Institute of Psychology
Polish Academy of Sciences

Graduate School for Social Research

Institute of Psychology, Polish Academy of Sciences

Perceptual anomalies from the perspective of experimental psychopathology: investigating mechanisms of auditory hallucinations in patients with schizophrenia spectrum disorders and hallucinatory-like experiences in the general population.

[Anomalie percepcyjne z perspektywy psychopatologii eksperymentalnej: badanie mechanizmów halucynacji słuchowych u pacjentów z zaburzeniami ze spektrum schizofrenii i doświadczeń podobnych do halucynacji w populacji ogólnej.]

mgr Adrianna Aleksandrowicz

Doctoral thesis under the supervision of

Prof. Łukasz Gawęda, PhD

and auxiliary supervision of Joachim Kowalski, PhD

Funding information: The thesis was supported by the grant PRELUDIUM BIS (2019/35/O/HS6/02982) titled: “Perceptual anomalies from the perspective of experimental psychopathology: the impact of cognitive expectancies on false auditory perceptions and its relevance to the continuum of auditory perceptual anomalies in clinical and non-clinical groups” (Principal Investigator: dr hab. Łukasz Gawęda, prof IP PAN). The author was also supported by the NAWA PRELUDIUM BIS travel grant (PPN/STA/2021/1/00016/U/00001) and a recipient of the GSSR GISA scholarship (2023).

Warsaw, 2024

Acknowledgements

First and foremost, I would like to express my deep gratitude to my supervisor, Prof. Łukasz Gawęda, for his constant support over the past four years. I am incredibly thankful for always providing valuable insights and helping me unravel the complexities of understanding psychosis, his advice, his patience with my last-minute work, and the good humor in the lab. I also extend my huge thanks to my auxiliary supervisor, Dr. Joachim Kowalski, for the hours spent together recruiting patients, his insightful comments and advice, his support in my writing, and always having a funny meme in store.

I am sincerely grateful to Prof. Steffen Moritz for the opportunity to complete a research internship in Hamburg during my PhD. I truly appreciate the insightful conversations during our walks in the park and sharing with me his extensive knowledge and collaboration we shared on various projects.

Special thanks go to Dr. Izabela Stefaniak for her kindness, support in patient recruitment and collaboration in projects, and to everyone who to everyone who supported me in conducting the studies especially Katarzyna Elert, with whom I spent many hours mastering clinical assessments. I also appreciate the help from Dr. Michał Jarkiewicz, Dr. Justyna Sędek, Joanna Gruhn-Devantier, Małgorzata Kostka, Alicja Fidler, and Martyna Tomczyk in participant assessments.

A huge thank you to my fellow lab members for exchanging ideas, support, and humor - especially Paulina Bagrowska, who started this PhD journey with me and supporting each other along the way, as well as Hania Gelner, Justyna Piwińska, and Martyna Krężołek for their companionship in a new scientific journey.

I am immensely grateful to all the participants for their involvement and to the reviewers and editors for their time and effort. Without a collective effort scientific research would not be possible. This research aimed to deepen our understanding of perceptual anomalies and hopefully add another small step to the many years of collaborative effort to improve interventions for distressing or disruptive perceptual anomalies.

My deepest gratitude goes to my partner, Paweł Jakuszyk, for being my best friend and my biggest rock throughout this journey, and to my friends, who have been my greatest cheerleaders and supporters. I could not do this without them. I am also forever thankful to my parents for always supporting my new ideas and dreams, regardless of the path I chose.

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1. Abstract

Perceptual anomalies refer to unusual or atypical experiences and misinterpretations of sensory information. They include a wide range of heterogeneous phenomena such as illusions, hallucinatory-like experiences (HLEs), hallucinations, and other distortions in sensory processing. Perceptual anomalies are common in patients diagnosed with schizophrenia spectrum disorders (SSD), where more severe forms of them, i.e., auditory hallucinations (AHs), are reported in up to 70-80% of patients. Simultaneously, numerous studies have shown that perceptual anomalies are common in non-clinical populations, with up to 89% of individuals reporting experiencing them at least once in their lifetime. HLEs in auditory modality usually include phenomena such as misinterpreting or falsely hearing sounds such as phantom phone signals (PPS), music, footsteps, doorbell, or human speech (hearing own's name, whispering, etc.).

According to contemporary theoretical models, perceptual anomalies have been placed on a continuum in which similar mechanisms could be involved in their formation in clinical and non-clinical populations, i.e., a continuum from easily dismissible singular sounds to complex and distressing auditory hallucinations. However, since perceptual anomalies encompass a wide range of experiences, it is still unclear whether their mechanisms could be more specific depending on the individual experience. Cognitive processes have been a topic of theoretical accounts for many decades. Recent theoretical models of hallucinations highlight the role of top-down processes, source monitoring and inhibitory control in the formation of perceptual anomalies. However, numerous factors have been explored in hallucination research, highlighting its complexities and the frequent occurrence of contradictory findings.

In general, my doctoral thesis aimed to investigate the mechanisms of various perceptual anomalies in clinical and non-clinical populations. We set five more specific aims. First, (1) we aimed to test the similarities and differences between several types of perceptual anomalies, such as PPS and other HLEs in top-down processing, beliefs about perception, attentional control, smartphone dependence and general psychopathology. Then, (2) we aimed to test the role of cognitive processes: source monitoring, top-down processes, and inhibitory control in auditory hallucinations. Moreover, we explored associations with psychosis symptoms in patients diagnosed with SSD. Our third objective (3) was to investigate the interrelationships between these three cognitive processes. Another main aim (4) was to verify whether similar cognitive mechanisms underlie perceptual anomalies in clinical and non-clinical contexts. Our final objective (5) was to test the associations between top-down processes, source monitoring, inhibitory processes, and perceptual anomalies, self-disturbances as well as social functioning on the entire continuum of various perceptual experiences. These aims have been investigated in four studies demonstrated in three scientific publications.

First, we employed a sample from a general population (n=236) to test similarities and differences between PPS and other types of HLEs by implementing self-reported measures of general psychopathology, attentional control, and smartphone dependence. Additionally, we developed a new experimental paradigm to measure the relationship between top-down processes and perceptual anomalies. To measure beliefs about perception, we designed a novel questionnaire - Beliefs about Perception Questionnaire.

In the second article, three experimental procedures have been utilized to measure how source monitoring bias (Action Memory Task), top-down processes (False Perception Task), and inhibitory control (Auditory Go/NoGo Task) contribute to AHs in individuals with SSD (n=89) and explore interconnections between these cognitive processes.

The last article describes two studies where the role of the aforementioned cognitive processes as well as self-disturbances and social functioning, have been investigated. Study I in the third paper involved hallucinating patients diagnosed with SSD (n=46) in comparison to non-hallucinating patients (n=43) and matched healthy controls (n=43). Study II comprised a sample derived from the general population (n=3143) and selected into those experiencing high (n=40) and low (n=43) HLEs. Then, the associations between variables of interest were investigated in the entire sample (n=217).

The results of the first study suggest that while PPS and other HLEs share some mechanisms, such as age and top-down beliefs about perception, they also exhibit distinct underlying factors. Moreover, we found no significant associations between false perceptions and investigated types of perceptual anomalies. The second study provided more evidence on the mechanisms of clinical hallucinations. Results exhibited that only the response bias (decision-making tendency in uncertain situations) parameter from the False Perception Task was positively associated with clinical AHs and source motoring errors. However, in the direction opposite than expected - the more AHs and misattribution errors, the less patients were biased towards reporting that the signal was present. Source monitoring and inhibitory errors were linked to other symptoms of schizophrenia. The final article, which consisted of both clinical and non-clinical populations, demonstrated that none of the cognitive processes tested was specific for the group with clinical AHs as well as for the non-clinical group with high HLEs. Yet, both patient groups exhibited more source monitoring errors and false perceptions than healthy controls. However, when the entire sample was combined, we found a link between perceptual anomalies and cognitive processes, particularly source monitoring and top-down errors. Similarly, self-disturbances were associated with both cognitive processes, while lower social functioning was specifically related to source monitoring errors.

The presented cycle of publications investigates whether mechanisms of various perceptual anomalies exhibit more continuities or discontinuities across clinical and non-clinical populations. This thesis provides new insights into the research on perceptual anomalies, showing that there are

some similarities but, at the same time, differences in their mechanisms, emphasizing the need for deeper exploration of specific experiences to improve psychological interventions.

Keywords: perceptual anomalies, hallucination continuum, cognitive processes, psychopathology, psychosis, psychotic-like experiences, auditory perception

2. Streszczenie

Anomalie percepcyjne odnoszą się do niezwykłych lub nietypowych doświadczeń i błędnych interpretacji informacji sensorycznych. Obejmują one szeroki zakres heterogenicznych zjawisk, takich jak iluzje, doświadczenia podobne do halucynacji (HLEs), halucynacje i inne zniekształcenia w przetwarzaniu sensorycznym. Anomalie percepcyjne są powszechne u pacjentów z rozpoznaniem zaburzeń ze spektrum schizofrenii (SSD), gdzie ich cięższe formy, tj. halucynacje słuchowe (AHs), są zgłaszane nawet u 70-80% pacjentów. Jednocześnie liczne badania wykazały, że anomalie percepcyjne są powszechne w populacjach nieklinicznych, gdzie nawet do 89% osób zgłasza, że doświadczyło ich przynajmniej raz w życiu. HLEs w modalności słuchowej zwykle obejmują zjawiska takie jak błędna interpretacja lub fałszywe słyszenie dźwięków, takich jak fantomowe sygnały telefoniczne (PPS), muzyka, kroki, dzwonek do drzwi lub ludzka mowa (słyszenie własnego imienia, szept itp.).

Zgodnie ze współczesnymi modelami teoretycznymi, anomalie percepcyjne zostały umieszczone na kontinuum, w którym podobne mechanizmy mogą być zaangażowane w ich powstawanie w populacjach klinicznych i nieklinicznych, tj. kontinuum pojedynczych dźwięków do złożonych i niepokojących halucynacji słuchowych. Ponieważ jednak anomalie percepcyjne obejmują szeroki zakres doświadczeń, nadal nie jest jasne czy ich mechanizmy mogą być bardziej specyficzne w zależności od indywidualnego doświadczenia. Procesy poznawcze są tematem rozważań teoretycznych od wielu dziesięcioleci. Najnowsze modele teoretyczne halucynacji podkreślają rolę procesów odgórnych (top-down), monitorowania źródła i kontroli hamowania w powstawaniu anomalii percepcyjnych. Jednakże badania nad halucynacjami podkreślają liczne czynniki, co ukazuje złożoność tego zjawiska i częste występowanie sprzecznych wyników.

Moja praca doktorska miała na celu zbadanie mechanizmów różnych anomalii percepcyjnych w populacjach klinicznych i nieklinicznych. Wyznaczyliśmy pięć bardziej szczegółowych celów. Po pierwsze (1) chcieliśmy przetestować podobieństwa i różnice między kilkoma rodzajami anomalii percepcyjnych, takich jak PPS i inne HLEs w przetwarzaniu odgórnym, przekonaniach na temat percepcji, kontroli uwagi, uzależnieniu od smartfonów i ogólnej psychopatologii. Następnie (2) chcieliśmy sprawdzić rolę procesów poznawczych: monitorowania źródła, procesów odgórnych i kontroli hamowania w halucynacjach słuchowych. Ponadto zbadaliśmy związki z objawami psychozy u pacjentów z rozpoznaniem SSD. Naszym trzecim celem (3) było zbadanie wzajemnych powiązań między tymi trzema procesami poznawczymi. Kolejnym głównym celem (4) było sprawdzenie, czy podobne mechanizmy poznawcze leżą u podstaw anomalii percepcyjnych w kontekście klinicznym i nieklinicznym. Naszym ostatnim celem (5) było przetestowanie powiązań między procesami odgórnymi, monitorowaniem źródła, procesami hamowania i anomaliami percepcyjnymi, zaburzeniami self (self-disturbances), a także funkcjonowaniem społecznym na

całym kontinuum różnych doświadczeń percepcyjnych. Cele te zostały zbadane w czterech badaniach przedstawionych w trzech publikacjach naukowych.

W pierwszym badaniu, zrekrutowaliśmy próbę z populacji ogólnej (n=236), aby przetestować podobieństwa i różnice między PPS a innymi typami HLE, wykorzystując miary ogólnej psychopatologii, kontroli uwagi i uzależnienia od telefonu. Ponadto opracowaliśmy nowy paradygmat eksperymentalny do pomiaru związku między procesami odgórnymi a anomaliami percepcyjnymi. W celu pomiaru przekonań na temat percepcji opracowaliśmy nowy kwestionariusz - Kwestionariusz Przekonań na Temat Percepcji.

W drugim artykule zostały wykorzystane trzy procedury eksperymentalne do pomiaru, w jaki sposób błędy monitorowania źródła (Action Memory Task), procesy odgórne (False Perception Task) i kontrola hamowania (Auditory Go/NoGo Task) przyczyniają się do halucynacji u osób z SSD (n=89) i badają wzajemne powiązania między tymi procesami poznawczymi.

W ostatnim artykule opisano dwa badania, w których sprawdzano rolę wspomnianych wyżej procesów poznawczych, a także zaburzeń self i funkcjonowania społecznego. Badanie I w trzecim artykule obejmowało pacjentów z halucynacjami, u których zdiagnozowano SSD (n=46) w porównaniu z pacjentami bez halucynacji (n=43) i grupą kontrolną (n=43). Badanie II obejmowało próbę pochodzącą z populacji ogólnej (n=3143) i podzieloną na osoby doświadczające wysokich (n=40) i niskich (n=43) HLEs. Następnie zbadano związki między testowanymi zmiennymi w całej próbie (n=217).

Wyniki pierwszego badania sugerują, że podczas gdy PPS i inne HLE mają wspólne mechanizmy, takie jak wiek i odgórne przekonania na temat percepcji, wykazują one również różne czynniki leżące u ich podstaw. Co więcej, nie znaleźliśmy znaczących powiązań między fałszywymi percepcjami a badanymi typami anomalii percepcyjnych. Drugie badanie dostarczyło więcej dowodów na mechanizmy halucynacji klinicznych. Wyniki wykazały, że tylko parametr tendencyjność odpowiedzi (tendencja do podejmowania decyzji w niepewnych sytuacjach) z zadania mierzącego fałszywą percepcję był pozytywnie związany z klinicznymi halucynacjami i błędami monitorowania źródła. Jednak w kierunku przeciwnym niż oczekiwano - im więcej halucynacji i błędów monitorowania źródła, tym mniej pacjenci byli skłonni do zgłaszania, że sygnał był obecny. Błędy monitorowania źródła i hamowania były powiązane z innymi objawami schizofrenii. Ostatni artykuł, który obejmował zarówno populacje kliniczne, jak i niekliniczne, wykazał, że żaden z testowanych procesów poznawczych nie był specyficzny dla grupy z klinicznymi halucynacjami, jak również dla grupy nieklinicznej z wysokimi HLEs. Jednak obie grupy pacjentów wykazywały więcej błędów monitorowania źródła i fałszywych spostrzeżeń niż zdrowe grupy kontrolne. Jednak po połączeniu całej próby znaleźliśmy związek między anomaliami percepcyjnymi a procesami poznawczymi, w szczególności monitorowaniem źródła i błędami odgórnymi. Podobnie, zaburzenia self były związane z oboma procesami poznawczymi, podczas gdy niższe funkcjonowanie społeczne było szczególnie związane z błędami monitorowania źródła.

Prezentowany cykl publikacji bada, czy mechanizmy różnych anomalii percepcyjnych wykazują więcej ciągłości czy nieciągłości w populacjach klinicznych i nieklinicznych. Niniejsza rozprawa dostarcza nowego spojrzenia na badania nad anomaliami percepcyjnymi, pokazując, że istnieją pewne podobieństwa, ale jednocześnie różnice w ich mechanizmach, podkreślając potrzebę głębszej eksploracji konkretnych doświadczeń percepcyjnych w celu ulepszenia interwencji psychologicznych.

Słowa kluczowe: anomalie percepcyjne, kontinuum halucynacji, procesy poznawcze, psychopatologia, psychoza, doświadczenia podobne do psychotycznych, percepcja słuchowa

3. Introduction

3.1. Perceptual anomalies - from illusions to hallucinations

Perception is our gateway to receiving information from the external world, where we perceive stimuli from all the modalities (Oxenham, 2018). Contemporary accounts describe perception as an active and dynamic process of testing hypotheses that results in learning the external stimuli qualities (Gregory, 1980). In his early works in the 19th century, Helmholtz argued that while perception specializes in processing environmental information, it also involves constant interaction with the world, shaping our final interpretations (Koenigsberger, 1906). This account provided insight into how intentional actions and environmental stimuli can interact and affect one another. As a result, the final perception is formed by comparing prior expectations with sensory inputs (de Lange et al., 2018). For instance, in circumstances where complete sensory information is unavailable (e.g., when navigating in a dark forest), perceptual experience is shaped by dynamic interactions with prior knowledge ("There could be wild animals"). Consequently, incoming stimuli are interpreted based on sensory input and pre-existing expectations ("The dark shadow in front of me could be a bear"). Thus, different objects hold no inherent meaning without subjective interpretation, and such interpretations rely on existing knowledge and cognitive frameworks to categorize these phenomena (Gregory, 2009).

Sensory perception often serves as the most compelling evidence of something's existence. When we perceive external stimuli, we interpret it as "objective" or "real", assuming our perception provides us with an accurate representation of reality (Carbon, 2014). Conversely, it has been argued that perception might be more accurately described as a "controlled hallucination," meaning that the brain creates a version of reality (i.e., a percept) designed to effectively guide our complex behaviors (Clark, 2015; Paolucci, 2021). When considering that perception is an active and dynamic process and involves interpretative significance, it can sometimes mislead us by distorting objects based on our beliefs or experiences (e.g., illusions) or creating false perceptions that hold a sense of reality (e.g., hallucinations) (Corlett et al., 2019). These experiences are often labelled as perceptual anomalies, encompassing a broad spectrum of disruptions across various sensory modalities (such as auditory, visual, kinesthetic, etc.) (Chesterman & Boast, 1994; Montagnese et al., 2021).

Perceptual anomalies commonly occur in everyday situations and can be exacerbated in conditions of extreme physiological or psychological stress, such as fatigue, sensory or sleep deprivation, bereavement (Bexton et al., 1954; Mason & Brady, 2009; Waters, Chiu, et al., 2018) or result from medical conditions, mental disorders or the influence of psychoactive substances (Burghaus et al., 2012; Schutte et al., 2020; M. J. Smith et al., 2009; Toh et al., 2015; Waters & Fernyhough, 2017). These abnormalities, in particular full-blown hallucinations, have been strongly associated with schizophrenia spectrum disorders (SSD) since the early clinical literature (Ross Diefendorf, 1907; Schneider, 1959).

