; $d = 0.393$). There were no significant differences between groups in the positive feedback condition, either during an easy or difficult part of the task ($ts < 1$; $ps > .1$).

These findings are in accordance with our hypotheses regarding weaker late response-related brain activation among HP and LP groups in the negative (vs. positive) feedback condition, although we did not predict the observed interaction with difficulty level.

3.3.3. Stimulus-related component (P300)

There was a difficulty x procrastination x feedback interaction ($F(1,145) = 6.78$; $p = .010$; $\eta_p^2 = 0.045$; Figs. 7 and 8). Additional ANOVAs (including stimulus as a within-group factor and procrastination as a between-group factor), conducted separately for each difficulty level and feedback condition, showed that there were main effects of procrastination for both difficulty levels of the negative feedback condition indicating that HP responded with lower P300 than LP subjects. However this main effect was slightly larger in the easy ($F(1,71) = 14.98$; $p < .001$; $\eta_p^2 = 0.174$; $M_D = 1.62$) than in the difficult ($F(1,71) = 9.10$; $p = .004$; $\eta_p^2 = 0.114$; $M_D = 1.20$) part of the task. There were no differences between procrastination groups in the positive feedback condition on any level of difficulty ($Fs < 2$; $ps > .1$ for main effects of procrastination in both difficulty levels).

Similarly to findings of response-related components, these results are in line with our predictions regarding lower stimulus-related neurophysiological response among HP than LP subjects in the negative (vs. positive) feedback condition.

4. Discussion

In the present study, we aimed to investigate the impact of positive and negative norm-referenced feedback on attention and performance monitoring among high and low procrastinating students. The efficacy of applied feedback manipulation was confirmed by the results of emotional valence and perceived performance scores: subjects from both

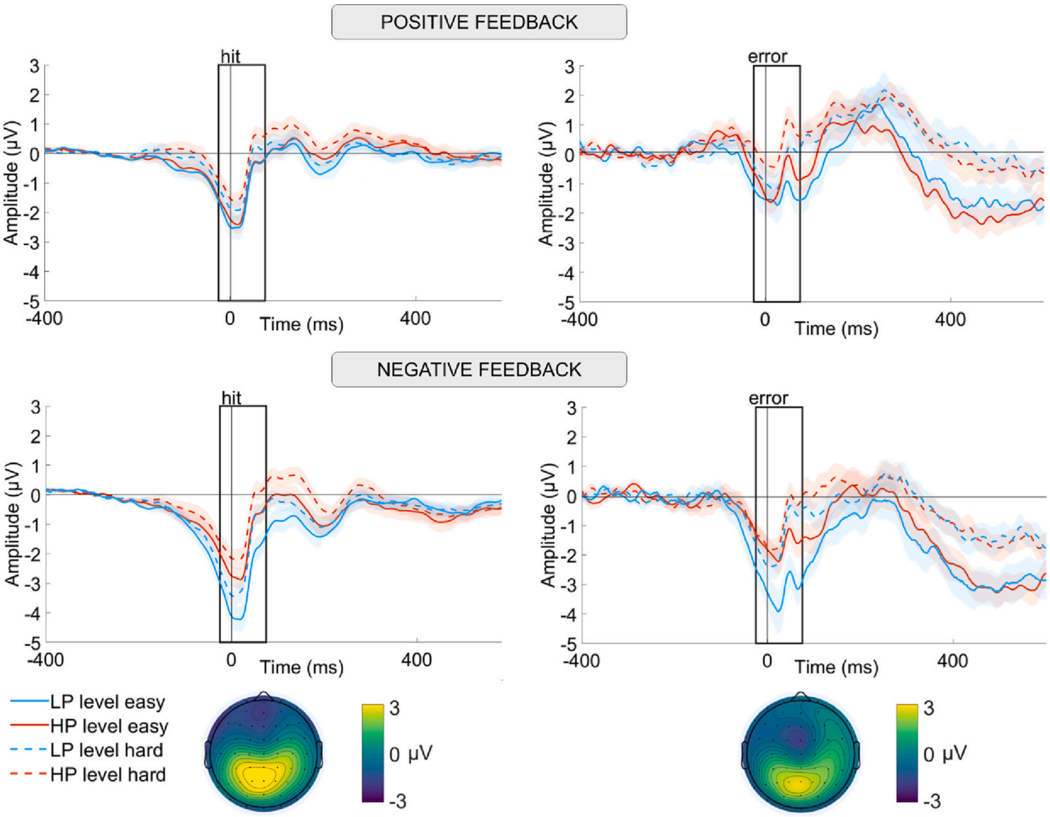

Fig. 4. Event-related potentials in response to hits and commission errors. The potentials were averaged at Fz in response to commission errors among high (HP) and low (LP) procrastinating participants performing the Parametric Go/No Go task with two difficulty levels (easy and hard). During task completion, participants received either positive or negative performance feedback. The black boxes include time windows chosen for the analyses of error-related negativity and correct-response negativity. See Fig. 6 for obtained results. Line shadows represent one standard error. Scalp maps represent potentials averaged from both feedback conditions and groups in the time window from −25 to 75 ms around reactions.

groups reported more positive emotions as well as estimated their performance as higher after receiving positive (vs. negative) feedback. We also observed that positive, as opposed to negative evaluation led to higher arousal and increased PES in HP (vs. LP) participants. On the other hand, during the negative feedback condition HP showed blunted neural activation linked to performance monitoring (ERN, CRN and Pe) and attentional control (P300). Obtained findings indicate that HP might be more sensitive to the motivating effects of success and the detrimental influence of failure.