Hallucinations can be characterized as perceptual anomalies that arise without the presence of corresponding external stimuli, usually possessing enough sense of reality to mimic a true perception, being beyond the subject's direct and voluntary control, and occurring while the individual is awake (David, 2004; O' Connor et al., 2019). Hallucinations can manifest across various sensory modalities, but auditory hallucinations (AHs) are the most commonly reported in psychosis, affecting up to 80% of SSD patients (McCarthy-Jones et al., 2017). Hallucinations have been associated with, e.g., severe distress, depression, and anxiety (Scott et al., 2020) as well as social isolation (Hoffman, 2007), decreased quality of life (Janaki et al., 2017), sleep problems (Koyanagi & Stickley, 2015; Reeve et al., 2015) and a higher risk of suicide (Harkavy-Friedman et al., 2003; Kjelby et al., 2015), highlighting the clinical importance of studying perceptual anomalies.

Hallucinatory-like experiences (HLEs) are another form of perceptual anomalies receiving growing attention in research. The term HLEs is used to describe a broader range of perceptual anomalies, typically brief and connected with uncertainty when they occur (Daalman et al. 2011; Johns et al. 2014)[1]. HLEs typically refer to perceptual distortions such as hearing one's name, a dog barking, a child crying, hearing thoughts aloud or whispering, etc. (Linszen et al., 2022). Moreover, studies on the general population indicate the presence of a group of voice hearers without a need for care (Baumeister et al., 2017; Daalman et al., 2011; Johns et al., 2014). Prevalence rates of perceptual anomalies differ depending on the specific type of experience and methodology implemented (Beavan et al., 2011; Linszen et al., 2022). Unlike clinical hallucinations, HLEs are typically not associated with significant distress and lack the uncontrollability characteristic of clinical symptoms, as they tend not to disrupt daily functioning significantly (Toh et al., 2022). Nevertheless, there is a line of studies demonstrating that psychotic-like experiences such as HLEs have been associated with a higher risk of suicidal behaviours (DeVylder & Hilimire, 2015; Gawęda et al., 2020).

One type of HLEs receiving increasing interest are Phantom Phone Signals (PPS) due to the omnipresence of smartphones in today's world. Studies revealed that PPS are linked to psychopathology, e.g., anxiety or depression (Lin et al., 2013a; Lin et al., 2013b). Although the lifetime prevalence of PPS has been reported in up to 89% of the population (Deb, 2015; Pisano et al., 2021), studies on its underlying mechanisms are limited and often investigated in isolation from research on other perceptual anomalies. Therefore, further investigation into the various types of perceptual anomalies and their mechanisms is needed.

[1] The boundaries of different perceptual anomalies definitions remain unspecified. However, the closer we are to the clinical psychopathology, the definitions have been more precise. Nevertheless, ongoing debate continues regarding specific definitions, such as those for hallucinations in the context of schizophrenia (see Moritz et al., 2023 for further discussion).

Due to the heterogeneity of perceptual anomalies and interconnections within clinical and non-clinical samples, it has been stated that perceptual anomalies should not be viewed as a binary condition (i.e., present, or absent). Instead, perceptual phenomena like illusions or hallucinations are not limited to specific clinical diagnoses but exist along a spectrum beyond phenomena that may be considered clinical symptoms. Perceptual anomalies are now considered part of an extended phenotype, reflecting recent updates to the continuum hypothesis of psychosis (van Os et al., 2009). The (simplistic) model of continuum suggests the existence of a wide range of experiences, varying from occasional false perceptions (e.g. hearing a phantom phone call) to complex and most often distressing experiences, like verbal hallucinations (Baumeister et al., 2017). It has been hypothesized that a common etiology may be shared within different perceptual anomalies (Johns, 2005; Johns & van Os, 2001; Myin-Germeys et al., 2003). However, it is important to note that there have been some criticisms over the continuum hypothesis (David, 2010; Sommer, 2010) due to challenges in methodology (e.g., differences in how perceptual anomalies are measured in epidemiological studies) and complexities in defining the continuum itself (which characteristics of perceptual anomalies should be included in the continuum - content, frequency, perceived localization etc.). Studying perceptual anomalies in the clinical and non-clinical context is important to test the continuum hypothesis further. Another reason to compare both populations is the inherent confounds in clinical samples (e.g., effects of pharmacotherapy, duration of illness, social exclusion, etc.). Moreover, studying a single symptom is challenging, as hallucinations in psychosis often co-occur with a wide variety of heterogeneous symptom profiles (Grube et al., 1998; D. A. Smith et al., 1998).

3.2. Cognitive mechanisms of perceptual anomalies

Decades after Helmholtz proposed that perception is the effect of unconscious inference, theories attempting to explain false perception have emerged. In the second half of the twentieth century, due to the growth in technological advances, the theories in the field of cognitive sciences started to be verified by, e.g., more complex experimental approaches or computational neuroscience, making it possible to build new theoretical models of perceptual anomalies. Several cognitive processes have been proposed to explain the mechanisms underlying the etiology of hallucinations (Bell et al., 2024). While theoretical accounts highlight different cognitive mechanisms, the current research cycle focuses in particular on processes proposed in the model of Waters et al. (2012) - source monitoring, top-down processing, and inhibition.

Source monitoring

In the '80s, Johnson and Raye (1981) introduced a theoretical concept of source monitoring that attempted to explain how we test reality to distinguish between internally and externally generated information. This concept was further empirically verified (for summary: Damiani et al., 2022; Gawęda et al., 2024) and formed into a source monitoring framework (Johnson et al., 1993) Later, Frith and Done (1988) proposed that auditory hallucinations result from misattributing internal experiences to external sources, which could result in perceiving e.g., internal speech or thoughts as coming from the outside world. Johnson et al. (1993) distinguished different types of source monitoring biases: a) reality monitoring, which differentiates between internal and external sources of information (e.g., misattributing self-generated speech to external sources); b) internal source monitoring (self-monitoring), which distinguishes between two internal sources (such as misattributing imagery and actual performance); and c) external source monitoring, which involves differentiation between two external sources (e.g., pictures and words). Several studies have demonstrated that patients with SSD generally tend to misattribute the source of information more frequently than healthy controls (Lavallé et al., 2021). A recent systematic review (Gawęda et al., 2024) summarizing the studies on different cognitive biases in psychosis showed that most studies implemented reality monitoring biases (49 studies), whereas other types were less frequently investigated. For example, internal source monitoring has been investigated in 23 studies. However, in this type of source monitoring, only three studies (Aleman et al., 2003; Franck et al., 2000; Gawęda et al., 2013) implemented a comparison between hallucinating and non-hallucinating patients, of which two showed that hallucinating patients more frequently confuse information from two internal sources (e.g., imagined/performed actions or silent/overt reading) in the experimental task (Franck et al., 2000; Gawęda et al., 2013). Nevertheless, source monitoring biases have also been linked to other symptoms of schizophrenia, such as delusions (Brodeur et al., 2009), disorganization (Docherty, 2012; Nienow & Docherty, 2004), or negative symptoms (Brébion et al., 2002; Moritz et al., 2003). Moreover, several studies have found that patients with SSD tend to exhibit source monitoring deficits regardless of the source monitoring type (Gawęda et al., 2024). Nonetheless, it is still unclear whether source monitoring deficits are specific to the continuum of different perceptual anomalies. Only a few studies verified the source monitoring paradigm in the non-clinical samples. One investigation exhibited that reality monitoring errors were connected to HLEs (Larøi et al., 2004), whereas others found no such link (Alderson-Day et al., 2019; Allen et al., 2006). Allen et al, (2006) found a link between misattribution errors and delusion proneness but not to hallucination proneness. Other studies showed that the ultra-high risk (UHR) group more often misattributed imagined actions as performed (internal source monitoring) than healthy controls. The amount of source monitoring errors was also similar for first-episode psychosis (FEP) groups, which could indicate that source monitoring deficits may serve as an early marker of the psychosis risk (Gawęda et al., 2018; Nelson et al., 2020). Nevertheless, research on non-clinical populations remains scarce compared to the extensive literature on clinical samples. To our knowledge, no studies have compared high and low

HLEs samples concerning internal source monitoring bias. Investigating non-clinical populations is crucial to exploring the confounding factors mentioned in clinical populations (e.g., effects of pharmacotherapy or chronicity of the condition). This dissertation aims to fill that part of the gap in the current knowledge.

Top-down processing (cognitive expectancy)

While source monitoring explains the experience of the voice as coming from outside, alternative models investigate the reasons behind perceptual experiences occurring in the absence of an adequate sensory stimulus. Current models of human perception emphasize the dynamic interaction between 'top-down' (cognitive processes) and 'bottom-up' (sensory input) processes, along with intermodal integration such as audiovisual integration (Erickson et al., 2014), indicating that perceptual experiences arise from a combination of prior expectations (e.g., existing knowledge or priors) that guide the perceptual system and sensory inputs from the environment. Recent theoretical models (de Lange et al., 2018) based on Bayesian principles align with these early observations, emphasizing that expectations shape perception. Like many other species, human brains are 'anticipatory systems' (Rosen, 2012) that create predictive models of themselves and their surroundings, enabling rapid and robust interpretation of incoming data. The brain, described as a 'prediction machine,' attempts to align sensory inputs with top-down expectations (de Lange et al., 2018). This concept, originating with Helmholtz, has long acknowledged the brain's predictive nature (von Helmholtz, 1867).

Human development involves acquiring knowledge regarding the mechanisms and principles governing the functioning of the world. Forming prior knowledge and expectations helps efficiently process and interpret incoming inputs. However, when sensory information is noisy (in terms of signal processing) or ambiguous, our perception can be biased by expectation, creating false perceptions (de Lange et al., 2018). For example, when someone is expecting an important call and the surrounding environment has a lot of noise (e.g. a busy street with bustling traffic), one can hear the phone ringing, where in fact there is no such signal (Horga & Abi-Dargham, 2019). These concepts have been formulated into theoretical models. One of the most prominent accounts is based on the predictive coding concept, where the perception is a product of Bayesian inference (Corlett et al., 2019; Powers et al., 2016). Previous expectations (priors) are integrated with new sensory information during perceptual decisions. This process may lead to an imbalance, a so-called prediction error, i.e., a discrepancy between the incoming data and the prediction. In this account, the main goal of an efficient perception system is to minimize prediction error through a process of gathering evidence or updating priors. This theoretical account assumes that in clinically at-risk individuals, too much reliance on prior predictions (strong priors) penetrates perception and thus leads to perceptual anomalies (Howes et al., 2020). The role of cognitive and semantic expectancies as strong priors has been highlighted in this line of perceptual anomalies research (Gawęda & Moritz, 2021; Horga & Abi-Dargham, 2019; Laloyaux et al., 2022). The experimental procedures testing the role of top-down processes are often based on Signal detection theory (SDT) principles (Green & Swets, 1966), which manipulate signal probability to investigate how prior expectations influence decision-making. During the task, participants decide if a signal is present in background noise by responding "yes" or "no". This approach measures the ability to detect signal and response bias (the tendency to respond "yes" or "no") (Brookwell et al., 2013; Waters et al., 2012).

Over the years, many studies have attempted to empirically verify the abovementioned theoretical models of perceptual anomalies. Preliminary findings have shown that higher cognitive expectancy led to more false perceptions in SSD patients compared to healthy controls (Gawęda & Moritz, 2021). Other results demonstrated an association between top-down errors and clinical hallucinations (Bristow et al., 2014). On the other hand, Chhabra et al. (2016) reported no significant correlation between clinical symptoms and signal detection task performance. Other studies demonstrated non-significant differences when hallucinating patients were compared to non-hallucinating (Kowalski et al., 2024) or yielded mixed results (Vercammen et al., 2008). Simultaneously, consistent evidence indicates that intermodular integration is essential in human perception (Erickson et al., 2014). A study by Gawęda and Moritz (2021) demonstrated that increased cognitive expectancy corresponded to a higher incidence of false perceptions in SSD patients relative to healthy controls; in particular, the integration of auditory stimuli and visual expectations influenced auditory perception. Conversely, this study found no significant relationship between an increased tendency for false alarms (i.e., overperceptualization) and hallucinations. The research investigating the role of top-down processes (i.e., overreliance on strong priors) in the formation of perceptual anomalies in the clinical samples needs further verification.

On the other hand, studies on non-clinical samples have shown more consistent results. A number of the findings demonstrated the association between experiencing perceptual anomalies (e.g., among healthy voice hearers or community samples scoring high on the self-reports measuring hallucinatory experiences) and top-down errors in the experimental task (de Boer et al., 2019; Laloyaux et al., 2022; Moseley et al., 2021, 2022; Vercammen & Aleman, 2010). Yet those studies differ in sampling methods, setting different inclusion criteria (e.g., not all implemented clinical interviews before entering the study). Moreover, various experimental procedures have been adopted. So far, only one study tested different expectancy levels in the non-clinical sample with high proneness to AHs (Laloyaux et al., 2022). Thus, more studies are needed to test the influence of cognitive expectancy on false perception errors both for clinical and non-clinical populations that experience perceptual anomalies.

Inhibitory processes

Other mechanisms frequently studied in schizophrenia are connected to inhibitory processes. Inhibition deficits have been associated with schizophrenia since Frith's work in 1979 (Frith, 1979). Subsequently, multiple studies found that patients diagnosed with schizophrenia exhibit difficulties with inhibitory processes, e.g., ignoring irrelevant stimuli (Park et al., 2002) and suppressing dominant, automatic responses (Weisbrod et al., 2000). As models of specific psychotic symptoms were developed, inhibitory processes became a vital process in theoretical accounts of understanding hallucinations (Jardri et al., 2016). Morrison et al. (1995) proposed a heuristic model suggesting that AHs occur when intrusive thoughts are misattributed to an external source to reduce cognitive dissonance. Later, it was confirmed in findings demonstrating that patients with AHs have more intrusive thoughts and consider them more uncontrollable, unacceptable, and distressing (Morrison & Baker, 2000). Inhibition has been suggested as one of the mechanisms to account for the intrusive nature of AHs (Badcock et al., 2007; Waters et al., 2006). Inhibitory processes can be considered a gatekeeper of cognition, allowing hallucinations to persist once they are elicited, being unable to suppress or inhibit false perceptions (Badcock & Hugdahl, 2014). Yet, the term inhibition encompasses a range of processes, each with distinct operating mechanisms. For instance, inhibitory processing can be categorized into various types, including cognitive (control of mental contents) versus behavioral inhibition (control of overt behavior), intentional (deliberately suppressing irrelevant stimuli) versus automatic inhibition (unconsciously suppressing stimuli) (Waters et al., 2012).

Previous research has demonstrated differences in tasks assessing various types of inhibitory processes when comparing patients with SSD to healthy controls (Barch et al., 2001; Cohen & Servan-Schreiber, 1992; Ertekin et al., 2017; Lipszyc & Schachar, 2010; MacDonald & Carter, 2003). In the context of AHs, studies on intentional cognitive inhibition showed a relationship with hallucinatory experiences in clinical (Soriano et al., 2009; Waters et al., 2003; Waters et al., 2006) and non-clinical populations (Alderson-Day et al., 2019; Paulik et al., 2007, 2008). Still, intentional behavioral inhibition in hallucinations has been less frequently explored. The Go/NoGo task is a well-established experimental paradigm where participants are required to respond promptly to frequent "Go" stimuli while refraining from responding to infrequent "NoGo" stimuli (Gomez et al., 2007). Inhibitory deficits investigated with the Go/NoGo paradigm have been found in SSD patients (Ertekin et al., 2017; Sun et al., 2021; Thakkar, 2012; L. Wright et al., 2014), but only a few studies compared hallucinating and non-hallucinating patients (Sun et al., 2021). Despite several existing studies utilising Go/NoGo tasks, most have concentrated on the visual modality (Sun et al., 2021), with only a few addressing the auditory modality (Weisbrod et al., 2000). Thus, more research is needed to explore different paradigms further to measure inhibitory processes and their interconnections with other processes considered the hallmark of perceptual anomalies.

3.3. Towards integration

Despite abundant empirical findings in hallucination research, the underlying mechanisms of different hallucinatory experiences remain unclear. The lack of integration across theoretical accounts and empirical studies may contribute to this uncertainty (Gawęda et al., 2024). Integrating different theoretical models into empirical verification could help to identify unifying principles and, ultimately, enhance understanding of basic human perceptual processes and contribute to developing new interventions. To date, no single factor has been determined to sufficiently account for the presence of hallucinations. Instead, it has been proposed that the interplay between multiple processes could underlie the emergence of perceptual anomalies (Toh et al., 2022). Recent cognitive models emphasize that combining different cognitive processes may underlie perceptual anomalies (Bell et al., 2024; Gawęda et al., 2024). However, it is still unclear whether similar mechanisms underlie perceptual anomalies in both clinical and nonclinical contexts.

In their review, Waters et al. (2012) proposed a model suggesting that a joint interaction between source monitoring (Brookwell et al., 2013), top-down processes (Powers et al., 2016), and inhibitory processes (Waters et al., 2006) may lead to the formation of hallucinations. The model of Waters et al. (2012) assumes that perceptual anomalies may arise from hyperactivation in auditory cortex networks, triggering aberrant signals in language-related areas. Environmental and emotional factors can contribute to this abnormal activation, leading to hyper salient auditory information that surpasses perceptual thresholds. This may cause source-monitoring difficulties, where internal material (like inner speech or intrusive memories) is misperceived as external. Top-down processes, such as prior experiences, could shape the form and content of AH. Deficits in inhibition mechanisms allow these signals to persist, while expectations and hypervigilance further increase the likelihood of their recurrence.

To date, only two studies have comprehensively tested the model. One recent study (Moseley et al., 2021) examined the roles of source memory, dichotic listening, backward digit span, and auditory signal detection in a community sample, finding that only the signal detection task significantly predicted HLEs. Another investigation (Moseley et al., 2022) compared patients with AHs to a control group and healthy voice hearers to healthy controls. Results indicated that patients with AHs performed worse on signal detection, dichotic listening, and memory-inhibition tasks while showing intact source-monitoring performance. In contrast, healthy voice hearers exhibited unusual patterns only in signal detection. These inconsistencies underscore the need for further research that integrates diverse paradigms on populations with different characteristics of perceptual experiences.