We hypothesized that in the negative feedback condition HP participants would report more negative emotions and higher arousal, as compared to LP subjects. However, this hypothesis was not confirmed by obtained results. Reported emotional valence in both groups was similarly affected by received evaluation. Regarding arousal, we did observe significant feedback x procrastination interaction, but it was in the opposite direction than predicted: HP, as compared to LP, were more aroused after the positive evaluation, but these differences between groups were insignificant in the negative feedback condition. This might indicate that positive evaluation is more motivating for HP students, which helps them sustain optimal arousal throughout the task. On the other hand, LP might perceive positive evaluation as less challenging and boring, which can lead to drops in energy levels.

The analyses of ERPs partially confirmed the formulated hypotheses. We expected that HP (vs. LP) would present lower values of neurophysiological indices of performance monitoring (ERN, CRN & Pe) and attentional control (P300) and that these differences between groups would be higher in the negative feedback condition. Although we did not observe the predicted general influence of procrastination on the above-mentioned ERPs, there was a significant interaction between feedback and procrastination: HP (vs. LP) showed lower values of all analyzed components, but only during the negative feedback condition. We did not observe similar group differences after success induction. These findings might be explained by elevated levels of fear of failure, maladaptive perfectionism and sensitivity to punishment among HP, which were observed in previous research (e.g. Haghbin et al., 2012; Sirois et al., 2017) and confirmed in our study (see supplementary materials). Individuals with higher levels of these traits are more sensitive to negative evaluation, which might have a disproportionate impact on their motivation and performance (Lerche et al., 2018), for example by inducing excessive rumination (negative, intrusive thoughts regarding one's self) and in consequence depleting the amount of available cognitive resources.

Another possible explanation for the observed effects is that the experience of success is more motivating for HP than LP. In previous studies (Michałowski et al., 2020; Wiwatowska et al., 2022) we found that HP presented reduced neural activation linked to attention and performance monitoring in the context without performance feedback. The present study showed similar results in the negative (not positive) feedback condition, which might indicate that positive evaluation attenuates procrastination-related cognitive deficits. Even though procrastination has been frequently associated with lower achievement motivation (see Steel, 2007 for meta-analysis) and previous research (Wypych et al., 2018) as well as the presented study have not found a significant relationship between procrastination and reported sensitivity to success, the experience of accomplishment might reduce resource-consuming negative emotions and ruminations resulting from fear of failure.

What is noteworthy, the above-mentioned differences between groups in the negative feedback condition, although clearly observed in the easy level of difficulty, were smaller (in the case of P300) or became