3.4. Other gaps in knowledge

Despite theoretical accounts suggesting similar mechanisms underlying the continuum of perceptual anomalies, there remains limited empirical verification to support these claims (Johns et al., 2014). The variety of phenomenological characteristics of perceptual anomalies brings many challenges in this field of research (Moritz et al., 2024). Most studies implement the approach of categorizing individuals based on pre-determined criteria (e.g., threshold in questionnaire, etc.). Although this approach is useful to search for differences between the extremities on the continuum, it lacks the possibility to compare similarities and differences in mechanisms between specific perceptual anomalies. Moreover, there is a need to design more contextually embedded procedures for the type of perceptual anomalies studied (e.g., stimuli that resemble specific types of HLEs, such as hearing a phone ring). Additionally, we need to identify predictors that could be the contextual "triggers" for the emergence of perceptual anomalies. For example, previous research has indicated that certain aspects of smartphone usage can predict the likelihood of experiencing PPS (Rothberg et al., 2010; Tanis et al., 2015). Thus, investigating perceptual anomalies more separately with an emphasis on the contextual factors and characteristics of those experiences is highly important to verify the continuum hypothesis further.

Alongside the significance of phenomenological characteristics and cognitive factors, the interpretations of perceptual experiences have emerged as one of the primary focuses of contemporary cognitive-behavioral interventions aimed at treating distressing hallucinations (Kingdon & Turkington, 2022; Pontillo et al., 2016). Maladaptive metacognitive beliefs, such as the need to control thoughts or viewing them as uncontrollable and dangerous, have been studied in the context of perceptual anomalies (Varese & Bentall, 2011). However, current tools to measure maladaptive beliefs do not directly pertain to perceptual processes (e.g., Cartwright-Hatton & Wells, 1997; Wells & Cartwright-Hatton, 2004). To our knowledge, no tools currently exist to systematically assess different sets of beliefs about perception. Additionally, there are no studies linking beliefs about perception to perceptual anomalies associated with schizophrenia spectrum disorders.

Moreover, self-disturbances (disruptions in one's sense of self) have recently been identified as potential core markers of schizophrenia (Nelson, Parnas, et al., 2014; Nelson & Raballo, 2015; Parnas, 2012; Parnas et al., 2003; Parnas & Henriksen, 2014), with evidence suggesting a connection with perceptual anomalies (Nelson, Parnas, et al., 2014; Nelson & Raballo, 2015; Raballo, 2017; Wright et al., 2020) and cognitive processes such as source monitoring (Nelson et al., 2020; Nelson, Whitford, et al., 2014). In addition to previously mentioned factors, other aspects such as psychopathology (e.g., depression, anxiety) have been extensively investigated in relation to perceptual anomalies or in connection to general functioning (de Leede-Smith & Barkus, 2013).

Despite numerous factors being linked to perceptual anomalies, there is still a lack of comprehensive studies that integrate and compare the various correlates across the continuum.

3.5. The aims of the dissertation

The presented thesis comprises a series of studies designed to systematically explore the correlates of perceptual anomalies in clinical and non-clinical populations to investigate the hallucination continuum hypothesis further. We used experimental designs and self-report questionnaires to examine the role of cognitive processes - source monitoring, top-down processes, and inhibitory processes in the emergence of perceptual anomalies. Moreover, other factors have been explored such as beliefs about perception, psychopathology, self-disturbances, and social functioning. Thus, we formulated the following main research questions:

Research Question 1: Are there similarities between Phantom Phone Signals (PPS) and other types of hallucinatory-like experiences (HLEs) in top-down processing, beliefs about perception, general psychopathology, attentional control, and smartphone dependence among the sample from the general population?

Building on a previous preliminary study (Gawęda & Moritz, 2021), we hypothesized (**H1**) that false perception errors in tasks contextually related to PPS would be linked to perceptual anomalies. Additionally, we hypothesized (**H2**) that false perceptions would increase as cognitive expectancy increases (stronger priors). Based on earlier findings, we proposed (**H3**) that perceptual anomalies would be associated with maladaptive beliefs about perception, attentional control, general psychopathology as well as smartphone dependence. Given the gaps in research on comparisons between different types of HLEs, the hypotheses are exploratory, and therefore, no specific directional hypotheses were proposed.

Research Question 2: Are the deficits in cognitive processes i.e., source monitoring, top-down processes, and inhibitory control connected to auditory hallucinations in the sample of patients diagnosed with SSD?

We hypothesized (**H4**) that the more severe the AHs the more auditory false perceptions, source monitoring and inhibitory errors would be present. Moreover, for exploratory purposes and based on previous studies (Gawęda et al., 2024; Gawęda & Moritz, 2021; Sun et al., 2021), we anticipated that performance deficits would be linked to other psychopathological symptoms of SSD.

Research Question 3: Are there interconnections between the three cognitive processes: source monitoring, top-down processes, and inhibitory control in the sample of patients diagnosed with SSD?

Based on previous theoretical models we hypothesized (**H5**) that a greater tendency to produce false perceptions in the experimental task would be positively correlated with an increased number of source monitoring errors as well as an increased number of inhibitory errors.

Research Question 4: Are similar cognitive processes - source monitoring, top-down processes, and inhibitory control underlie perceptual anomalies in the clinical and non-clinical populations?
We hypothesized that (**H6**) group with clinical hallucinations and (**H7**) group with frequent HLEs in the non-clinical sample would commit more auditory false perceptions, source monitoring and inhibitory errors in the experimental tasks in comparison to the healthy controls and low HLEs group. Additionally, we measured expectancy-dependent top-down errors, hypothesizing that higher expectancy levels would result in more errors, as demonstrated in a previous study (Gawęda & Moritz, 2021). We anticipated that false perceptions would increase gradually, with the effect being most pronounced in clinical samples, especially among hallucinating patients compared to non-hallucinating patients (**H8**) and in high HLEs compared to low HLEs (**H9**).
Research Question 5: Are there associations between cognitive processes (top-down processes, source monitoring, inhibitory processes) and perceptual anomalies self-disturbances as well as social functioning on the entire continuum of perceptual experiences?
Based on the assumptions of the continuum approach we hypothesized (**H10**) that the frequency of perceptual anomalies will be positively associated with the number of false perceptions, source monitoring and inhibitory errors along the entire continuum of perceptual experiences (i.e., all the research groups). Additionally, (**H11**) we hypothesized that self-disturbances and social functioning are related to errors in the three cognitive tasks.

4. Methods and Results

Below is a summary of each publication. However, the methods, results, and discussions are presented in greater detail in the individual publications that constitute the series of studies in this dissertation.

Publication 1: Aleksandrowicz, A., Kowalski, J., & Gawęda, Ł. (2023). Phantom phone signals and other hallucinatory-like experiences: Investigation of similarities and differences. *Psychiatry Research*, *319*, 114964. https://doi.org/10.1016/j.psychres.2022.114964 (IF=11.3)

A significant part of theoretical accounts assumes shared mechanisms in different types of perceptual anomalies. However, so far, most studies have not compared potential mechanisms between various types of HLEs. Specifically, PPS have been studied as an isolated experience. Thus, the first study in this cycle aimed to investigate the similarities and differences between PPS and different types of HLEs in a community sample. We tested various predictors of these experiences, like general psychopathology, smartphone dependence, attentional control, and beliefs about perception, as well as the role of top-down processes to answer our research question.
Methods: The final sample consisted of n = 236 participants (aged 18-69) non-probabilistically recruited via social media platforms. The experimental procedure, based on the false perception task

(Gawęda & Moritz, 2021), featured two expectancy conditions: low (no visual cue) and high (visual cue with auditory stimuli). Auditory stimuli included notification sounds from social media platforms like Facebook/Meta Messenger and WhatsApp, along with background noise. The task lasted 4-6 minutes and comprised 40 trials, with 60% audible (24 trials) and 40% non-audible (16 trials) stimuli. Participants indicated whether they heard a sound by pressing a keyboard button. False positives (responses indicating they heard non-audible stimuli—served as an indicator of their tendency for false perceptions). Then, participants completed surveys on PPS (Tanis et al., 2015), questionnaires measuring HLEs (Multi-Modality Unusual Sensory Experiences Questionnaire - MUSEQ), general psychopathology (Symptom Checklist-27- plus - SCL-27-plus), smartphone dependence (Mobile Phone Problematic Use Scale - MPPUS-10), attentional control (Attentional Control Scale - ACS) and beliefs about perception (Beliefs about Perception Questionnaire - BaPQ).

Results: The correlation analysis indicated no significant relationship between the false perceptions in the experimental task and any form of self-reported PPS. When comparing the experimental task with the self-reported measures of HLEs (MUSEQ), no correlations remained significant after the Holm correction for multiple comparisons. Moreover, we found no differences between high and low expectancy conditions (p=0.061). Two regressions were created to model proneness to PPS and other HLEs (MUSEQ). Chosen predictors were three subscales concerning beliefs about perception (BaPQ): top-down influence (TDI), blurred boundaries (BB), normalization (N), general psychopathology (SCL-27-plus), attentional control (ACS), and smartphone dependence (MPPUS-10). Results showed that the most important predictors of the MUSEQ score were the BaPQ TDI and the SCL-27-plus. Collectively, these variables accounted for 55.3% of the variance in the MUSEQ score. The most important predictor of PPS was MPPUS and BAPQ TDI. Together, all the variables explained 24.7% of the variation in PPS.

Discussion: Results showed no relationship between experimentally measured top-down processes and PPS. For other types of HLEs, the correlations did not survive the correction for multiple comparisons. On the other hand, regression analyses showed that the only shared predictors for both PPS and other HLEs were age and top-down beliefs about perception. Smartphone dependency proved to be a stronger predictor of PPS than other measured variables, whereas for HLEs, general psychopathology was the strongest predictor. Surprisingly, general psychopathology was not a significant predictor of PPS. Current results suggest that PPS and HLEs may have independent underlying factors despite sharing some mechanisms.

Publication 2: Aleksandrowicz, A., Kowalski, J., Stefaniak, I., Elert, K., & Gawęda, Ł. (2023). Cognitive correlates of auditory hallucinations in schizophrenia spectrum disorders. *Psychiatry research*, *327*, 115372. https://doi.org/10.1016/j.psychres.2023.115372 (IF=11.3)

The first study examined correlates of perceptual anomalies in the non-clinical population, while the current study focused on clinical hallucinations in patients with SSD. Waters et al. (2012) model emphasizes source monitoring, top-down influence, and inhibitory processes, but the contribution of these processes to auditory hallucinations and their interconnections remains unclear. To explore this, three experimental paradigms were conducted with SSD patients. It was hypothesized that more severe hallucinations would be linked to greater deficits in all tasks, including increased false perceptions, source misattributions, and errors in inhibitory control.

Methods: Ninety inpatients and outpatients diagnosed with SSD (aged 18–45 years) participated in the study (as part of the PRELUDIUM BIS project 2019/35/O/HS6/02982). The severity of the symptoms was assessed with semi structured interviews: Positive and Negative Syndrome Scale (PANSS), and the Hallucinations subscale from the Psychotic Symptom Rating Scales (PSYRATS). Then, three experimental tasks were performed: False Perception Task (FPT) - measuring top-down processes; Action Memory Task (AMT) - measuring source monitoring; and Go/NoGo Task - inhibitory control. Then, the correlations between psychopathology measured by PANSS and PSYRATS, demographic characteristics and experimental tasks were examined.

Results: The second study found no significant correlations between AHs and the primary outcome variables. However, AHs measured by PSYRATS were positively linked to response bias on the FPT, suggesting that patients with more severe AHs required more evidence to confirm auditory signals. Source monitoring errors were positively correlated with response bias and negatively with Hits on the FPT, but no other task parameters were significantly related. Psychopathological symptoms showed that PANSS total scores were positively correlated with source monitoring bias and false alarms on the Go/NoGo task. Moreover, disorganized symptoms were linked to source monitoring errors and false alarms, and negative symptoms were associated with hits and false alarms, though not all correlations did not hold after correcting for multiple comparisons.

Discussion: The results showed mixed findings, conflicting with contemporary cognitive models of AHs. While links were found between AHs and top-down processes, as well as between top-down and source monitoring processes, these relationships were in the opposite direction expected—the more severe the AHs, the more conservative the patients were in reporting signals. Additionally, source monitoring errors and inhibitory control were related to overall SSD symptom severity and disorganized symptoms, with negative symptoms linked to inhibitory control. However, only source monitoring results survived correction for multiple comparisons, suggesting that source monitoring deficits may be more related to general SSD symptoms than to AH severity.

Publication 3: Aleksandrowicz, A., Kowalski, J., Moritz, S., Stefaniak, I., & Gawęda, Ł. (2024). A cognitive model of perceptual anomalies: The role of source monitoring, top-down influence and inhibitory control processes for hallucinations in schizophrenia spectrum disorders and hallucinatory-like experiences in the general population. https://doi.org/10.31234/osf.io/ercjv (preprint)

The final publication tested the theoretical model of perceptual anomalies by combining clinical and non-clinical perceptual anomalies into a unified model of the hallucination continuum. It included two studies: one involving patients with SSD (split into those with current auditory hallucinations and those without) and another with a general population sample categorized by the severity of hallucinatory-like experiences (high and low HLEs).

Methods: Study I included 46 patients with SSD experiencing current auditory hallucinations (SH group), 43 patients without current hallucinations (SN group), and 46 healthy controls (HC) from the PRELUDIUM BIS project (2019/35/O/HS6/02982). Study II recruited participants from the general population through an online screening of 3,141 individuals using the Revised Hallucination Scale (RHS). Then, the top and bottom 5-10% of scorers were selected based on inclusion criteria. Self-disturbances were evaluated using the Examination of Anomalous Experiences (EASE) interview, and symptom severity was assessed with PANSS (only for Study I). All participants completed three cognitive tasks (AMT, FPT, Go/NoGo), questionnaires on perceptual anomalies (CAPS, MUSEQ, RHS), and social/occupational functioning (SOFAS). Between-group differences in experimental tasks were analyzed for both studies, and associations among primary measurements, HLEs, self-disturbances, and social functioning were examined for the combined sample (n=217).

Results: Both patient groups exhibited significantly more source monitoring errors and false perceptions (after accounting for response bias) than HC, with no significant differences between the SH and SN groups or between high and low HLEs. There were no significant group differences in false alarms on the Go/NoGo Task. However, when the entire sample was analyzed, perceptual anomalies were significantly related to cognitive processes, self-disturbances, and functioning. Source monitoring errors were associated with all measures of perceptual anomalies, self-disturbances, and lower social functioning. For top-down processes, false perception errors exhibited the strongest link to self-disturbances and perceptual anomalies (measured by CAPS). Inhibitory processes showed only weak correlations with perceptual anomalies and social functioning, which did not survive correction for multiple comparisons.

Discussion: These findings enhance our understanding of the mechanisms behind perceptual anomalies along the hallucination continuum. To our knowledge this research was the first to directly compare clinical samples with current auditory hallucinations to non-hallucinating groups, as well as high and low HLEs, using the same experimental design. Notably, we found significant associations between perceptual anomalies and cognitive processes across the entire sample, suggesting a need to view the continuum holistically rather than categorically. The strongest correlations were observed between source monitoring errors and social functioning as well as between top-down processes, self-disturbances, and perceptual anomalies (measured by CAPS). These results highlight the complexities of hallucination research and the need to consider additional factors in future studies.

5. General Discussion

The collection of studies in this research cycle sought to verify further the continuities and discontinuities of the perceptual anomalies in clinical and non-clinical contexts.

Firstly, we began our series of studies by addressing the existing research gaps in the part of the continuum that is usually connected to non-clinical hallucinatory experiences. The main goal of the first publication (Aleksandrowicz et al., 2023) was to investigate the similarities and differences between phantom phone signals and other HLEs. To our knowledge, this was the first study to experimentally investigate false perceptions contextually connected to PPS and to directly compare PPS with other types of HLEs. Consequently, the study was of an exploratory nature. The first main aim was to investigate the role of top-down processes in both PPS and other HLEs in the novel experiment that was designed to contextually reproduce the PPS experiences, where familiar smartphone notification sounds (WhatsApp and Messenger) were used to examine (**H1**) the associations between top-down processes and perceptual anomalies. Results demonstrated a weak association between other types of HLEs and false perception errors that did not survive the correction for multiple comparisons. The correlations with PPS were not significant. Moreover, based on prior research with schizophrenia patients (Gawęda & Moritz, 2021), we expected (**H2**) false perceptions to increase with higher expectancy, but this effect was not confirmed. This lack of significant effect may be due to the online, brief nature of the task or the fact that participants were from the general population, unlike previous studies that selected individuals prone to hallucinations or on the schizophrenia spectrum (Moseley et al., 2022; Powers et al., 2017; Vercammen & Aleman, 2010). Moreover, the study may have lacked sufficient power to detect smaller effects. Future research could address this using a multisite approach (Moseley et al., 2021) to gather larger samples from these difficult populations.

False perceptions are complex phenomena and can be influenced by contextual and intrapersonal factors. Previous findings suggest that PPS have been predominantly linked to the intensity of smartphone usage (Tanis et al., 2015). Thus, future studies could compare groups with high and low levels of smartphone addiction. Additionally, providing the same sound of the notification for all participants might not significantly alter the balance between sensory input and expectations, highlighting the challenge of achieving adequate ecological validity in experimental studies conducted under laboratory conditions (Holleman et al., 2020). Thus, further studies are needed that focus more on contextual-qualitative distinction. In the current study, we focused on PPS due to their prior standalone research and documented connections to contextual factors. (Sauer et al., 2015). Furthermore, the task's design may not have been adequately connected to other HLEs, potentially accounting for the lack of significant results. For other types of HLEs, more contextually relevant stimuli might be necessary to capture the most frequently reported experiences, such as music or hearing footsteps.

Additionally, we explored the similarities and differences between PPS and other types of HLEs in beliefs about perception, general psychopathology, attentional control and smartphone dependence (**H3**). Smartphone dependency was a stronger predictor of PPS than other variables measured, while general psychopathology emerged as the strongest predictor for HLEs. Conversely, the subscale assessing top-down influence on perception and age emerged as significant predictors for both PPS and other HLEs. These results indicate that beliefs about top-down influence on perception are related to both PPS and other HLEs, which is in line with previous research investigating the role of perceptual priors in the general populations (de Boer et al., 2019; Moseley et al., 2021) as well as studies showing the relationship between metacognitive beliefs and non-clinical perceptual anomalies (Varese & Bentall, 2011). However, as this is the first study to directly compare PPS and other HLEs, further investigation is necessary. Future research should examine the frequency and content of HLEs to determine whether their mechanisms align or differ, contributing to a better understanding of the continuum of perceptual anomalies.

The first study explored both continuities and discontinuities in different types of HLEs. In contrast, the second study (Aleksandrowicz et al., 2023) focused on the correlates of clinical auditory hallucinations, which are assumed to represent the extreme end of the continuum (Baumeister et al., 2017). The primary objective of the second study in the cycle was to empirically verify the existing theoretical models (Waters et al., 2012), stating that deficits in source monitoring, top-down processing, and inhibitory processes could account for the emergence of hallucinations (**H4**). Contrary to our assumptions, we found no link between AHs severity and source monitoring and inhibitory errors. Moreover, we found a positive association between AHs and response bias in the task measuring top-down influence, indicating that patients with more severe AHs were less likely to report the presence of the signal in noise. At the same time, results exhibited that source monitoring errors and inhibitory errors correlated with negative, disorganized symptoms as well as total symptom severity of schizophrenia, which supports earlier findings of executive function impairments in patients with SSD (Thai et al., 2019) as well as account connecting source monitoring errors to SSD (Gawęda et al., 2012; Moritz et al., 2003). Another aim was (**H5**) to explore the interconnections between top-down influence, source monitoring and inhibitory processes based on the assumption that perceptual anomalies result from the combined effects of multiple factors rather than a single process (Waters et al., 2012). Results revealed a negative association between source monitoring errors and correct responses in the task measuring top-down processes. The correlation between source monitoring errors and response bias was opposite than expected - as the number of source monitoring errors increased, more evidence was required to confirm the presence of an auditory signal in the false perception task. These contradictory results could be discussed in the concept stating that perhaps patients with frequent AHs are more vigilant to auditory cues, scanning the environment for auditory signals, which could paradoxically make them more accurate in tasks where the discrimination between a signal and noise is required (Vercammen et al., 2008). Still, it is worth noting that those theoretical accounts regarding the role of top-down processing have been more frequently studied on non-clinical samples, with only a few studies that compare patients with AHs to non-hallucinating patients, where mixed results have been presented (Kowalski et al., 2014.; Vercammen et al., 2008). To our knowledge, this was the first study to verify the interconnection among the three investigated processes. Further verification of the model is needed to draw more definitive conclusions.

While the first and second articles examined the mechanisms of perceptual anomalies in isolation, the third article integrates clinical and non-clinical samples to investigate the continuum of perceptual experiences. We aimed to empirically test the theoretical claim that clinical and non-clinical hallucinations share common mechanisms. Specifically, we hypothesized that (**H6**) patients with current AHs and (**H7**) a group with frequent HLEs would commit more auditory false perceptions, source monitoring and inhibitory errors in the experimental tasks compared to the healthy controls and low HLEs group. Results revealed that both patient groups committed significantly more source monitoring errors and false perceptions (but only after accounting for response bias) than HC. However, there were no differences between hallucinating and non-hallucinating patients with SSD. We also found no group differences between high HLEs and low HLEs in any of the primary outcomes. The lack of group differences in the HLEs groups could pertain to the severity of perceptual anomalies in the high HLEs group - most participants reported experiences such as PPS, single words (e.g., hearing their name) or other brief experiences with relatively low frequency. Perhaps less intense experience may be weakly related to the measured cognitive processes or less prominent experiences limited the variability in the data, constituting a floor-effect. Future studies may benefit from assessing whether more severe and frequent perceptual experiences are more closely linked to researched cognitive mechanisms. Perhaps our experimental procedures that tried to elicit perceptual anomalies lack ecological validity, as they lack contextual factors exacerbating such experiences, like interpersonal stress. Notably, the non-clinical sample was selected based on specific inclusion criteria and screened for current mental disorders to exclude individuals with clinically relevant problems. For that reason, many participants with higher frequency of HLEs experiences were not qualified for the study. Some previous studies on samples from general population did not report screening with structured interviews for mental disorders (de Boer et al., 2019; Laloyaux et al., 2022; Moseley et al., 2021), despite evidence that perceptual anomalies are transdiagnostic, occurring in various mental disorders (Waters, Blom, et al., 2018; Waters & Fernyhough, 2017). This indicates that previous studies with high-HLEs samples may be confounded by presence of individuals with disorders in which perceptual anomalies commonly occur.

Moreover, we expected that the higher the expectancy, the more false perceptions would be present, especially among hallucinating patients compared to non-hallucinating and HC (**H8**) and in high HLEs compared with low HLEs (**H9**). We found a gradual increase in both patient groups, yet there was no significant interaction between groups and conditions. Non-clinical samples showed a V-shaped effect, with more false perception errors in the low expectancy condition than in the medium, and similar errors in the high expectancy condition, though this effect was not significant. The results for patients with SSD are consistent with previous preliminary findings showing the gradual impact of cognitive expectancy (Gawęda & Moritz, 2021). Yet, no effect of cognitive expectancy for non-clinical groups indicates discontinuities between clinical and non-clinical samples.

Additionally, we assumed (**H10**) that perceptual anomalies would be connected to impairments in source monitoring, top-down and inhibitory processes across the entire continuum of perceptual experiences (combined clinical and non-clinical samples). As hypothesized, there were significant relationships between perceptual anomalies and all the cognitive processes. Interestingly, the strongest associations between cognitive processes and perceptual anomalies were found for parts of the CAPS scale (yet results for inhibitory processes did not survive the correction for multiple comparisons) that measured various perceptual experiences (e.g., thought echo, hearing thoughts out loud or sensory flooding - feeling overwhelmed by sensory information). The results suggest that broader perceptual experiences, such as those linked to thought processes, may be more closely tied to cognitive processes. These findings show continuity across a wide spectrum of perceptual experiences, highlighting that a connection between cognitive processes and the frequency of these anomalies might not be restricted to clinical or non-clinical categories. Moreover, we hypothesized (**H11**) that self-disturbances and social functioning will be connected to impairments in the three cognitive tasks. We found that self-disturbances were connected to more false perceptions and source monitoring errors. Moreover, the lower social functioning the more source monitoring errors were committed. These findings indicate a complex interaction between perceptual experiences, cognitive processes, self-disturbances, and social functioning. Still, the correlates included in the current dissertation represent only some of the factors considered in perceptual anomalies research, including psychopathology, cognitive processes, neural mechanisms or sociocultural context (Bell et al., 2024; Powers et al., 2020; Toh et al., 2022). More comprehensive studies with advanced designs are needed to explain the complex nature of perceptual anomalies.

Limitations

The presented studies have several limitations. Firstly, as presented in the course of the thesis, perceptual anomalies consist of diverse experiences that differ in content, severity and frequency, making it challenging to establish clear definitions of these experiences in clinical and non-clinical contexts (Moritz et al., 2024). At the same time, searching for mechanisms has been a great challenge over the decades of research. The diverse manifestations of hallucinatory experiences among participants in the current studies pose challenges in distinguishing between their different categories. Our participants had relatively low symptom severity, including hallucinations, suggesting that results could vary significantly with differences in overall symptom severity among samples. Thus, future studies should further explore the mechanisms of perceptual anomalies with a greater focus on comparisons between different phenomenological characteristics.

In addition to phenomenological challenges in perceptual anomalies research, their mechanisms have been studied by implementing various experimental paradigms, making it difficult to generalize results and compare different studies. Further replications of experimental paradigms across diverse samples and comparisons to other experimental approaches are essential. Another limitation pertains to the challenges of reproducing real-life scenarios in laboratory conditions. Although in the first study, we designed a novel task that was supposed to mimic real-life experiences, the phone notifications were not displayed on participants' smartphones and implemented unified notification sound, which could take out from the usual patterns of usage that differ in each individual (some have notifications on silent mode, some on vibrations and some with sound) and interfere with their conditioned default notification display. Similarly, other tasks implemented in the current study posed a challenge to imitate a real-life situation when actual perceptual anomalies occur. Furthermore, even specific background noise may have influenced the results, as a recent study indicated that participants experienced more false perceptions of speech-related noise than speech-unrelated noise (Laloyaux et al., 2022).

Moreover, the study did not account for participants' current emotional state, which could influence results. Previous research showed that negative emotions and reduced cognitive resources increase false perceptions in signal detection tasks (Laloyaux et al., 2019). Similarly, high caffeine intake and stressful life events have been linked to more false perception errors (Crowe et al., 2011). Thus, current emotional states, arousal, and stressful events could be considered in future investigations.

Future research should take into account emotional states, cognitive resources as well as additional cognitive processes, such as attentional control, intentional inhibition, working memory, and language functions (Bell et al., 2024). It is possible that distinct perceptual features are linked to specific cognitive markers, indicating that we should look for mechanisms connected to specific characteristics of perceptual anomalies. Furthermore, the current study design does not permit the identification of causal relationships. Therefore, future studies should employ longitudinal designs and incorporate a broader range of methods to better capture the temporal variability of perceptual experiences.

Summary

In summary, the presented series of studies provided new insights into the correlates of perceptual anomalies both in clinical and non-clinical populations. We demonstrated that there are not only similarities between different types of non-clinical perceptual anomalies (phantom phone signals and other types of HLEs) but also differences in their predictors. Furthermore, in contrast to previous theoretical accounts, we found no direct confirmation of Waters et al. (2012) cognitive model of hallucinations. Our results indicated that cognitive processes such as internal source monitoring might be more connected to general symptoms of psychosis rather than specific to hallucinations. When comparing hallucinating patients to non-hallucinating patients and HC, we observed a similar pattern across all groups, indicating a lack of specificity in internal source monitoring, top-down processing, and inhibitory control related to hallucinations. Additionally, no differences were found between high and low HLEs groups in any of these cognitive processes. On the other hand, when the entire sample was included, we found that more frequent perceptual anomalies were associated with greater deficits in cognitive processes, particularly in source monitoring and top-down processes. These findings suggest the need for a holistic rather than a categorical view of the continuum. The presented cycle provides the first comprehensive empirical verification of different aspects of the perceptual anomalies' continuum, yielding new insights for future research and the development of therapeutic programs. Addressing the impact of cognitive processes (e.g., cognitive expectancy, source monitoring biases) or beliefs about perception could be an important direction for developing new therapeutic techniques (e.g., providing psychoeducation on cognitive biases or techniques based on reframing maladaptive beliefs about perception) to work with patients experiencing distressing or disruptive perceptual anomalies.

6. References

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Psychiatry Research 319 (2023) 114964

Contents lists available at ScienceDirect

Psychiatry Research

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

Phantom phone signals and other hallucinatory-like experiences: Investigation of similarities and differences

Adrianna Aleksandrowicz *, Joachim Kowalski, Łukasz Gawęda

Experimental Psychopathology Lab, Institute of Psychology, Polish Academy of Sciences, Warsaw, Poland

ARTICLE INFO

Keywords:
Phantom vibration
Perceptual abnormalities
False perception task
Top-down-processes
Survey

ABSTRACT

Phantom Phone Signals (PPS) and other hallucinatory-like experiences (HLEs) are perceptual anomalies that are commonly reported in the general population. Both phenomena concern the same sensory modality, but PPS are restricted to smartphone use. The current study aimed to assess similarities and differences between these types of anomalies in relation to general psychopathology, metacognitive beliefs about perception, smartphone dependence, and susceptibility to top-down influences on perception. We analyzed data from a Polish community sample ($N = 236$, aged 18–69). We used questions pertaining to PPS, a questionnaire pertaining to HLEs (Multi-Modality Unusual Sensory Experiences Questionnaire), and other variables of interest (Symptom Checklist-27-plus, Mobile Phone Problematic Use Scale, and the Beliefs about Perception Questionnaire). Additionally, a false-perception task manipulating cognitive expectancy (i.e., a visual cue associated with auditory stimuli vs. no visual cue) was devised to measure top-down influences on perception. Regression analyses showed that only top-down beliefs about perception predicted both PPS and HLEs. Smartphone dependency proved to be a stronger predictor of PPS than other measured variables, whereas for HLEs, general psychopathology was the strongest predictor. Current results suggest that despite sharing some mechanisms, PPS and HLEs may have independent underlying factors.

1. Introduction

Hallucinations are a key symptom in the diagnosis of schizophrenia spectrum disorders. It is estimated that hallucinations occur in approximately 80% of patients with schizophrenia spectrum disorders, with the most common being auditory hallucinations (Toh et al., 2022). According to the continuum hypothesis, hallucinations in the clinical context are considered as an extreme manifestation of phenomena that range from vivid daydreams, through infrequent experiences of different sounds (e.g., mistakenly hearing one's name being called) to full-blown hallucinations (e.g., hearing distressing voices). Yet, a significant body of work has shown that hallucinatory-like experiences (HLEs), which lie on the hallucination continuum, are frequently reported in the non-clinical population (Linszen et al., 2022). It has been suggested that auditory hallucinations occur in 13.2% of the general population (Beavan et al., 2011). These data suggest that HLEs and hallucinations also occur outside the clinical context. Investigation of HLEs in the general population is important, as it helps us better understand the mechanisms underlying hallucinations and other perceptual anomalies (Barkus et al., 2007; Daalman et al., 2010).

Recently, in addition to studies on general HLEs, Phantom Phone Signals (PPS) are being increasingly studied as perceptual phenomena (Drouin et al., 2012; Horga & Abi-Dargham, 2020; Lin et al., 2013a,b, 2020; Pisano et al., 2019; Tanis et al., 2015). PPS are perceptual anomalies wherein feedback from phones is experienced without having occurred, such as the sensation of a phone ringing, an incoming message, or a notification coming from various applications. PPS are experienced in auditory (as a ringing phone), visual (a blinking notification displayed on a smartphone screen), and tactile (phantom vibration) modalities (Tanis et al., 2015). It is estimated that between 27.4% and 89% of people from the general population experience PPS (Deb, 2015; Pisano et al., 2021). This relatively high prevalence suggests that PPS are common experiences and may be associated with the growing usage of smartphones (Pisano et al., 2021). Indeed, it is estimated that about 3.5 billion people worldwide use smartphones (O'Dea, 2020). In 2018 in Poland, almost 80% of the population used smartphones (Mobirank, 2020), and 74.8% of all cell-phone users did so on a daily basis. Importantly, cellphone addiction is rising alongside smartphone usage

* Corresponding author at: Institute of Psychology, Polish Academy of Sciences, Jaracza 1, 00-378, Warsaw, Poland.
E-mail address: aaleksandrowicz@psych.pan.pl (A. Aleksandrowicz).

https://doi.org/10.1016/j.psychres.2022.114964
Received 11 July 2022; Received in revised form 25 October 2022; Accepted 17 November 2022
Available online 19 November 2022

(Olson et al., 2022). Thus, PPS and associated phenomena are becoming an important field of research.

Previous studies have shown that some characteristics of smartphone usage are predictors of experiencing PPS (Rothberg et al., 2010; Subba, 2013; Tanis et al., 2015). A study conducted by Al-Ani et al. (2009) showed that PPS experiences were very common among participants who rated themselves as "mobile addicted." Moreover, another study also provided evidence of a significant relationship between PPS and excessive smartphone usage, smartphone addiction, and phone importance (Tanis et al., 2015). Still, some studies found that characteristics of smartphone usage are not related to PPS (Catchings et al., 2010). It should be noted that conclusions from studies that link PPS to characteristics of smartphone usage are limited by the low number of studies. For this reason, further studies on the mechanisms of PPS are needed.

With regard to the mechanisms of PPS, some studies reported that contextual factors, such as expecting a call or being in a noisy environment, are important in reinforcing the experience of PPS (Sauer et al., 2015). For instance, being in a workplace where smartphones are essential for communicating with co-workers has been shown to reinforce the occurrence of PPS. A study on medical students showed a substantial change in experiences of PPS during a medical internship. For instance, at baseline, 78.1% students reported phantom vibrations and 27.4% reported phantom ringing. At follow-up, these rates increased to 95.9% and 87.7% respectively (Lin et al., 2013a, 2013b). Although the evidence indicates a high prevalence of PPS among medical students, more research on the general population is still needed (Pisano et al., 2021).

Importantly, although PPS have been found to correlate with high stress levels, anxiety, and depressive symptoms (Lin et al., 2013a,b, 2020), few studies have focused on the relationships between PPS and psychopathology (Pisano et al., 2021). One study among adolescents found a relationship between experiencing PPS and both emotional problems and temper tantrums (Pisano et al., 2019). At the same time, the association between a wide range of HLEs and psychopathology is well documented (Allen et al., 2005; Gaweda et al., 2012; Johns, 2005). Additionally, the cognitive mechanisms of HLEs have been investigated in a rich line of research. For instance, attentional processes, cognitive control (Conn & Posey, 2000; Hugdahl et al., 2013), as well as different cognitive biases have been found to be important factors related to HLEs. With regard to PPS, there is much less research on cognitive mechanisms associated with this phenomenon.

One of the leading theoretical accounts suggests that perceptual anomalies are the result of an imbalance between top-down processes (i.e., priors or cognitive expectancy) and bottom-up processes. The role of top-down processes in shaping percepts is particularly emphasized in situations of perceptual uncertainty, where cognitive expectancy can influence the final percept (Corlett et al., 2019; Horga & Abi-Dargham, 2020; Powers et al., 2016). Cognitive expectancy may be considered as a prior that impacts perception (Corlett et al., 2019). It has been shown that priors have a stronger impact on perception in people who hallucinate than those without hallucinations (Powers et al., 2016). Thus, this suggests that cognitive expectancy (i.e., priors) may have an important impact on perception. Similarly, regarding PPS, it has been proposed that these experiences may emerge from the anticipation of phone signals through expectations (Rothberg et al., 2010). For instance, PPS may emerge in the context of a belief that the phone should ring because one is waiting on an important phone call. A limited number of studies have investigated this account in the context of semantic expectancy and its relationship to HLEs (Vercammen & Aleman, 2010). More recently, a study by Gawęda & Moritz (2021) suggested that audiovisual integration might play an essential role in the formation of false percepts in patients with schizophrenia. Participants performed a task in which they were asked to detect a target word in a noisy background (the word was audible in 60% of cases and absent in 40%). Conditions consisted of three levels of expectancy (1. low – no cue prior to the stimulus; 2. medium – semantic priming; 3. high – semantic priming accompanied by a video of a man mouthing the word). The results indicated that higher expectancy significantly increased the likelihood of false auditory perceptions among schizophrenia patients only. This provides preliminary evidence that the visual modality might play an important role in the complex mechanisms of auditory perceptual anomalies. Nonetheless, more research on visual and auditory modalities in the context of hallucinations and the hallucination continuum is needed.