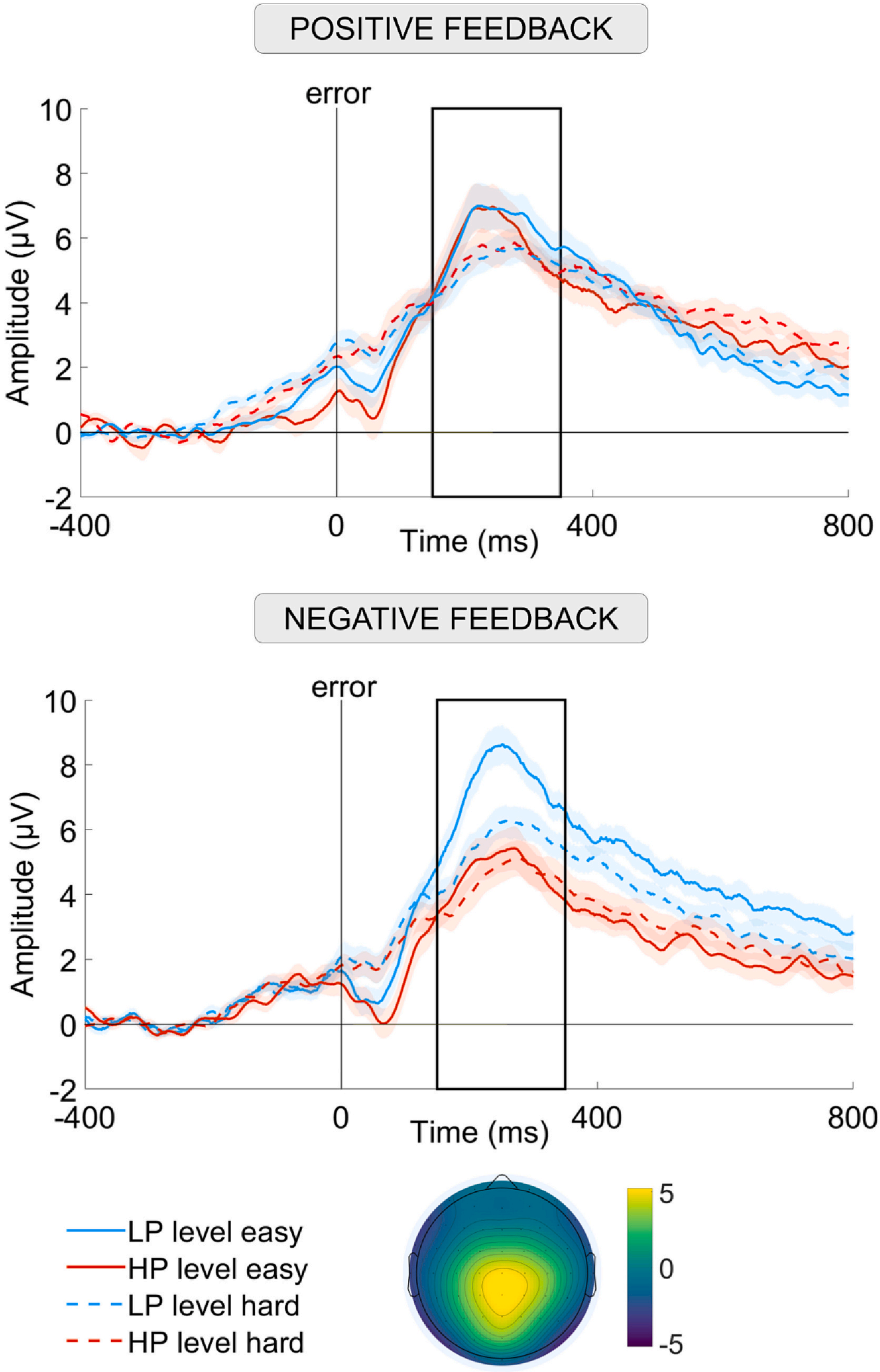

Fig. 5. Event-related potentials in response to commission errors. The potentials were averaged at CPz in response to commission errors among high (HP) and low (LP) procrastinating participants performing the Parametric Go/No-Go task with two difficulty levels (easy and hard). During task completion, participants received either positive or negative performance feedback. The black boxes include time windows chosen for error positivity analyses. See Fig. 6 for obtained results. Line shadows represent one standard error. A scalp map represents potentials averaged from both feedback conditions and groups in the time window from 150 to 350 ms after commission errors.

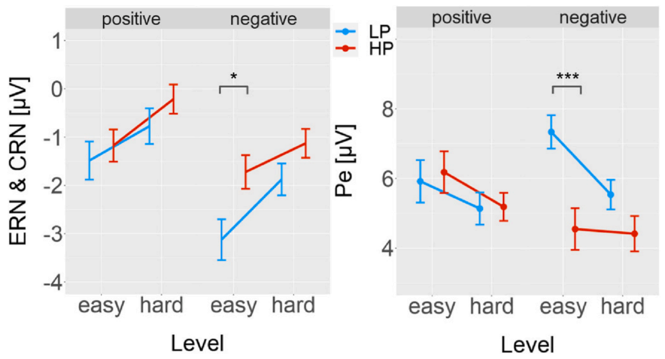

Fig. 6. The mean values of early response-related potentials. The mean values of correct-response negativity (CRN) in response to hits as well as error related negativity (ERN) and error positivity (Pe) in response to commission errors among high (HP) and low (LP) procrastinating participants performing the Parametric Go/No-Go task with two difficulty levels. During task completion, participants received either positive or negative performance feedback. Analyses revealed significant difficulty x feedback x procrastination interaction. The ERN & CRN amplitudes are averaged in the graph only for the purposes of clear results presentation. Error bars represent one standard error.
* $p < .05$; *** $p < .001$.

insignificant (for ERN, CRN & Pe) during the difficult part of the task. As the difficult part was always preceded by the easy part, this might indicate that HP gradually habituated to the presented feedback, which in the end lost its detrimental effects. Also, as the task got more demanding, it might have elicited increased top-down cognitive control, reorienting HP students' attention away from task-unrelated thoughts induced by negative evaluation. Another possible explanation is that although less impacted by failure during the first few blocks of the task, LP progressively lost their motivation after repeatedly receiving negative feedback. However, the interactions with difficulty were not accounted for in the formulated hypotheses and therefore, they should be interpreted with caution.