To date, PPS and other HLEs have been studied independently. A growing line of research investigates PPS as an isolated type of experience without comparison to other HLEs. Therefore, the main aim of our study was to compare PPS and other types of HLEs with general psychopathology, smartphone dependence, and attentional control to investigate their similarities and differences in the non-clinical population. Furthermore, we also considered the relationships of both PPS and HLEs with priors (i.e., top-down factors, such as knowledge and beliefs), which have been linked to perceptual anomalies (Corlett et al., 2019; Horga & Abi-Dargham, 2020; Powers et al., 2016). In our study, we conceptualized priors as meta-cognitive beliefs about perception (Gawęda et al., in preparation). We hypothesized that meta-cognitive beliefs about perception and interpretations of perceptual experiences may tentatively influence how perception operates, and conversely actual perceptual experiences may shape individuals' beliefs about perceptions. Hence, we expected that there would be a relationship between false perceptions and meta-cognitive beliefs about perception. Moreover, despite some existing research investigating the potential predictors of PPS (Drouin et al., 2012; Horga & Abi-Dargham, 2020; Lin et al., 2013a,b, 2020; Pisano et al., 2019; Tanis et al., 2015), to our knowledge, there are no studies that explore in-depth the mechanisms of this phenomenon using an experimental approach. Therefore, the objective of our study was to experimentally verify the effect of top-down processes on false auditory perceptions using a False Perception Task design (Gawęda & Moritz, 2021). Our experimental task was tailored to examine perceptual experiences that are contextually related to smartphone use (e.g., the moment of an incoming smartphone notification on the screen) with two conditions of expectancy: low (no visual cue associated with an auditory stimulus) and high (a visual cue associated with an auditory stimulus). We hypothesized that more false recognitions would occur in the high expectancy condition than in the low expectancy condition. To our knowledge, this is the first study to investigate experimentally-induced false perceptions that are contextually connected to PPS. Moreover, we aimed to investigate whether there is a relationship between experimentally-induced false perceptions in the context of social media use and PPS alongside other HLEs.

2. Methods

2.1. Materials

2.1.1. Phantom phone signals

The questions were taken from a previous study by Tanis et al. (2015): "Have you ever experienced the sensation that your cell phone was VIBRATING, while in fact it was not?'', "Have you ever experienced the sensation that your cell phone was BLINKING, while in fact it was not?'', "Have you ever experienced the sensation that your cell phone was RINGING, while in fact it was not?''. Respondents were asked to answer on a 10-point scale containing the following options: 1 (*never*), 2 (*less than once a month*), 3 (*once a month*), 4 (*2–3 times a month*), 5 (*once a week*), 6 (*2–3 times a week*), 7 (*4–6 times a week*), 8 (*daily*), 9 (*twice a day*), and 10 (*more than twice a day*).

2.1.2. Hallucinatory-like experiences

Hallucinatory-like experiences were measured using the Multi-Modality Unusual Sensory Experiences Questionnaire (MUSEQ; Mitchell et al., 2017). The MUSEQ is a 43-item self-report measure that assesses perceptual anomalies in six modalities: auditory, visual, olfactory, gustatory, bodily sensations, and sensed presence. The MUSEQ shows good reliability and construct validity and can differentiate between non-clinical and clinical populations. In the current study, the MUSEQ was adapted for the Polish language by our research group (publication in preparation) using the back-translation procedure. In the current study, an item relating to phantom phone signals ("I have heard my phone ring then found that it wasn't ringing at all") was discarded to prevent spurious associations between the results of this questionnaire and other measures that refer to PPS. Cronbach's alpha for the 42-item scale was 0.94. Additionally, the main focus of our current analysis was on the three subscales that pertain to modalities in which PPS also occur: the auditory modality, such as "I thought of a song and could almost hear it with distinct clarity", the visual modality, such as "I have looked at a patterned object, (e.g., wallpaper, curtains, 3 tiled floor) and a figure or face has emerged", and bodily sensations, such as "I have experienced the sensation that my body (or part of my body) was different in shape or size". Therefore, these subscales were summed to give a single total score for the purposes of the current study.

2.1.3. Beliefs about perception

The Beliefs about Perception Questionnaire (BaPQ; Gawęda et al., in preparation) is a questionnaire with 47 items that was designed by our research group. The BaPQ is based on the Metacognitions Questionnaire (Cartwright-Hatton & Wells, 1997). It was designed to measure attitudes and metacognitive beliefs towards perceptual experiences in greater detail and consists of seven subscales: top-down influence (TDI), blurred boundaries (BB), normalization (N), perceptual self-consciousness (SC), need to control perception (NC), lack of perceptual confidence (LC), and lack of acceptance (LA). In the current study, we excluded two questions from the BaPQ TDI subscale that referred to phantom phone signals to avoid spurious associations between the results of this questionnaire and other measures that refer to PPS: "When I am waiting on an important call, I can hear my phone ringing even from a distant place." and "I think that if I was waiting for an important call, I would be able to hear the ringing even though nobody actually called". Cronbach's alpha for the 45-item scale was 0.87. Three subscales were selected for further analyses. The first was top-down influences – this scale reflects beliefs about how cognition and mindset may influence perception. Items concern beliefs about expectancies, intensive thought processes, and priors piercing through perceptual processes and producing experiences in the absence of actual stimuli (e.g., "If I often think about something, it is easier for me to hear, see, or feel it"). The second was blurred boundaries – this scale reflects beliefs about troubles with monitoring sources of perceptual and cognitive experiences. Items concern blurred boundaries between experiences and imagination, actual memories and fantasies, and actual experiences and dreams (e.g., "Sometimes I'm not sure whether I only thought about something or if it really happened"). The third was normalization. This scale reflects beliefs that normalize variability in perceptual experiences and how perception may be dependent on individual characteristics or circumstances. Items concern how one's perception may be different from that of other people, how states (e.g., exhaustion or mood) may cause altered perception, and how senses can be unreliable (e.g., "I know that what I hear, see, or feel may be different from other people's experiences").

2.1.4. Problematic smartphone usage

The Mobile Phone Problematic Use Scale (MPPUS-27) is a comprehensive scale for assessing problematic mobile phone usage (Bianchi & Phillips, 2005). In the current study, we used a 9-item version (MPPUS-10) from a Polish validation study (Mach et al., 2020). The scale contains questions about the overuse of smartphones, such as "I feel anxious if I have not checked for messages or switched on my mobile phone for some time." Cronbach's alpha for the 9-item version of the scale was 0.84.

2.1.5. General psychopathology

The Symptom Checklist-27-plus (SCL-27-plus) is a short screening instrument for mental health symptoms such as anxiety and depression (Hardt, 2008). It contains statements such as "Feeling hopeless about the future" and "Feeling fearful" and was adapted to the Polish population (Kuncewicz et al., 2014). Cronbach's alpha for this scale was 0.91.

2.1.6. Attentional control

The Attentional Control Scale (ACS) measures the ability to focus attention, switch attention between tasks, and flexibly control thoughts through subjective measures, for example "It's very hard for me to concentrate on a difficult task when there are noises around" (Derryberry & Reed, 2002). The Polish adaptation was used here (Fajkowska & Derryberry, 2010). Cronbach's alpha for this scale was 0.88.

2.1.7. Experimental task

The study was conducted through Qualtrics, but the experiment was carried out on the Pavlovia platform. The task design was based on the false perception task (Gawęda & Moritz, 2021), which was piloted on 29 participants who did not take part in the main experiment. Due to the nature of the study, before starting the experimental part participants were asked, if possible, to turn off or mute all unnecessary programs, browsers, or other devices. The experiment began with written instructions in which participants were asked to wear headphones and adjust the volume to a comfortable level. Detailed instructions for the task were then provided and followed by a practice trial. Participants were informed that some sounds would be played at different volumes – some sounds would be heard clearly, while some sounds would be presented on the threshold of normal hearing (hard to hear). The task contained two conditions with two levels of cognitive expectancy: low (without a visual cue) and high expectancy (with a visual cue). The auditory stimuli were notification sounds from popular social media platforms (Facebook/Meta Messenger and WhatsApp) along with background noise. After reading the entire introductory text, the respondents moved on to the practice trial and then to the primary task. The whole task took about 4–6 minutes and consisted of 40 trials. Stimuli were presented at different levels of audibility: 60% were audible ($n = 24$) and 40% were non-audible ($n = 16$). In the low expectancy condition, the auditory notifications were presented without any additional cue. In the high expectancy condition, stimuli were presented with a visual cue in the form of a notification on the phone screen as a short video. Participants then had to decide, as soon as possible, whether they heard a given sound or not by pressing the appropriate button on the keyboard.

2.2. Procedure

An online survey was distributed between February and May 2021 through social media platforms. The survey was conducted on the Polish population, with the non-probabilistic convenience sampling method being used for recruitment purposes. The experiment was created using PsychoPy (Peirce et al., 2019) and hosted on Pavlovia, which is a platform for running well-controlled experimental procedures ((Bridges et al., 2020; Peirce et al., 2019). At the beginning of the study, each respondent was asked to complete a survey using a keyboard and to wear headphones during the experimental part of the study. Participants completed the behavioral task first and were then asked to fill in the questionnaires. Then, after entering the link in the advertisement, information about the study was presented. Respondents could proceed to the study only by clicking a button labeled "I give my informed consent to participate in the study." The study was conducted in accordance with the latest version of the Declaration of Helsinki, and the project was approved by the Ethics Committee of the Institute of Psychology of the Polish Academy of Sciences in Warsaw.

2.3. Data preparation

A total of 707 entries were made into Qualtrics and 374 into the

Pavlovia platform (Peirce et al., 2019). Due to drop out during the experimental task, the final sample consisted of $N = 252$ full responses. The data were screened for duplicates and technical errors, with one entry being removed in each case. Responses that were unreliable (reaction time below 500 ms) were excluded from further analyses blind to results (Gawęda & Moritz, 2021) due to the fact that visual and auditory stimuli were presented after the first 500 ms. This threshold was implemented to exclude impulsive or random responses. Additionally, we excluded participants from the analysis if they did not react to more than 50% of audible stimuli to control for the validity of responses ($n = 7$). Furthermore, we excluded participants who were not social media users, as the experimental task relied heavily on familiarity with social media. For this purpose, we asked the following question: "Do you use social media?" and we excluded participants who replied "no." The final analysis sample included 236 participants (64.8% female, average age = 30.85, *SD* = 10.6). Only 1.2% of participants had primary or vocational education, 33.5% had secondary education, and 65.3% had higher education. Demographic characteristics are presented in Table 1. Some respondents did not answer all questions in the further questionnaires, which explains why some analyses had a smaller sample.

2.4. Data analysis

All statistical analyses were conducted using RStudio software version 3.0 (RStudio Team, 2015). To analyze the false perception task, hits (number of correctly recognized audible stimuli) and false alarms (the number of times respondents pressed a button that indicated hearing a sound when it was not presented) were calculated. As we were primarily interested in false perceptions, for the purpose of this study, we only used false alarms from the experimental task in the analyses. Next, data were analyzed in accordance with parametric test assumptions. Since PPS total score was positively skewed, a logarithmic transformation was used. Nonparametric tests were conducted when parametric test assumptions were violated. Differences in the experimental conditions were compared using the Wilcoxon signed-ranks test. Spearman correlations were performed in order to investigate relationships between the measured variables. The Holm correction for multiple comparisons was implemented as it is less conservative than the Bonferroni correction, reducing the probability of type I errors but not increasing the probability of type II errors (Holland & Copenhaver, 1998; Rice et al., 2008). Two independent hierarchical regression models were created to search for possible predictors of PPS and HLEs. In order to verify whether the assumptions were met for both hierarchical regression models, the normality of residuals was assessed by plotting them on histograms.

Table 1
Descriptive information

	N(%)		M (SD)	Range
Sex		Age	30.85 (10.60)	18-69
Female	153 (64.8)	PPS	7.48 (4.34)	3-26
Male	72 (30.5)	MUSEQ	31.17 (15.86)	1-79
Other	11 (4.7)	MUSEQ Au	10.32 (4.90)	0-24
Education		MUSEQ Vi	11.10 (6.43)	0-28
Primary	1 (0.4)	MUSEQ BS	9.75 (7.20)	0-31
Vocational	2 (0.8)	BAPQ	93.59 (15.66)	62-143
Secondary	79 (33.5)	SCL-27-plus	62.54 (16.99)	28-116
Higher	154 (65.3)	ACS	52.63 (9.34)	29-76
Psychiatric diagnosis	88 (37.3)	MPPUS	38.27 (16.70)	9-90
Current medication use	46 (19.5)			
Substance use in the past 12-months	48 (20.3)			

Note: PPS – Phantom Phone Signals (sum of phantom vibrating, ringing, and blinking); MUSEQ – The Multi-Modality Unusual Sensory Experiences (sum of auditory, visual, and bodily sensation subscales); BAPQ – Beliefs about Perception Questionnaire (total score); SCL-27-plus – Symptoms Checklist-27-plus, ACS – Attentional Control Scale; MPPUS – Mobile Phone Problematic Use.

3. Results

A total of 37.3% of respondents declared a diagnosis of a mental disorder at some point in their lifetime, with anxiety and depressive disorders (11%) being the most common, 20% declared currently taking psychiatric medications, and 20% admitted to using psychoactive substances in the past 12 months. The summary of demographic characteristics and questionnaires is shown in Table 1.

The correlation analysis showed no significant relationship between the experimental task and any form of self-reported PPS. When the experimental task and the MUSEQ subscales were compared, no correlation survived Holm correction for multiple comparisons. The remaining results of the correlation analysis are shown in Table 2.

3.1. False perception task

A Wilcoxon signed-rank test was performed on the participant's false alarm rates between two experimental conditions: low (no visual cue; $M = 0.147$, $SD = 0.262$) and high (with a visual cue; $M = 0.168$, $SD = 0.274$) expectancy. The results were at the level of statistical trend ($z = 1714.500$, $p = 0.061$, $d = -0.181$), showing no significant differences between the two levels of expectancy. However, the mean scores showed that the effect was visible in the hypothesized direction: more false recognitions were committed in the high expectancy condition than in the low expectancy condition.

3.2. Predictors of PPS and HLEs

Two hierarchical linear regressions were created to model self-reported proneness to PPS and other hallucinatory-like experiences with metacognitive beliefs about perception (BaPQ), general psychopathology (SCL-27-plus), attentional control (ACS), and smartphone dependence (MPPUS-10) as independent predictors. For beliefs about perception (BaPQ), only the following subscales were used as predictors in both regression models: top-down influence (TDI), blurred boundaries (BB), and normalization (N).

The appropriate assumptions for our two hierarchical linear regression models were met, and there was no evidence of multicollinearity. Tables 3 and 4 summarize the results of the regression analyses. All models were statistically significant at all three steps. For the model with MUSEQ (a measure of HLEs) as the dependent variable, at step one, age was a significant predictor: $F(1,226) = 6.425$, $p = 0.01$, $R^2 = 0.027$. Introducing the BaPQ subscales (TDI, BB, N) and false alarm rate in the false perception task explained an additional 42.9% of the variation in the MUSEQ score, and the change in R^2 was significant: $F(5,222) = 37.13$, $p < 0.01$. Finally, adding MPPUS, SCL-27-plus, and ACS to the regression model explained an additional 9.6% of the variation in the MUSEQ score, and this change in R^2 was also significant: $F(8,219) = 33.31$, $p < 0.01$. After including all variables in the third step of the regression model, age, false alarm rate, MMPUS, and ACS failed to predict HLEs. The most important predictors of the MUSEQ score were BaPQ TDI and the SCL-27-plus. Together, all variables accounted for 55.3% of the variance in the MUSEQ score. For log-transformed PPS as the dependent variable, at stage one, age was a significant predictor – $F(1,226) = 20.25$, $p < 0.01$) – and accounted for 8.2% of variance. Introducing the BaPQ subscales (TDI, BB, N), MPPUS, and false alarm rate in the false perception task explained an additional 16% of the variation in PPS, and the change in R^2 was significant: $F(6,221) = 11.67$,

Table 2
Correlation matrix

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. False alarms																				
2. PPS	-0.030																			
3. PPS vibration	-0.100	0.825***																		
4. PPS blink	0.052	0.669***	0.327***																	
5. PPS ring	-0.028	0.729***	0.460***	0.378***																
6. MUSEQ	0.182	0.261**	0.201	0.126	0.266**															
7. MUSEQ Auditory	0.114	0.353***	0.309***	0.141	0.331***	0.736***														
8. MUSEQ Visual	0.177	0.181	0.178	0.041	0.116	0.815***	0.573***													
9. MUSEQ Bodily Sensations	0.140	0.235***	0.099	0.093	0.280**	0.841***	0.544***	0.610***												
10. BAPQ	0.188	0.141	0.141	0.050	0.147	0.626***	0.486***	0.532***	0.512***											
11. BAPQ BB	0.076	0.219	0.177	0.135	0.205	0.508***	0.454***	0.402***	0.453***	0.684***										
12. BAPQ N	0.175	0.003	-0.007	-0.079	0.066	0.471***	0.381***	0.455***	0.397***	0.719***	0.377***									
13. BAPQ SC	0.111	0.048	0.070	0.032	0.041	0.459***	0.317***	0.394***	0.338***	0.725***	0.326***	0.394***								
14. BAPQ NC	0.171	0.016	-0.005	0.071	-0.005	0.216	0.106	0.149	0.116	0.549***	0.291***	0.236*	0.444***							
15. BAPQ LC	0.089	0.148	0.148	0.039	0.134	0.397***	0.391***	0.326***	0.308***	0.618***	0.463***	0.422***	0.243*	0.388***						
16. BAPQ TDI	0.106	0.244*	0.195	0.146	0.266**	0.586***	0.469***	0.484***	0.468***	0.628***	0.441***	0.433***	0.399***	0.157	0.311***					
17. BAPQ LA	-0.084	0.030	0.097	0.030	-0.036	-0.271**	-0.260**	-0.257*	-0.190	-0.062	-0.102	-0.313***	-0.141	0.005	-0.151	-0.166				
18. MPPUS	0.079	0.421***	0.305***	0.352***	0.277**	0.194	0.208	0.136	0.215	0.194	0.268**	0.018	0.084	0.087	0.158	0.229*	0.015			
19. SCL 27 plus	0.042	0.264**	0.192	0.186	0.219	0.561***	0.451***	0.448***	0.574***	0.506***	0.528***	0.362***	0.289***	0.180	0.391***	0.318***	-0.055	0.304***		
20. ACS	-0.021	-0.200	-0.103	-0.185	-0.168	-0.121	-0.157	-0.113	-0.181	-0.182	-0.273**	-0.227	0.097	0.053	-0.242*	-0.130	-0.014	-0.289***	-0.358***	

Note: PPS – Phantom Phone Signals (sum of phantom vibrating, ringing, and blinking); MUSEQ – The Multi-Modality Unusual Sensory Experiences (sum of auditory, visual, and bodily sensation subscales); MUSEQ Auditory – MUSEQ Auditory Subscale; MUSEQ Visual – MUSEQ Visual Subscale; MUSEQ Bodily Sensations – MUSEQ Bodily Sensations Subscale; BAPQ – Beliefs about Perception Questionnaire (total score); BAPQ TDI – Top-down Influence Subscale; BAPQ BB – Blurred Boundaries Subscale; BAPQ N – Normalization Subscale; BAPQ LC – Lack of Perceptual Confidence Subscale; BAPQ NC – Need to Control Perception Subscale; SCL-27-plus – Symptoms Checklist-27-plus; ACS – Attentional Control Scale; MPPUS – Mobile Phone Problematic Use.