Regarding behavioral results, similarly to the hypotheses for neurophysiological indices, we also expected to observe impaired performance monitoring (higher PES) and attentional control (higher RTV) in HP (vs. LP) subjects along with higher differences between groups in the negative (vs. positive) feedback condition. However, we did not find confirmation for these predictions. Although PES analyses revealed feedback x procrastination interaction, it was in the opposite direction than hypothesized, showing that HP presented higher PES than LP students, but only in the positive feedback condition. In our previous study (Michałowski et al., 2020), we observed that increased procrastination is related to higher PES, which was interpreted as increased difficulties in reorienting attention away from committed mistakes (Notebaert et al.,

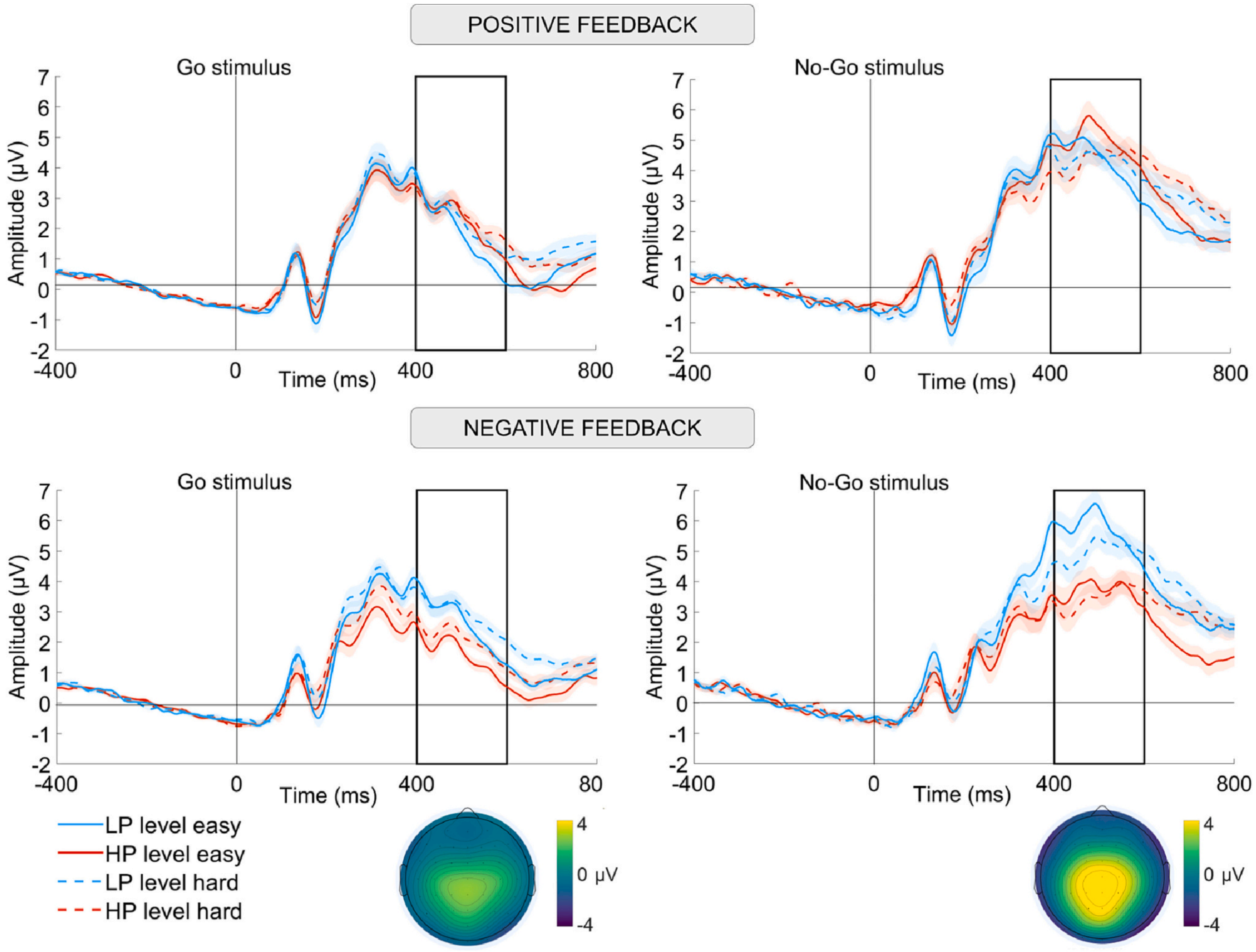

Fig. 7. Event related potentials in response to Go and No-Go stimuli. The potentials were averaged at Pz among high (HP) and low (LP) procrastinating students performing the Parametric Go/No-Go task with two difficulty levels (easy and hard). During task completion, participants received either positive or negative performance feedback. Black boxes include time windows chosen for P300 analyses. See Fig. 8 for obtained results. Line shadows represent one standard error. Scalp maps represent potentials averaged from both feedback conditions and groups in the time window from 400 to 600 ms after stimuli onsets.