Table 3
Regression results using the mean of Auditory, Visual, and Bodily Sensation subscales of the MUSEQ questionnaire as the criterion

Predictor	B	b 95% CI [LL, UL]	beta	beta 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	r	Fit	Difference
Step 1									
Age	-0.24*	[-0.43, -0.05]	-0.17	[-0.29, -0.04]	.03	[.00, .08]	-.17*		
								R^2 = .027* 95% CI[.00, .08]	
Step 2									
Age	-0.16*	[-0.31, -0.01]	-0.11	[-0.21, -0.01]	.01	[-.01, .03]	-.17*		
BAPQ TDI	1.75**	[1.14, 2.35]	0.33	[0.22, 0.44]	.08	[.03, .13]	.55**		
BAPQ BB	0.94**	[0.53, 1.34]	0.26	[0.15, 0.37]	.05	[.01, .09]	.51**		
BAPQ N	0.70**	[0.35, 1.05]	0.23	[0.12, 0.35]	.04	[.00, .08]	.49**		
False alarms	4.33	[-1.83, 10.48]	0.07	[-0.03, 0.17]	.00	[-.01, .02]	.15*		
								R^2 = .457** 95% CI[.35, .52]	ΔR^2 = .429** 95% CI[.33, .53]
Step 3									
Age	-0.09	[-0.23, 0.04]	-0.06	[-0.16, 0.03]	.00	[-.01, .01]	-.17*		
BAPQ TDI	1.57**	[1.00, 2.14]	0.30	[0.19, 0.40]	.06	[.02, .10]	.55**		
BAPQ BB	0.51*	[0.10, 0.91]	0.14	[0.03, 0.25]	.01	[-.01, .03]	.51**		
BAPQ N	0.51**	[0.18, 0.84]	0.17	[0.06, 0.28]	.02	[-.01, .04]	.49**		
False alarms	3.98	[-1.66, 9.62]	0.06	[-0.03, 0.16]	.00	[-.01, .01]	.15*		
MPPUS	0.00	[-0.09, 0.09]	0.00	[-0.10, 0.10]	.00	[-.00, .00]	.22**		
SCL-27-plus	0.35**	[0.25, 0.45]	0.38	[0.27, 0.49]	.09	[.04, .15]	.60**		
ACS	0.13	[-0.03, 0.30]	0.08	[-0.02, 0.18]	.01	[-.01, .02]	-.18**		
								R^2 = .553** 95% CI[.45, .61]	ΔR^2 = .096** 95% CI[.04, .15]

Note. A significant *b*-weight indicates the beta-weight and semi-partial correlation are also significant. *b* represents unstandardized regression weights; *beta* indicates the standardized regression weights; sr^2 represents the semi-partial correlation squared; *r* represents the zero-order correlation; *LL* and *UL* indicate the lower and upper limits of the confidence interval, respectively.
* indicates $p < .05$. ** indicates $p < .01$.
Abbreviations: BAPQ – Beliefs about Perception Questionnaire; BAPQ TDI – Top-down Influence Subscale; BAPQ BB – Blurred Boundaries Subscale; BAPQ N – Normalization Subscale; MPPUS – Mobile Phone Problematic Use;SCL-27-plus – Symptoms Checklist-27-plus; ACS – Attentional Control Scale.

$p < 0.01$. Finally, adding SCL-27-plus and ACS to the regression model did not significantly change R^2. After including all variables in the third step of the regression model, BaPQ BB, NN, false alarm rate, SCL-27-plus, and ACS failed to predict PPS. The most important predictor of PPS was MPPUS. Together, all variables accounted for 24.7% of the variance in PPS.

4. Discussion

Phantom phone signals (PPS) are a relatively new phenomenon in the literature. Most studies have investigated PPS as a separate phenomenon (Lin et al., 2020, 2013b; Pisano et al., 2019; Rothberg et al., 2010; Sauer et al., 2015; Tanis et al., 2015) without comparison to other types of hallucinatory-like experiences (HLEs). In the present study, we investigated similarities and differences between PPS and other HLEs that are not limited to phone use. For this purpose, we compared PPS and HLEs in the context of general psychopathology, beliefs about perception, attentional control, and smartphone dependence measures. Moreover, we aimed to investigate the role of expectancy in false auditory perceptions by implementing an experimental procedure with two levels of cognitive expectancy: 1. auditory stimuli presented (or not) with no cue (low) and 2. auditory stimuli presented (or not) with a visual cue. Additionally, we aimed to verify whether experimentally-induced false auditory perceptions contextually connected with smartphone usage correlate with both PPS and HLEs. This was done by applying a novel paradigm to examine the impact of top-down processes on false auditory perceptions.

We established that PPS and other HLEs may share some correlates but nonetheless differ. For instance, age was related to both PPS and HLEs, which is consistent with the literature; PPS are especially prevalent in the younger population as the omnipresence of smartphones is a relatively new phenomenon (Sauer et al., 2015; Tanis et al., 2015). Importantly, our results suggest that beliefs about perception, which were conceptualized as priors in this study, are a stronger predictor of HLEs than PPS. More specifically, we found that three BaPQ subscales – top-down influence (TDI), blurred boundaries (BB), and normalization (N) – and false alarms explained an additional 42.9% of the variation in HLEs. At the same time, with the addition of smartphone dependency in the second step, a similar set of variables explained only 16% of the variation in PPS. General psychopathology, attentional control, and smartphone dependence explained a further 9.6% of variance in HLEs. Together, all variables accounted for 55.3% of the variance in HLEs. In contrast, the same model explained only 24.7% of PPS when considering all factors.

Interestingly, although PPS and HLEs might both be defined as perceptual anomalies, at the same time these phenomena may have different correlates. With regard to the HLEs as measured with the MUSEQ, top-down influence (BAPQ TDI) and general psychopathology (SCL-27 plus) were the most important predictors. In contrast, we found that the strongest predictor of PPS was smartphone dependency (MPPUS). Surprisingly, general psychopathology was not a significant predictor of PPS. This may suggest that unlike other HLEs, PPS are not associated with emotional burden. However, further research is needed to explore these findings, as some evidence has suggested a relation between PPS and emotional distress (Lin et al., 2013a,b, 2020; Pisano et al., 2019).

On the other hand, the subscale measuring top-down influence on perception (BaPQ TDI) turned out to be a significant predictor for both PPS and other HLEs, which indicates a possible shared mechanism between these two types of perceptual anomalies. These findings might indicate that beliefs about top-down influence on perception play a role in both PPS and other HLEs. Our study was not controlled in standard experimental conditions due to its online form. Nevertheless, our results can be interpreted in line with a previous study (Powers et al., 2016) that

Table 4
Regression results using the total PPS score (log-transformed) as the criterion

Predictor	*b*	*b* 95% CI [LL, UL]	*beta*	*beta* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	*r*	Fit	Difference
Step 1									
Age	-0.01**	[-0.02, -0.01]	-0.29	[-0.41, -0.16]	.08	[.03, .16]	-.29**		
								$R^2 = .082$** 95% CI[.03, .16]	
Step 2									
Age	-0.01**	[-0.01, -0.00]	-0.20	[-0.32, -0.08]	.04	[-.01, .08]	-.29**		
BAPQ TDI	0.02*	[0.00, 0.05]	0.16	[0.02, 0.30]	.02	[-.01, .05]	.24**		
BAPQ BB	0.01	[-0.01, 0.02]	0.07	[-0.07, 0.20]	.00	[-.01, .02]	.19**		
BAPQ N	-0.01	[-0.02, 0.00]	-0.11	[-0.24, 0.03]	.01	[-.01, .03]	-.00		
MPPUS	0.01**	[0.01, 0.01]	0.33	[0.20, 0.45]	.10	[.03, .16]	.40**		
False alarms	-0.04	[-0.25, 0.17]	-0.02	[-0.14, 0.10]	.00	[-.00, .01]	-.01		
								$R^2 = .242$** 95% CI[.13, .31]	$\Delta R^2 = .160$** 95% CI[.08, .24]
Step 3									
Age	-0.01**	[-0.01, -0.00]	-0.19	[-0.31, -0.07]	.03	[-.01, .07]	-.29**		
BAPQ TDI	0.02*	[0.00, 0.05]	0.16	[0.03, 0.30]	.02	[-.01, .05]	.24**		
BAPQ BB	0.00	[-0.01, 0.02]	0.04	[-0.11, 0.18]	.00	[-.01, .01]	.19**		
BAPQ N	-0.01	[-0.02, 0.00]	-0.13	[-0.27, 0.02]	.01	[-.01, .03]	-.00		
MPPUS	0.01**	[0.00, 0.01]	0.31	[0.18, 0.43]	.08	[.02, .14]	.40**		
False alarms	-0.04	[-0.25, 0.17]	-0.02	[-0.14, 0.10]	.00	[-.00, .01]	-.01		
SCL-27-plus	0.00	[-0.00, 0.01]	0.07	[-0.08, 0.21]	.00	[-.01, .01]	.23**		
ACS	-0.00	[-0.01, 0.00]	-0.04	[-0.17, 0.09]	.00	[-.01, .01]	-.17*		
								$R^2 = .247$** 95% CI[.13, .31]	$\Delta R^2 = .005$ 95% CI[-.01, .02]

Note. A significant *b*-weight indicates the beta-weight and semi-partial correlation are also significant; *b* represents unstandardized regression weights; *beta* indicates the standardized regression weights; sr^2 represents the semi-partial correlation squared; *r* represents the zero-order correlation; *LL* and *UL* indicate the lower and upper limits of the confidence interval, respectively.
* indicates $p < .05$. ** indicates $p < .01$.
Abbreviations: BAPQ – Beliefs about Perception Questionnaire; BAPQ TDI – Top-down Influence Subscale; BAPQ BB – Blurred Boundaries Subscale; BAPQ N – Normalization Subscale; MPPUS – Mobile Phone Problematic Use;SCL-27-plus – Symptoms Checklist-27-plus; ACS – Attentional Control Scale.

showed the important impact of priors (e.g., beliefs) on perception. Beliefs about top-down influence on perception were measured by a new self-report measurement – the Beliefs About Perception Questionnaire (BaPQ; Gawęda et al., in preparation) – which may be a promising tool for measuring the perceived influence of top-down processes on perception. Nevertheless, more research is needed to confirm our findings.

Several studies using the Signal Detection task found more false alarms in both patients (Gawęda and Moritz, 2021; Vercammen et al., 2008) and healthy individuals prone to hallucinations (Daalman et al., 2012; Laloyaux et al., 2022). Most previous studies used verbal material as target stimuli (Barkus et al., 2007, 2011; Chhabra et al., 2016; de Boer et al., 2019; Laloyaux et al., 2022; Vercammen & Aleman, 2010). In the current study, we introduced a paradigm with contextualized sounds of familiar smartphone notifications (WhatsApp and Messenger notification sounds) and investigated the impact of top-down processes on false auditory perceptions in two levels of cognitive expectancy. According to a recent study conducted on patients with schizophrenia (Gawęda & Moritz, 2021), we expected that false auditory perceptions would increase with an increased level of expectancy. However, in the current study, this effect was not confirmed – there was no significant difference between high and low expectancy conditions. One explanation may be that the task was performed online and was relatively short. Another explanation may be the sample characteristics. Participants were selected from the general population and not from a population of people susceptible to this type of experience (i.e., people on the schizophrenia spectrum or who are prone to hallucinations) as in previous studies (Barkus et al., 2007; de Boer et al., 2019; Laloyaux et al., 2022).

At the same time, no significant association was found between false perceptions and any form of HLEs as well as total PPS or for any specific PPS (phantom ringing, vibrating, and blinking). Our results show no differences in proneness to false perceptions in the task inducing cognitive expectancy in HLEs and PPS. Despite growing evidence for the role of priors in perceptual anomalies such as auditory hallucinations (Daalman et al., 2011, 2012; Laloyaux et al., 2022; Vercammen & Aleman, 2010), there is still much to explore in other specific types of perceptual abnormalities such as PPS, which are strongly prevalent experiences with understudied mechanisms. False perceptions are a complex phenomenon and can depend on many contextual factors, but also on intrapersonal factors. In our task, the level of expectation was manipulated with a simple visual cue. Previous studies that show a link between PPS and smartphone addiction (Tanis et al., 2015) suggest that the presence of PPS may be more dependent on other factors, such as patterns of smartphone use (as shown in regression analyses). For those who are most susceptible to PPS – that is, people who habitually use smartphones and who have a long history of conditioning and associated neural changes (neuroplasticity) – a simple visual cue may not have such a strong effect and may not "shift" the balance between sensory input and expectations. On the other hand, the lack of significant effects for HLEs might be a result of the task design. The task was designed to contextually connect to PPS experiences. The lack of significant results could be explained by not being connected enough to other types of HLEs. Still, more research is needed to explore different perceptual abnormalities and their complex relations with contextual factors.

4.1. Limitations

Although it has been shown that online experimental research can be comparable to that performed in laboratory settings (Bridges et al., 2020), studies with auditory stimuli are more challenging. To solve this issue in the current study, we excluded participants with any hearing impairments and controlled for correctly identified audible stimuli. Therefore, future research could replicate the procedure in laboratory settings. Another limitation includes the sample size, as previous research using the Signal Detection task online (de Boer et al., 2019) was performed on a large sample of participants ($N = 5115$), where the variability of different hallucinatory experiences in the studied population made it possible to divide participants into groups by the frequency of those experiences. The lack of significant difference could be due to the small sample size. Thus, future studies on larger samples may further explore the mechanisms of PPS and HLEs. Furthermore, 37% of our participants reported having been diagnosed with a mental illness at some point in their life. This relatively high percentage might be a result of the question type: participants were asked about their entire lifetime. Reports on the lifetime prevalence of any psychiatric disorder are estimated at between 25% and 45% (Kessler et al., 2005; Kiejna et al., 2015). Therefore, we believe our sample is similar in this regard to the general population.

4.2. Conclusions

To our knowledge, this was the first study to compare both PPS and other HLEs in investigating PPS on the theoretical basis of contemporary models of perceptual abnormalities – including the role of priors. Our investigation was both experimental and by self-report using a newly designed questionnaire – the Beliefs about Perception Questionnaire, in which one of the subscales, in particular, aims to measure the role of top-down processes. Furthermore, we introduced the first experimental task measuring false auditory perceptions contextually designed to recreate phantom phone signals by using popular smartphone notifications as stimuli, in contrast to previous paradigms that concentrated on verbal material (Barkus et al., 2007, 2011; Chhabra et al., 2016; de Boer et al., 2019; Laloyaux et al., 2022; Vercammen & Aleman, 2010). Although our study did not reveal a relationship between PPS and false perceptions, there was an association with top-down processes measured by self-report. Therefore, it shows a potential path for future research to further investigate the role of priors in PPS. Moreover, differences in other measures between PPS and other HLEs might suggest that there are different risk factors depending on the type of perceptual aberration. Therefore, more research is needed to explore different types of perceptual abnormalities separately as they may form different factorial structures

Financial support

This study was supported by the PRELUDIUM BIS grant from the National Science Centre, Poland (ŁG, 2019/35/O/HS6/02982).

Author statement

Adrianna Aleksandrowicz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. Joachim Kowalski: Methodology, Formal analysis, Writing – review & editing. Łukasz Gawęda: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Ethical standards

The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

Declaration of Competing Interest

The authors have declared that there are no conflicts of interest in relation to the subject of this study.

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Psychiatry Research 327 (2023) 115372

Contents lists available at ScienceDirect

Psychiatry Research

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

Cognitive correlates of auditory hallucinations in schizophrenia spectrum disorders

Adrianna Aleksandrowicz [a,*], Joachim Kowalski [a], Izabela Stefaniak [b], Katarzyna Elert [b], Łukasz Gawęda [a,*]

[a] Experimental Psychopathology Lab, Institute of Psychology, Polish Academy of Sciences, Warsaw, Poland
[b] First Department of Psychiatry Institute of Psychiatry and Neurology, 02-957 Warsaw, Poland

ARTICLE INFO

Keywords:
Schizophrenia spectrum disorder
Auditory hallucinations
Source monitoring
Top-down processes
Inhibitory control

ABSTRACT

Auditory hallucinations (AHs) are one of the central symptoms of schizophrenia spectrum disorders (SSD). Current cognitive models of AH implicate source monitoring, top-down processes, and inhibitory control. However, research combining these processes is limited. Our study aimed to examine how source monitoring bias, top-down processes, and inhibitory control contribute to AHs in individuals with SSD. Eighty seven patients (aged 18–45 years) with SSD were included in the analyses. Participants completed cognitive tasks assessing source monitoring (Action Memory Task), top-down processes (False Perception Task; FPT), and inhibitory control (Auditory Go/NoGo task). AH was positively associated with response bias on the FPT. Correlations between AH and the other cognitive tasks were nonsignificant. Source monitoring errors correlated positively with response bias measures and negatively with Hits on the FPT. PANSS total score was positively correlated with source monitoring bias and False Alarms on the Go/NoGo task. The severity of disorganized symptoms was related to Source Monitoring Errors and False Alarms in the Go/NoGo task. Negative symptoms were associated with Hits and False Alarms in the Go/NoGo task.

Future studies are necessary to further elucidate the relationships between different cognitive processes that may be related to clinical symptoms of psychosis.

1. Introduction

Perceptual abnormalities are one of the most prominent symptoms of schizophrenia spectrum disorder (SSD). Of the different types of perceptual anomalies, hallucinations constitute one of the most distressing and frequent experiences, with a prevalence rate estimated at up to 80% among patients with SSD (Toh et al., 2022). Importantly, evidence shows that perceptual abnormalities also occur in the general population, with prevalence rates estimated between 5% to 60% in some studies (Linszen et al., 2022). To date, no single cognitive process has been identified as the sine qua non for the presence of hallucinations. For this reason, recent cognitive models stress the role of a combination of different cognitive functions as potential mechanisms of auditory hallucinations (AHs) that may operate in both clinical and nonclinical contexts. In their review, Waters et al. (2012) proposed a model in which source monitoring (Brookwell et al., 2013), top-down processes (Powers et al., 2016), as well as inhibitory control (Waters et al., 2006) play an important role in the formation of hallucinations.

Source monitoring (SM; Johnson et al., 1993) – discriminating between different sources of information – was one of the first cognitive processes suggested to be involved in hallucinations. Indeed, as was elegantly expressed by Frith and Done (1988), hallucinating patients tend to experience their own internal states as coming from external agents. For three decades, source monitoring and its deficits have been intensively studied in the context of SSD (Damiani et al., 2022). Source monitoring can be divided into several subtypes: internal source monitoring (discrimination between two internal sources; e.g., imagined and performed actions), external source monitoring (discrimination between two external sources; e.g., pictures and words), and reality monitoring (discrimination between internal and external experiences; e.g., self-generated speech and the speech of others). A number of studies have shown that, in general, patients with SSD tend to misattribute the source of information more often than do healthy controls (Lavallé et al., 2021). In the context of hallucinations, it has been shown that

* Corresponding authors at: Institute of Psychology, Polish Academy of Sciences, Jaracza 1, 00-378 Warsaw, Poland.
E-mail addresses: aaleksandrowicz@psych.pan.pl (A. Aleksandrowicz), l.gaweda@psych.pan.pl (Ł. Gawęda).

https://doi.org/10.1016/j.psychres.2023.115372
Received 12 April 2023; Received in revised form 9 June 2023; Accepted 24 July 2023
Available online 2 August 2023
0165-1781/

externalization, in particular, is present (Brookwell et al., 2013). Indeed, a meta-analysis has confirmed that patients with AHs tend to misattribute their own actions to other sources (Waters et al., 2012). It should be noted, however, that other misattribution biases have also been linked to hallucinations, such as internal (Franck et al., 2000; Gawęda et al., 2013) and external source monitoring errors (Brébion et al., 2000; Woodward et al., 2007; Gawęda et al., 2013). It further complicates the picture that source monitoring biases have also been linked to other symptoms of schizophrenia. For instance, one line of studies found that similar response patterns are linked to delusions (Brodeur et al., 2009), disorganization (Docherty, 2012; Nienow and Docherty, 2004), and negative symptoms (Brébion et al., 2002; Moritz et al., 2003). At the same time, several studies have found that patients with SSD, irrespective of their symptom profile, tend to have source monitoring deficits (Gawęda et al., 2012; Moritz et al., 2003). Hence, the existing findings suggest the possibility of shared mechanisms across various psychotic symptoms and that SM deficits alone might be insufficient for explaining the onset and maintenance of AHs (Waters et al., 2012).

Indeed, cognitive models that apply Signal Detection Theory (SDT) principles present another approach to understanding the mechanisms underlying AHs (Corlett et al., 2019; Powers et al., 2016). These models stress the role of top-down processing in forming perceptual abnormalities. In other words, according to the basic models of perception, perceptual experience is shaped in the context of the dynamic interplay between top-down and bottom-up processes (Horga and Abi-Dargham, 2020). However, the theory states that perceptual abnormalities are the effect of an imbalance between these processes in which top-down processing dominates the process of shaping perceptual experience. Indeed, it has been shown that perceptual anomalies are more strongly linked to top-down impact on perception in non-clinical populations (de Boer et al., 2019; Laloyaux et al., 2022; Moseley et al., 2021; Vercammen and Aleman, 2010). Studies on patients with SSD have provided confirmation of the relationship between biased performance on auditory signal detection tasks and proneness to hallucinations (Aleman et al., 2003; Bristow et al., 2014). Another study (Gawęda and Moritz, 2021) further showed that the higher the cognitive expectancy, the more false perceptions were made by patients with SSD as compared to healthy controls. However, there was no significant relationship between a greater tendency to false alarms (i.e., overperceptualization) and hallucinations. Similarly, there was no significant correlation between clinical symptoms and an SDT task in the study of Chhabra et al. (2016). One study demonstrated mixed results when hallucinating patients were compared to non-hallucinating and healthy controls (Vercammen et al., 2008), whereas Daalman et al. (2012) did not confirm these findings.

Another line of research emphasizes the role of inhibition in AHs (Waters et al., 2012). It has been suggested that atypical attentional and inhibitory processes underlie the uncontrolled and intrusive component of AHs (Waters et al., 2003). Waters et al. (2006) showed that intentional cognitive inhibition might be involved in AHs. Moreover, inhibitory errors were not associated with other SSD symptoms. These results could be preliminary evidence of the specificity of inhibitory processes in AHs. Therefore, the role of inhibitory processes should be further explored. For instance, the Go/No-Go task has been confirmed in many studies to measure inhibitory control (Gomez et al., 2007). One study (Sun et al., 2021) showed differences in Go/No-Go task performance between patients diagnosed with schizophrenia and healthy controls but not between patients with and without auditory–verbal hallucinations. Despite some already existing studies in which Go/No-Go tasks were implemented, most studies focus solely on the visual modality, while only some focus on the auditory modality (Weisbrod et al., 2000).

In order to integrate existing knowledge on cognitive processes, Waters et al. (2012) proposed an integrated cognitive framework in which a combination of source monitoring deficits, top-down processes, and cognitive inhibition plays a role in the experience of hallucinations. Yet, to date, there is only a limited number of empirical studies that try to investigate relationships between these three processes themselves and with the symptomatology of SSD. A recent study combining these perspectives investigated the relationship between hallucinatory-like experiences (HLEs) and source monitoring, top-down processes, as well as attentional control in the general population, but the results were mixed (Moseley et al., 2021). The results suggest that only the SDT task significantly predicted HLEs. Recently, another study investigating predictors of phantom phone signals and other types of HLEs showed that only top-down beliefs about perception predicted both of those perceptual abnormalities (Aleksandrowicz et al., 2023). Whereas other studied variables were found to be stronger predictors of only one of the perceptual abnormalities studied (i.e., smartphone dependency was the strongest predictor of phantom phone signals, and general psychopathology was the strongest predictor of HLEs). These findings might question whether we should generalize all perceptual abnormalities and attempt to explain the mechanisms of clinical AHs with studies on non-clinical populations. One study on a clinical population (Moseley et al., 2022) showed that patients experiencing psychosis and AHs tend to perform worse on SDT, dichotic listening, and memory-inhibition tasks but have intact performance on source-monitoring tasks compared to healthy controls. Despite some existing research combining the main cognitive processes involved in AHs, to our knowledge, no study to date has investigated the relationships of these variables together with AHs in patients with SSD only.

Existing findings in the field suggest that different symptoms (e.g., delusions and hallucinations) may share cognitive mechanisms. For instance, source monitoring deficits have been linked also to delusions (Brodeur et al., 2009), negative symptoms (Brébion et al., 2002; Moritz et al., 2003), and disorganization (Docherty, 2012; Nienow and Docherty, 2004). Nevertheless, there are no studies investigating relationships between the severity of different symptoms and the aforementioned set of cognitive processes at once in the same sample. In other words, it is still unclear whether source monitoring, signal detection deficits, and inhibitory control are independent processes that may have an impact on symptoms or whether they are interconnected. Therefore, we aimed to explore whether there are interrelationships between source monitoring, inhibition control, and the impact of top-down processes of perception among patients with SSD. At the same time, our study aimed to investigate the links between the aforementioned cognitive processes and the severity of psychopathology – in particular, hallucinations. Based on theoretical models (Waters et al., 2012) and previous research (Aleman et al., 2003; Bristow et al., 2014; Gawęda et al., 2013; Moseley et al., 2022; Waters et al., 2003, 2006), we expected that the more severe the hallucinations reported, the more performance deficits on all tasks would be. In other words, we expect more false alarms and response bias errors on the top-down processing task, more source misattributions on the source monitoring task and more false alarms, and fewer correct responses on the task measuring inhibitory control in patients with more severe hallucinations. Moreover, for exploratory purposes, based on previous accounts (Brodeur et al., 2009; Docherty, 2012; Nienow and Docherty, 2004; Brébion et al., 2002; Moritz et al., 2003), we expected that deficits in the performance would be connected to other psychopathological symptoms of SSD. Finally, based on the theoretical model of Waters et al. (2012), we hypothesized that the investigated cognitive processes would be interconnected, as all have been shown to be potential mechanisms of AHs.

2. Methods

2.1. Participants

Ninety in- and out-patients diagnosed with SSD participated in the study. Patients were recruited from the Institute of Psychiatry and Neurology, Warsaw (Poland), outpatient clinics across Warsaw, as well as via advertisement on social media platforms. The clinical diagnosis was confirmed by a structured interview with the Neuropsychiatric

Interview (MINI 5.0; Lecrubier et al., 1997), and symptom severity was assessed with the PANSS interview (Kay et al., 1987). The inclusion criteria for the study were: being aged between 18 and 45 years old, that patients were stable in terms of their symptoms (i.e., no agitation, able to make contact with the person administering the experiment) and medication (the same dosage for at least two weeks), and lack of severe formal thought disorders. Exclusion criteria for the study were: alcohol or other substance dependence and abuse in the past 12 months, the presence of severe neurological disorders, or intellectual disability. All participants received written and verbal information about the study. Before participating in the study, all participants provided written informed consent. All patients received reimbursement for participation (117.5 PLN – approximately 27.5 USD). The study was approved by the local ethics committee at the Institute of Psychology, Polish Academy of Sciences.

2.2. Psychopathology assessment

Psychopathology was assessed using the Positive and Negative Syndrome Scale (PANSS; Kay et al., 1987; Kay and Savy, 1990; Kay, 1991) following a structured clinical interview. We calculated PANSS scores based on the five-factor model: Positive ($\alpha = 0.66$), Negative ($\alpha = 0.90$), Disorganized ($\alpha = 0.61$), Excited ($\alpha = 0.43$), and Depressed ($\alpha = 0.60$) symptoms. Cronbach's alfa for the total PANSS was 0.67. Then, the Hallucinations subscale from the Psychotic Symptom Rating Scales (PSYRATS; Drake et al., 2007) was assessed. PSYRATS was adapted to the Polish language in the previous study (Gawęda, 2012). In addition, we recorded basic demographic information: age at illness onset, duration of the illness, number of inpatient and outpatient hospitalizations, as well as chlorpromazine equivalent.

2.3. False perception task

We used the False Perception Task (FPT; Gawęda and Moritz, 2021). In this task, participants heard words together with nonverbal 'street noise' through stereo headphones. The words were presented in three expectancy conditions. In the low expectancy condition, the target stimulus was not introduced by any cue. In the intermediate expectancy condition, the target stimulus was presented as text on the computer screen (the same word as the target stimulus) before the target stimulus was shown. In the high expectancy condition, participants were presented with an integrated audio and visual stimulus of a video recording of an actor mouthing the word. Participants were asked to decide (press a button on the keyboard) whether or not they had heard the word; 60% ($n = 108$) of all stimuli were present and audible and 40% ($n = 72$) were not audible. The stimuli included 60 neutral words from the Polish version of the Berlin Affective Word List Reloaded. Stimuli were grouped into blocks of six words. Three different blocks (three conditions) were repeated five times. Stimuli within the block were pseudorandomized and the block order was randomized. Each word was repeated three times for each different expectancy condition, resulting in 180 trials. Each target stimulus was present for 2 s, and then, if the participant did not respond right away, they were given an additional 3 s to respond after the stimulus had occurred. Inter-stimulus intervals ranged between 750 and 1500 ms, and inter-block intervals ranged between 1500 and 2500 ms.

2.4. Source monitoring task

The Action Memory Task (AMT) has been used in previous studies (Gawęda et al., 2012, 2013). In this task, participants were presented with verbal instructions or nonverbal pictograms of actions. Instructions in a green frame had to be performed by the participant (actions involving one extremity could be performed with the chosen arm/leg/hand/foot), whereas actions set in a red frame had to be imagined. Before the experiment, participants were told to memorize the presented actions as later they would be asked to distinguish between imagined or performed actions during the task. Then there was a practice trial to familiarize participants with the task instructions. In the main phase, 18 verbal and 18 nonverbal action instructions were presented and each included nine items to be performed and nine items to be imagined. Instructions were presented for precisely 10 s, after which a button press was required for participants to proceed to the next action. Before the recognition phase, the Go/No-Go task was administered, which took 10 min. Then, 36 verbal instructions for the studied items were presented along with 20 new action instructions (the recognition items were presented in a different font from the items in the primary phase to prevent physical matching). Participants were asked three questions: 1) whether the corresponding instruction was presented either verbally or nonverbally or was not presented at all (presentation type differentiation); 2) to rate their confidence in their previous answer on a four-point scale ranging from 100% certain (response 1) to extremely uncertain (response 4); and 3) to choose whether the action had been performed or imagined (self-monitoring), graded for confidence (1 – *certain imagined*; 2 – *not certain imagined*; 3 – *certain performed*; 4 – *not certain performed*; 5 – *new action*). All items were randomized both in the learning and recognition phases.

2.5. Go/No-Go task

This task was based on the previous auditory Go/No-Go task (Weisbrod et al., 2000). Participants heard four blocks of 40 infrequent high-pitched tones, pseudorandomly interspersed between 160 frequent low-pitched tones. All tones were presented binaurally for 40 ms. The interstimulus interval varied randomly between 1.3 and 1.7 s. Participants were instructed to press the space key on the keyboard using their dominant hand when the frequent tone was presented and to withhold the response when the rare tone was presented. The frequent tone was presented at 1000 Hz and the infrequent tone at 2000 Hz. The order of

Table 1
Descriptive information ($n = 87$).

Characteristics	*M* (*SD*)
Basic characteristics	
Gender (female/male)	42/45
Age	32.93 (7.90)
Duration of illness	10.99 (7.45)
Age of the onset	22.03 (6.76)
Number of hospitalizations:	
inpatient	5.26 (5.05)
outpatient	1.46 (2.89)
Chlorpromazine eqv (mg/day)	620.79 (308.85)
Symptoms Severity	
PANSS Total Score	56.81 (12.45)
PANSS Positive	9.65 (4.08)
PANSS Negative	11.34 (5.80)
PANSS Disorganized	5.65 (2.52)
PANSS Excited	5.13 (1.67)
PANSS Depressed	8.60 (2.84)
PANSS P3	2.87 (1.69)
PSYRATS hallucination subscale	12.30 (13.14)
Cognitive Processes	
Source monitoring errors:	
Imagined actions recognized as performed	4.17 (3.58)
Performed actions recognized as imagined	3.11 (2.64)
False Perception Task:	
Hits	93.48 (15.94)
False alarms	13.56 (16.69)
d'	2.65 (1.23)
beta	2.56 (4.21)
c	−0.10 (0.65)
Go-No/Go task:	
Hits	152.00 (21.60)
False alarms	5.71 (7.42)

Note: $n = 3$ did not take antipsychotic meditation during the study and, for $n = 8$, it was impossible to calculate the chlorpromazine equivalent.

Table 2
Correlation matrix.

	1	2	3	4	5	6	7	8	9	10	11
1. Age											
2. Gender	-0.097										
3. Education	0.226*	0.048									
4. Illness duration	**0.598*****	-0.069	0.066								
5. Age of onset	**0.488*****	-0.063	**0.311****	**-0.314****							
6. Inpatient hospitalizations	0.218*	0.063	-0.134	**0.430*****	-0.221*						
7. Outpatient hospitalizations	0.296**	0.118	-0.037	**0.506*****	-0.178	**0.342****					
8. Chlorpromazine Eqv	-0.075	-0.101	-0.114	-0.037	-0.050	0.094	-0.072				
9. PANSS Total	-0.127	0.005	-0.009	-0.031	-0.085	0.020	-0.040	**0.374****			
10. PANSS Positive	-0.184	-0.116	0.099	0.028	-0.179	0.074	0.047	0.241*	**0.703*****		
11. PANSS Negative	-0.130	0.232*	-0.237*	-0.170	-0.089	-0.025	-0.132	0.232	**0.547*****	0.092	
12. PANSS Disorganized	0.093	0.023	-0.084	0.199	-0.127	0.173	0.154	0.142	**0.564*****	0.202	0.204
13. PANSS Excited	-0.040	-0.154	0.102	0.049	-0.009	-0.073	-0.009	-0.021	0.186	0.272*	**-0.335****
14. PANSS Depressed	0.041	0.155	0.227*	-0.057	0.240*	-0.029	0.024	0.018	0.222*	0.065	-0.083
15. PANSS P3	-0.128	-0.064	-0.024	0.139	-0.278*	0.188	0.054	**0.385*****	**0.538*****	**0.710*****	0.250*
16. PSYRATS Hallucination Subscale	-0.022	-0.001	0.088	0.195	-0.163	0.234*	0.130	0.285*	**0.411*****	**0.596*****	0.042
17. FPT False Alarms	-0.072	0.138	0.031	0.084	-0.140	-0.084	0.078	-0.074	0.020	-0.039	0.091
18. FPT Hits	-0.049	-0.077	0.291**	-0.094	0.168	-0.101	-0.223*	-0.026	-0.089	-0.043	-0.051
19. d prime	0.030	-0.199	0.149	-0.099	0.188	0.015	-0.167	0.057	-0.085	0.021	-0.125
20. beta	0.066	-0.008	-0.222*	-0.022	0.003	0.101	0.077	0.058	0.060	0.008	0.008
21. c	0.111	-0.077	-0.226*	0.022	0.014	0.125	0.092	0.037	0.049	0.043	-0.003
22. Imagined as Performed Actions	0.083	-0.183	-0.256*	0.124	-0.032	0.122	0.032	-0.039	**0.341****	0.111	0.183
23. Performed as Imagined Actions	-0.045	0.035	-0.103	-0.011	-0.041	0.167	0.145	0.121	0.128	0.015	0.004
24. Go/No-Go Hits	-0.082	**-0.346****	-0.022	-0.132	-0.039	-0.004	0.020	0.062	-0.078	0.055	-0.227*
25. Go/No-Go False Alarms	-0.121	0.137	-0.090	-0.019	-0.151	-0.035	-0.033	0.088	0.247*	0.135	0.219*

Computed correlation used spearman-method with listwise-deletion. Bold values are significant after FDR correction for multiple comparisons.
ns P > 0.05
*P ≤ 0.05
**P ≤ 0.01
***P ≤ 0.001

the tones was randomized between the participants. The main task was preceded by the presentation of the tones and 12 practice trials, with feedback given after every trial. Participants proceeded to the main task after carefully reading the instructions and performing correctly on the practice trials. The main task did not contain feedback.