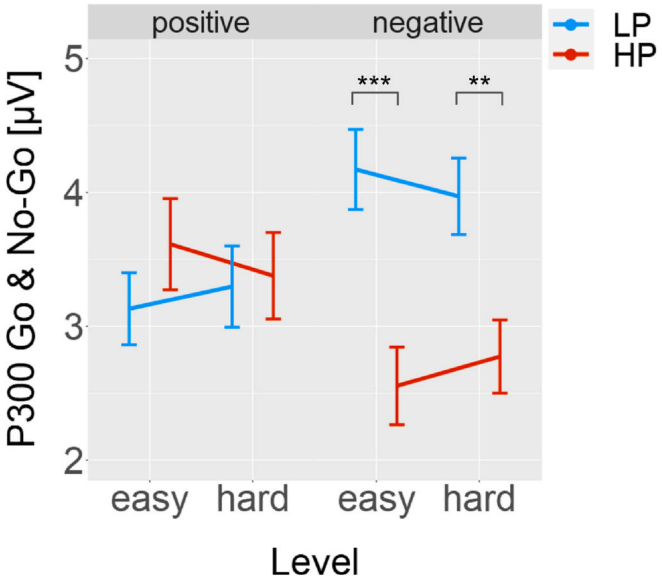

Fig. 8. The mean values of P300 in response to Go and No-Go stimuli. The potentials were averaged at Pz among high (HP) and low (LP) procrastinating students performing the Parametric Go/No-Go task with two difficulty levels (easy and hard). During task completion, participants received either positive or negative performance feedback. Analyses revealed significant difficulty x feedback x procrastination interaction. The significant differences between difficulty levels are not pointed out in the plot (see the main text for detailed results). Error bars represent one standard error.
** $p < .01$; *** $p < .01$.

2009). However, alternative interpretation states that this measure reflects temporary enhancement of cognitive control in order to decrease the probability of making another error (e.g. Botvinick et al., 2001). Increased PES among HP (vs. LP) subjects in the positive feedback condition was accompanied by the normalization of the Pe in this group, i.e. lower Pe amplitudes were observed in HP (vs. LP) during the induction of failure, but the group difference was absent in the positive feedback condition. Both Pe and PES are larger for consciously (vs. unconsciously) committed errors (Nieuwenhuis et al., 2001; Ullsperger et al., 2010). This might indicate that negative, as opposed to positive feedback decreases the awareness of mistakes among HP students, leading to reduced performance monitoring. On the other hand, higher consciousness of committed errors in the positive feedback condition might be associated with increased allocation of attentional resources towards mistakes, which would result in difficulties with reorienting attention to task-relevant stimuli in trials following errors. Therefore, both interpretations of increased PES in the positive feedback condition (higher cognitive control and attention reorientation difficulties) seem plausible.

Regarding RTV, opposite to what we expected, we did not observe any interaction between feedback and procrastination. We only found the predicted main effect of group, which showed higher RTs fluctuations among HP (vs. LP) irrespective of received feedback. This indicates that despite increased allocation of attentional resources to process presented stimuli and committed mistakes after success induction, HP still show some instability within their RTs. We suspect that these fluctuations might be associated with higher PES in the positive feedback condition, which would increase RTV in procrastinating individuals despite their increased rumination tendencies, as excessive slowing after errors introduces increased variability in RTs. Also, higher RTV in both experimental conditions might indicate that HP students present some deficits in attentional control, which are independent of motivational factors.

4.1. Limitations and future directions

The present study is not free from limitations. First, as there were no control groups, which would receive neutral feedback or no evaluation at all, the applied design does not allow for concluding whether the observed differences between groups are driven mostly by positive or negative feedback.

Second, it is not clear if the obtained results are the effect of norm-referenced feedback or positive vs. negative mood induction. However, it might be impossible to distinguish between these two factors, as receiving positive or negative evaluation will impact one's mood at the same time. Nevertheless, future studies could address this issue and directly compare the effects of standard mood manipulation (e.g. presenting emotionally valenced pictures or movies prior to task completion) with the influence of norm-referenced feedback.

Third, the fixed order of difficulty levels in the PGNG task, precludes understanding the mechanisms underlying the observation that HP and LP groups differed significantly mostly during the easy level of the task in the negative feedback condition. This issue might be addressed in future research, by using the design with alternating order of difficulty levels.

Also, it is worth mentioning that procrastination might not be a homogenous construct and that observed effects might not apply to all students who struggle with chronic task delay. Future research might involve a bigger sample of participants and investigate whether there are any variables which would moderate the interactions obtained in the present study.

4.2. Concluding remarks

Despite its limitations, the presented research has some noteworthy assets. To our knowledge, this is the first study evaluating the influence of positive vs. negative norm-referenced feedback on performance monitoring and attention among individuals with different levels of trait procrastination. Obtained results indicate that HP, as compared to LP subjects, might be either more sensitive to boosting effects of positive feedback or more vulnerable to negative evaluation (or both). Different types of feedback might influence procrastinators' performance via increasing or decreasing the level of cognitive control and associated internal distraction. These findings might lead to interesting implications for choosing the form of students' evaluation in academic settings. For example, it might be beneficial to withdraw from feedback based on social comparisons and instead, to focus on the individual progress and emphasize the strengths of one's performance. The results of this study might also be applied in therapeutic interventions aimed at improving the performance of HP individuals, which might focus on dealing with difficulties in attention and performance monitoring or developing positive reappraisal strategies when faced with the perspective of negative evaluation. Moreover, conclusions from this research might be applicable to other conditions associated with self-regulation problems or executive dysfunctions, such as addictions or ADHD. Future studies might take a closer look at psychological and neural mechanisms responsible for the observed effects as well as at potential factors protecting against the detrimental influence of negative feedback.

Data availability

The data and code are available to download from a public repository at the following link: https://repod.icm.edu.pl/privateurl.xhtml?token=77209a8f-cd85-41d6-a0d8-001d6a8050ae.

Acknowledgments

This research was supported by a grant from the National Science Centre (Narodowe Centrum Nauki, NCN) to the senior author Jarosław M. Michałowski, decision number: DEC-2017/27/B/HS6/03065. The authors are grateful to the students and interns of Poznan Laboratory of Affective Neuroscience for their assistance in data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijpsycho.2023.07.004.

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1. Supplementary methods

1.1. Additional questionnaires

To confirm higher levels of fear of failure, maladaptive perfectionism and sensitivity to punishment among HP (vs. LP), all participants completed the Polish versions of the following questionnaires:

Performance Failure Appraisal Inventory (PFAI, Conroy, 2001; polish version in Golińska, 2017) consisting of 35 items organized into four subscales: Fear of Self-Devaluation, Fear of Important Others' Losing Interest, Fear of Blaming Self and Self-Protection Despite Failure. Participants respond on a 5-point Likert scale, with responses ranging from 1 (I strongly disagree) to 5 (I strongly agree).

Frost Multidimensional Perfectionism Scale (FMPS; Frost et al., 1990; polish version in Piotrowski & Bojanowska, 2019) consisting of 29 items and measures five facets of perfectionism, four of which are considered maladaptive perfectionism: Parental Expectations, Parental Criticism, Concerns over Mistakes and Doubts about Actions. Adaptive perfectionism is measured by the Personal Standards subscale. Participants respond on a 5-point Likert scale, with responses ranging from 1 - I strongly disagree to 5 - I strongly agree.

Sensitivity to Punishment and Sensitivity to Reward Questionnaire – Short Form (SPSRQ-SF; Cooper & Gomez, 2008; Wytykowska et al., 2014) includes 21 questions regarding one's tendency to seek rewards (Sensitivity to Rewards subscale) or avoid punishments (Sensitivity to Punishments subscale). Participants respond to questions in a yes/no format.

1.2. Number of trials included in the ERPs analyses.

Table S1. The number of trials (mean and standard deviation) included in the analyses of the event-related potentials.

	positive feedback		negative feedback	
	level easy	level hard	level easy	level hard
ERN & Pe	27.30 (12.83)	34.55 (13.29)	27.57 (11.19)	34.01 (11.30)
CRN	257.10 (12.15)	258.32 (15.23)	244.49 (39.06)	251.21 (23.32)
Go-P300	261.74 (21.67)	262.78 (13.97)	250.12 (39.04)	258.12 (21.88)
No-Go-P300	64.77 (5.70)	65.42 (4.04)	60.80 (10.62)	63.61 (5.83)

Note. ERN - error-related negativity*; Pe* - error positivity; *CRN* - correct response negativity

2. Supplementary results

2.1. Additional questionnaires

Table S2. Mean (SD) values of questionnaire subscales for low (LP) and high (HP) procrastination groups.

Questionnaire/subscale	LP	HP	*t*(130)	*p*	*d*
PFAI					
General result	97.58 (24.90)	115.61 (26.48)	4.33	< .001	.702
Fear of self-devaluation	39.57 (12.45)	46.45 (11.65)	3.52	< .001	.570
Fear of important others' losing interest	24.10 (9.32)	30.83 (10.38)	4.20	< .001	.682
Fear of blaming self	18.71 (3.59)	20.09 (3.34)	2.45	.015	.397
Self-protection despite failure	20.81 (4.37)	17.76 (4.84)	-4.08	< .001	-.661
FMPS:					
Personal standards	27.57 (4.18)	24.61 (5.40)	-3.79	< .001	-.614
Parental expectations	12.95 (5.30)	15.19 (5.10)	2.65	.009	.431
Parental criticism	8.14 (3.80)	10.09 (3.95)	3.10	.002	.504
Doubts about actions	10.17 (3.14)	14.81 (3.40)	8.75	< .001	1.419
Concerns over mistakes	25.45 (7.94)	29.57 (9.01)	2.99	.003	.485
SPSRQ-SF					
Sensitivity to punishments	6.05 (4.00)	8.59 (4.02)	3.90	< .001	.485
Sensitivity to rewards	5.81 (2.02)	6.03 (2.21)	0.65	.519	.105

Note. PFAI - Performance Failure Appraisal Inventory*; FMPS* - Frost Multidimensional Perfectionism Scale; *SPSRQ-SF* - Sensitivity to Punishment and Sensitivity to Reward Questionnaire – Short Form

2.2. Response Accuracy and Reaction Times

Table S3. The percentage of correct responses to Go stimuli among low (LP) and high (HP) procrastinating participants.

difficulty	feedback	procrastination	*M* [%]	*SD*	*N*
easy	positive	LP	97.51	3.70	37
		HP	98.04	2.25	36
	negative	LP	97.91	2.44	36
		HP	96.43	4.78	37
hard	positive	LP	97.37	3.31	37
		HP	97.68	2.46	36
	negative	LP	96.21	4.37	36
		HP	95.67	5.11	37

Table S4. The percentage of correct responses to No-Go stimuli among low (LP) and high (HP) procrastinating participants.

difficulty	feedback	procrastination	*M* [%]	*SD*	*N*
easy	positive	LP	55.86	22.68	39
		HP	56.62	18.00	38
	negative	LP	52.56	16.50	38
		HP	52.12	14.66	37
hard	positive	LP	46.08	23.19	39
		HP	46.77	16.01	38
	negative	LP	44.40	17.55	38
		HP	44.74	16.31	75

Table S5. Reaction times in response to Go stimuli among low (LP) and high (HP) procrastinating participants.

difficulty	feedback	procrastination	*M* [ms]	*SD*	*N*
easy	positive	LP	339.74	48.67	39
		HP	345.19	43.67	37
	negative	LP	340.95	43.15	38
		HP	356.69	41.68	37
hard	positive	LP	348.22	59.45	39
		HP	364.97	60.84	37
	negative	LP	365.08	58.79	38
		HP	368.45	56.17	37

Table S6. The results of the ANOVA performed for analyzing the response accuracy to Go stimuli.

	F(1.142)	*p*	η^2_p
Within-group effects			
difficulty	9.65	.002	.064
difficulty * feedback	4.29	.040	.029
difficulty * procrastination	0.56	.454	.004
difficulty * feedback * procrastination	1.48	.225	.010
Between-group effects			
feedback	3.74	.055	.026
procrastination	0.28	.601	.002
feedback * procrastination	1.58	.210	.011

Table S7. The results of the ANOVA performed for analyzing the response accuracy to No-Go stimuli.

	F(1.148)	*p*	η^2_p
Within-group effects			
difficulty	109.44	< .001	.425
difficulty * feedback	1.78	.184	.012
difficulty * procrastination	0.10	.750	.001
difficulty * feedback * procrastination	0.13	.719	.001
Between-group effects			
feedback	0.96	.329	.006
procrastination	0.02	.881	< .001
feedback * procrastination	0.01	.918	< .001

Table S8. The results of the ANOVA performed for analyzing the reaction times.

	F(1,147)	*p*	η^2_p
Within-group effects			
difficulty	26.14	< .001	.151
difficulty * feedback	0.37	.544	.003
difficulty * procrastination	0.01	.932	< .001
difficulty * feedback * procrastination	3.55	.061	.024
Between-group effects			
feedback	1.10	.296	.007
procrastination	1.71	.192	.012
feedback * procrastination	0.01	.922	< .001

2.3. Reaction Time Variability

Table S9. Reaction time variability among low (LP) and high (HP) procrastinating participants.

difficulty	feedback	procrastination	*M*	*SD*	*N*
easy	positive	LP	0.264	0.064	38
		HP	0.276	0.042	37
	negative	LP	0.268	0.040	37
		HP	0.288	0.048	35
hard	positive	LP	0.280	0.060	38
		HP	0.312	0.071	37
	negative	LP	0.315	0.063	37
		HP	0.325	0.073	35

Table S10. The results of the ANOVA performed for analyzing the reaction time variability.

	F(1.143)	*p*	η^2_p
Within-group effects			
difficulty	38.18	.001	.211
difficulty * feedback	2.08	.152	.014
difficulty * procrastination	0.23	.631	.002
difficulty * feedback * procrastination	1.77	.185	.012
Between-group effects			
feedback	3.95	.049	.027
procrastination	5.49	.021	.037
feedback * procrastination	0.16	.687	.001

2.4. Early response-related components (ERN/CRN)

Table S11. The mean amplitudes of error-related negativity (ERN) and correct response negativity (CRN) among low (LP) and high (HP) procrastinating participants.

component (response type)	difficulty	feedback	procrastination	*M* [μV]	*SD*	*N*
ERN	easy	positive	LP	-1.40	3.02	39
			HP	-0.92	2.35	38
		negative	LP	-3.14	3.39	37
			HP	-1.62	2.60	37
	hard	positive	LP	-1.02	1.92	39
			HP	-0.65	1.65	38
		negative	LP	-2.23	1.96	37
			HP	-1.21	1.77	37
CRN	easy	positive	LP	-1.57	2.20	39
			HP	-1.43	1.95	38
		negative	LP	-3.10	2.30	37
			HP	-1.82	1.98	37
	hard	positive	LP	-0.52	2.87	39
			HP	0.22	2.17	38
		negative	LP	-1.52	2.38	37
			HP	-1.04	2.03	37

Table S12. The results of the ANOVA performed for analyzing the mean amplitudes of early response-related components (error-related negativity & correct response negativity)

	F(1,147)	*p*	η^2_p
Within-group effects			
difficulty	84.40	< .001	.365
difficulty * feedback	0.19	.663	.001
difficulty * procrastination	1.11	.294	.007
difficulty * feedback * procrastination	5.58	.019	.037
response type	12.53	.001	.079
response type * feedback	1.36	.245	.009
response type * procrastination	0.24	.623	.002
response type * feedback * procrastination	1.37	.244	.009
difficulty * response type	4.11	.044	.027
difficulty * response type * feedback	< 0.01	.978	< .001
difficulty * response type * procrastination	1.13	.290	.008
difficulty * response type * feedback * procrastination	1.28	.260	.009
Between-group effects			
feedback	9.56	.002	.061
procrastination	4.93	.028	.032
feedback * procrastination	0.88	.349	.006

2.5. Late response-related component (Pe)

Table S13. The mean amplitudes of error positivity (Pe) among low (LP) and high (HP) procrastinating participants.

difficulty	feedback	procrastination	*M* [μV]	*SD*	*N*
easy	positive	LP	5,92	3,81	39
		HP	6,18	3,64	37
	negative	LP	7,34	2,96	38
		HP	4,55	3,64	37
hard	positive	LP	5,14	2,89	39
		HP	5,19	2,45	37
	negative	LP	5,54	2,62	38
		HP	4,41	3,09	37

Table S14. The results of the ANOVA performed for analyzing the mean amplitudes of the late response-related component (error positivity).

	$F(1,147)$	p	η^2_p
Within-group effects			
difficulty	18.77	< .001	.113
difficulty * feedback	0.03	.855	< .001
difficulty * procrastination	2.88	.092	.019
difficulty * feedback * procrastination	4.82	.030	.032
Between-group effects			
feedback	0.10	.755	.001
procrastination	3.66	.058	.024
feedback * procrastination	5.05	.026	.033

2.6. Stimulus-Related Component (P300)

Table S15. The mean amplitudes of P300 in response to Go and No-Go stimuli among low (LP) and high (HP) procrastinating participants.

stimulus	difficulty	feedback	procrastination	*M* [µV]	*SD*	*N*
Go	easy	positive	LP	1.84	1.50	38
			HP	2.26	1.75	38
		negative	LP	2.65	1.51	38
			HP	1.53	1.16	35
	hard	positive	LP	2.25	1.52	38
			HP	2.41	1.78	38
		negative	LP	2.95	1.57	38
			HP	2.08	1.28	35
No-Go	easy	positive	LP	4.42	2.15	38
			HP	4.96	2.66	38
		negative	LP	5.69	2.39	38
			HP	3.58	2.54	35
	hard	positive	LP	4.34	2.45	38
			HP	4.35	2.37	38
		negative	LP	5.00	2.26	38
			HP	3.47	2.23	35

Table S16. The results of the ANOVA performed for analyzing the mean amplitudes of the stimulus-related component (P300)

	F(1.145)	*p*	η^2_p
Within-group effects			
difficulty	0.03	.870	< .001
difficulty * feedback	0.08	.778	.001
difficulty * procrastination	< 0.01	.956	< .001
difficulty * feedback * procrastination	6.78	.010	.045
stimulus type	361.64	< .001	.714
stimulus type * feedback	0.69	.408	.005
stimulus type * procrastination	3.22	.075	.022
stimulus type * feedback * procrastination	2.95	.088	.020
difficulty * stimulus type	31.18	< .001	.177
difficulty * stimulus type * feedback	0.59	.443	.004
difficulty * stimulus type * procrastination	0.02	.892	< .001
difficulty * stimulus type * feedback * procrastination	1.39	.240	.010
Between-group effects			
feedback	539.31	< .001	.788
procrastination	< 0.01	.964	< .001
feedback * procrastination	3,.78	.054	.025

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Załącznik nr 3A – Oświadczenia współautorów o wkładzie pracy w realizację i publikację badań nad wpływem informacji zwrotnej na przetwarzanie błędów i kontrolę uwagową w prokrastynacji

Warszawa, dnia 18.09.2023

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Oświadczenie o współautorstwie

Niniejszym oświadczam, że w pracy Wiwatowska, E., Wypych, M., Michałowski, J.M. (2023). Improved Attention and Performance Monitoring in High Procrastinating Students After Positive Relative to Negative Norm-Referenced Feedback. *International Journal of Psychophysiology*, *192,* 1–12. mój udział polegał na pracy koncepcyjnej, rekrutacji uczestników, zbieraniu i analizowaniu danych, interpretacji uzyskanych wyników, przygotowaniu pierwszej wersji manuskryptu oraz jego późniejszej korekcie, złożeniu artykułu do czasopisma i odpowiedzi na uwagi recenzentów. Mój udział w powstaniu pracy wynosi 55%.

PODPIS ZAUFANY
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Niniejszym oświadczam, że w pracy Wiwatowska, E., Wypych, M., Michałowski, J.M. (2023). Improved Attention and Performance Monitoring in High Procrastinating Students After Positive Relative to Negative Norm-Referenced Feedback. *International Journal of Psychophysiology, 192,* 1–12. mój udział polegał na pozyskiwaniu środków na realizację badań, współpracy koncepcyjnej, wsparciu merytorycznym, monitorowaniu postępów realizacji badań, interpretacji uzyskanych wyników, korekty powstałego manuskryptu. Mój udział w powstaniu pracy wynosi 30%.

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Podpis