2.6. Data preparation

We calculated Hits and False Alarms for the FPT and the Go/No-Go task as the primary variables of interest. Additionally, for the FPT, we calculated Signal Detection Theory parameters (Stanislaw and Todorov, 1999): task sensitivity, d' (how well the participant could distinguish signal from noise), calculated as standardized False Alarm Rate (FA) subtracted from the Hit Rate (H); and response bias measures: β and c (the tendency to be biased in responding yes/no on the task or the criterion the participant uses to decide on the presence of a stimulus; $\beta = e\left\{\frac{Z(FA)^2 - Z(H)^2}{2}\right\}$). For the AMT, we calculated the number of imagined actions misattributed as performed actions as a primary outcome variable and performed actions misattributed as imagined actions (internal source monitoring errors).

2.7. Data analysis

Statistical analyses were conducted using RStudio software version 3.0 (RStudio Team, 2015). First, we calculated z-scores for each correct response parameter. Then, we excluded participants with z-scores of −3 or more for one or more tasks. Next, data were analyzed in accordance with parametric test assumptions and nonparametric tests were conducted when parametric test assumptions were violated. Then, we examined the association between psychopathology measured by PANSS and PSYRATS and measures of basic demographic characteristics. In order to calculate the associations between task performance and symptom scores, we calculated Spearman's rho correlations. Benjamini–Hochberg False Discovery Rate (FDR) correction for multiple comparisons was implemented, as it is less conservative than the Bonferroni correction, reducing the probability of type I errors but not increasing the probability of type II errors (Rice et al., 2008)

3. Results

3.1. Patient characteristics

Ninety patients met the inclusion criteria. However, after data inspection, we excluded $n = 3$ from the study due to poor performance on multiple tasks. Thus, the final sample included $n = 87$ patients diagnosed with SSD. Additionally, for the final analyses, we excluded experimental data for $n = 5$ participants due to difficulties completing one of the three behavioral tasks: four patients did not complete the PSYRATS interview and one did not complete the PANSS due to interruptions caused by COVID-19. Some respondents did not answer some questions in subsequent surveys. A significant proportion of the patients had no positive symptoms when participating in the study; 48 patients had active auditory hallucinations (present for at least a week prior to participation in the study), and 47 had delusions. Participant characteristics are presented in Table 1.

3.2. Source monitoring

Correlations with demographic data showed a significant relationship between years of education and Imagined as Performed Actions ($r = -0.26$, $p < 0.05$), but not with Performed as Imagined Actions. There was no significant relationship between source monitoring errors and age, gender, illness duration, age of onset, number of hospitalizations, or

12	13	14	15	16	17	18	19	20	21	22	23	24	25
0.109													
0.018	0.239*												
0.111	0.122	-0.012											
0.052	0.094	0.163	**0.841***										
-0.012	-0.012	-0.105	-0.085	-0.212									
-0.292**	-0.119	-0.029	-0.065	-0.096	0.029								
-0.169	-0.099	0.056	0.033	0.102	**-0.732***	**0.617***							
0.231*	0.136	0.087	0.061	0.155	**-0.625***	**-0.731***	-0.024						
0.176	0.056	0.076	0.105	0.224*	**-0.756***	**-0.646***	0.164	**0.924***					
0.342	0.024	0.038	0.178	0.162	-0.080	-0.284**	-0.143	**0.310**	0.275*				
0.271*	0.046	0.103	0.004	0.040	0.064	-0.158	-0.133	0.095	0.041	0.226*			
-0.031	0.147	0.006	0.092	0.006	0.009	0.007	0.059	-0.096	-0.026	-0.107	0.120		
0.264*	0.004	-0.082	0.087	0.062	0.085	-0.071	-0.123	0.039	-0.005	0.004	-0.011	**-0.416***	

chlorpromazine equivalent. Correlations with PANSS scores showed a positive relationship between Imagined as Performed Actions and Total Score ($r = 0.34$, $p < 0.01$), and Disorganized symptoms ($r = 0.34$, $p < 0.01$). There was no significant correlation between Source Monitoring Errors and Hallucination Scores (P3) measured by PANSS and PSYRATS. After implementing FDR correction for multiple comparisons, only the correlation between the General Score and Disorganized subscale of the PANSS remained significant.

3.3. Top-down processing

Results on the FPT showed that education correlated positively with Hits ($r = 0.29$, $p < 0.01$) as well as negatively with response bias measures (for c: $r = -0.23$, $p < 0.05$; for beta: $r = -0.22$, $p < 0.05$). The number of outpatient hospitalizations correlated negatively with Hits on the FPT ($r = -0.22$, $p < 0.05$). There was no significant relationship between FPT measures and age, gender, illness duration, age of onset, inpatient hospitalizations, or chlorpromazine equivalent. There was a negative relationship between Disorganized symptoms and Hits on the FPT ($r = -0.29$, $p < 0.01$) as well as a positive relationship between Disorganized symptoms and the beta value ($r = 0.23$, $p < 0.05$). The correlations between FPT measures and the remaining PANSS subscales were nonsignificant. However, the criterion in the FPT showed a positive relationship with the Hallucination score from PSYRATS ($r = 0.22$, $p < 0.05$), indicating that an increased PSYRATS score was associated with a higher threshold for accepting the presence of stimuli. In other words, the more severe the AHs reported, the more evidence was needed to confirm that the auditory signal was present in the FPT. After implementing FDR correction for multiple comparisons, no correlation remained significant.

3.4. Inhibitory control

There was a significant relationship between gender and Hits on the Go/No-Go task ($r = -0.35$, $p < 0.001$). No significant correlation was found between education, age, illness duration, age of onset, number of hospitalizations, or chlorpromazine equivalent. There was a positive correlation between the total PANSS score and False Alarms on the Go/NoGo task ($r = 0.26$, $p < 0.05$). Negative symptoms measured by PANSS correlated positively with False Alarms in the Go/NoGo task ($r = 0.22$, $p < 0.05$) and negatively with Hits ($r = 0.23$, $p < 0.05$). Moreover, there was a positive relationship between Disorganized symptoms and False Alarms ($r = 0.25$, $p < 0.05$). The remaining correlations did not reach statistical significance. After implementing FDR correction for multiple comparisons, only the correlation between gender and Hits remained significant.

3.5. Correlations between the experimental tasks

Imagined as Performed Actions correlated positively with response bias measures in the FPT (for criterion: $r = 0.28$, $p < 0.05$, for beta: $r = 0.31$, $p < 0.01$). Moreover, Imagined as Performed Actions correlated negatively with Hits on the FPT ($r = -0.28$, $p < 0.01$). The remaining correlations were nonsignificant. After implementing FDR correction for multiple comparisons, only the correlation between beta from the FPT and Imagined as Performed Actions on the AMT remained significant. However, the relationship between Hits on the FPT and Imagined as Performed Actions remained at the statistical trend level ($p = 0.070$). The correlational analyses are presented in Table 2.

4. Discussion

The main aim of our study was to investigate the role of three cognitive processes – top-down processing, source monitoring (SM), and inhibitory control – in auditory hallucinations (AHs) among patients with schizophrenia spectrum disorder (SSD). The second aim was to investigate the interrelationships between these processes. Moreover, we aimed to refer the investigated processes to demographic characteristics and the symptomatology of SSD.

First, contrary to some prior studies (Brookwell et al., 2013; Waters et al., 2012), our study showed no association between AHs severity and source monitoring errors in SSD. Early cognitive models of AHs indicate source monitoring as one of the potential mechanisms of AHs (Bentall, 1990; Bentall et al., 1991; Frith, 1992). However, a recent review showed that the results are actually rather mixed, especially when taking different source monitoring subtypes into account (Gawęda et al., under review). Additionally, we did not find a significant relationship with other positive symptoms. Yet, our results showed a relationship between SM errors and other SSD characteristics, such as total symptom severity, and Disorganized symptoms from the PANSS. These results indicate that SM errors might be more connected to general SSD symptoms rather than specifically to AHs severity. Thus, SM errors could potentially be considered a trait in patients with SSD and may constitute a risk factor for psychosis (Gawęda et al., 2018), including schizotypal traits (Anselmetti et al., 2007; Ilankovic et al., 2011; Moritz et al., 2003, 2005; Nienow and Docherty, 2004; Serrone et al., 2019; Stephane et al., 2010; Szöke et al., 2009). At the same time, varying results across other studies may be explained by the significant differences in SM task designs (e.g., the time between the generation and recognition phase, differences between sensory modalities or the difficulty of tasks, and the confounding influence of individual differences in memory capacity). One study (Brébion et al., 2008) showed no significant differences between patients with and without AHs in terms of SM misattributions, but when patients with and without visual hallucinations were compared, there was a significant group difference. Therefore, it is possible that the modality of the task and the sensory modality of hallucinations are important factors. The clinical state of the participants (chronic, acute, or stable state) could also play a significant role in differences in results across studies. In the current study, some patients were in the remission stage at the time of the study. Thus, the severity of the symptoms was not that high in comparison to other studies (Szöke et al., 2009). Importantly, in this context, our sample with AHs consisted of patients with relatively less severe hallucinations, which might have affected the results. At the same time, the link between SM and hallucinations may be weakened by the fact that some of the patients without recent AHs might have had hallucinations in the past (i.e., trait).

Secondly, when investigating relationships between AHs and the False Perception Task (FPT) measuring the top-down influence on auditory perception, the results showed a pattern opposite from that which was expected – the more severe the AHs, the less the patients' bias towards reporting that the signal was present (i.e., they exhibited a more conservative approach). Although these results seem to contrast with contemporary cognitive models (Corlett et al., 2019; Powers et al., 2016), most of the previous research investigating the role of top-down processing in AHs was conducted on non-clinical populations. Those studies found that top-down errors (guided by cognitive expectancy; e.g., our knowledge or previous experiences) in the cognitive task were connected to hallucinatory-like experiences (HLEs; Barkus et al., 2007; de Boer et al., 2019; Laloyaux et al., 2022; Moseley et al., 2021; Vercammen and Aleman, 2010). However, few studies have investigated such effects on clinical populations. One study on patients with SSD (Gawęda and Moritz, 2021) showed that patients made more top-down errors than healthy controls in a cognitive task. Thus, the effect was not specific to AHs. In a similar vein, Chhabra et al. (2016) found no significant relationship between a signal detection task and hallucination severity as well as other clinical parameters. Some studies found an association between top-down processes and semantic processing in participants with non-clinical HLEs but not those in the clinical group (Daalman et al., 2012).

It should be noted that despite the literature commonly describing psychotic phenomena using a continuum, there are some criticisms of this approach (David, 2010; Luhrmann, 2011). In particular, different patterns (categories) have been identified in clinical and non-clinical AH groups, such as the fact that non-clinical AHs might be more influenced by contextual factors (making them more prone to the influence of expectations). Perhaps, the top-down processing model explains hallucinatory-like experiences in the general population, but other processes should be considered when it comes to clinical hallucinations. Another explanation could be the variability in experimental tasks measuring top-down processes. Some tasks measuring the influence of top-down processes rely mostly on basic auditory perception (Aleman and Larøi, 2008; Vercammen et al., 2008) and others more on working memory capacity. Further research may benefit from different task designs in the within-subject study paradigm.

Following the framework of Waters et al. (2012), we investigated the cognitive process of inhibitory control. Previous findings showed differences in tasks measuring inhibitory processes when patients with SSD were compared to healthy controls (Barch et al., 2001; Cohen and Servan-Schreiber, 1992; Lipszyc and Schachar, 2010; MacDonald and Carter, 2003). Moreover, some studies emphasize the role of inhibitory processes in the formation of hallucinations (Sun et al., 2021; Waters et al., 2003, 2006). However, in the current study, there was no significant relationship between these processes and AHs. On the other hand, our results demonstrated an association between inhibitory control and Negative, Disorganized symptoms as well as total symptom severity, which confirms evidence from previous research showing executive function deficits in patients with SSD (Thai et al., 2019). One possible explanation of these results is that the effect emerges in patients with SSD in general, and might not be specific to hallucinating patients. One study (Sun et al., 2021) that investigated differences between AH and non-AH patients showed significant differences between both patient groups and healthy controls in reaction times on a Go/No-Go task, but no differences were observed between the patient groups. In the current study, we implemented an immediate/momentary assessment of inhibitory control, while some studies emphasize intentional inhibition connected to memory processes (Waters et al., 2012). Therefore, the current study could show that basic inhibitory control processes might not play a significant role in AHs; instead, a different task design should be implemented. Thus, this line of research is still understudied and further exploration is needed to provide more reliable conclusions.

Finally, an important aim of our study was to identify interrelations between source monitoring, top-down influence on perception, and inhibition. To our knowledge, this is the first study to investigate the associations between these cognitive processes. According to the theoretical model of Waters et al. (2012), AHs are formed based on the interaction between hypervigilance to salient auditory signals and the inability to suppress incoming information caused by decreased intentional inhibition processes, leading to source monitoring errors and the predominance of top-down mechanisms. A recent systematic review showed a neural overlap between source monitoring and aberrant salience in psychosis, partly confirming possible shared mechanisms between these processes (Kowalski et al., 2021). We hypothesized that there would be relationships between source monitoring errors, top-down influence on perception, and inhibitory processes. The results revealed a significant negative relationship between SM errors and Hits in the top-down processing tasks. More precisely, we found that the more misattributions of imagined actions as being performed, the fewer correct responses on the top-down processing task. At the same time the reverse misattribution pattern (i.e., performed actions recognized as being imagined) was not observed in the top-down processing task. However, when investigating the association between SM errors and response bias (willingness to accept ambiguous noise as meaningful stimuli), the effect was opposite from that which was expected – the more SM errors, the more evidence was needed to confirm that an auditory signal was present in the false perception task. Thus, our preliminary data suggest that there is a connection between SM and false perception in SSD, rather than these processes being independent factors. At the same time, inhibitory control seems to be more independent of false perception errors and SM. To the best of our knowledge, this study is one of the very first to investigate interconnections between processes related to AHs as proposed by Waters et al. (2012). We have found that at least some of these processes may be related to each other; however, their relation to AHs was not confirmed. Future research may benefit from exploring further interconnections between different cognitive processes associated with AHs and other symptoms, providing a better understanding of the interactions between risk factors that may underlie or maintain symptoms of SSD.

4.1. Limitations

There are limitations to the current study. First, despite the fact that the most recent systematic reviews and meta-analyses identify the investigated cognitive processes as being of central importance, they do not fully represent the complex mechanisms underlying AHs (Moseley et al., 2021). Other potentially key processes include attentional control (Conn and Posey, 2000; Moseley et al., 2022), intentional inhibition of memories (Waters et al., 2003), and metacognition (Varese and Bentall, 2011). Moreover, as previously mentioned, task variability is vast across each investigated domain; perhaps the inconclusiveness or variability of results between different studies is due to the implementation of different research methods. As such, it may be difficult to compare the results of this study with those of others. Future studies should take into account the designs of previous studies. Furthermore, there is a wide range of different perceptual abnormalities in patients with SSD, and AHs are only one manifestation. In the present study, we had difficulty choosing how to measure AHs, as PANSS measures hallucinations in all modalities. The goal of the current study was to focus specifically on AHs, which are the most common in SSD. In comparison, PSYRATS provides detailed information on the characteristics of voices while omitting other types of AHs, such as music hallucinations or hearing different kinds of sounds. Future studies may benefit from a structured interview that better represents the complex characteristics of perceptual abnormalities in the auditory modality. Moreover, in the current study, we included patients with current AHs, patients who experienced AHs in the past but not currently, and patients who had never experienced AHs. Therefore, we cannot distinguish whether these findings apply to a state or a trait characteristic of the perceptual system. At the same time, it should be noted that our patients had relatively low symptom severity, including hallucinations; it is possible that results may differ significantly due to differences in overall symptom severity between samples. Finally, the current design does not allow for causal inference. Perhaps the results regarding top-down processes could indicate that patients that constantly experience AHs pay attention to auditory stimuli more carefully and learn to be more alert to any sensory clue and create interpretations. Thus, the causality could be the opposite of that expected – maybe it is the result, rather than the cause, of AHs (Vercammen et al., 2008).

4.2. Conclusions

In conclusion, the current study contributes to previous work on the cognitive mechanisms of AHs in clinical samples. The results showed mixed findings that contrast with contemporary cognitive models of AHs, but, at the same time, revealed the existence of links between AHs and top-down processes as well as intercorrelations between top-down and source monitoring processes – however, in the direction opposite to that which was expected. Future research should further investigate the model of Waters et al. (2012) and compare the tasks' variabilities to shed light on whether the effect depends on task characteristics; future research should also include a sample with higher symptom severity. More studies are needed to further investigate whether there are continuities or discontinuities in the cognitive mechanisms of AHs between clinical and non-clinal samples.

Financial support

This study was supported by the PRELUDIUM BIS grant from the National Science Centre, Poland (ŁG, 2019/35/O/HS6/02982).

Ethical standards

The authors assert that all procedures used in this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

CRediT authorship contribution statement

Adrianna Aleksandrowicz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. **Joachim Kowalski:** Methodology, Writing – review & editing. **Izabela Stefaniak:** Investigation, Writing – review & editing. **Katarzyna Elert:** Investigation, Writing – review & editing. **Łukasz Gawęda:** Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest in relation to the subject of this study.

Data availability

Summary and anonymized data would be available on the basis of a written reasonable request.

Acknowledgments

We would like to thank Joanna Gruhn-Devantier for her help with the clinical assessment of patients. Moreover, we would like to thank all the patients for their participation in the study.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.psychres.2023.115372.

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A cognitive model of perceptual anomalies: The role of source monitoring, top-down influence and inhibitory control processes for hallucinations in schizophrenia spectrum disorders and hallucinatory-like experiences in the general population

Adrianna Aleksandrowicz[1]*, Joachim Kowalski[1], Steffen Moritz[2], Izabela Stefaniak[3], Łukasz Gawęda[1]

[1]Experimental Psychopathology Lab, Institute of Psychology, Polish Academy of Sciences, Warsaw, Poland

[2]Department of Psychiatry and Psychotherapy, University Medical Center Hamburg-Eppendorf, Hamburg

[3]Faculty of Medicine, Lazarski University, Warsaw, Poland

***Corresponding authors:**

Institute of Psychology, Polish Academy of Sciences, Jaracza 1, 00-378 Warsaw, Poland. E-mail addresses: aaleksandrowicz@psych.pan.pl (A. Aleksandrowicz)

abstract length: 244

main text length: 6148

Abstract:

Background: Cognitive models emphasise that source monitoring, top-down processes, and inhibitory control are mechanisms of perceptual anomalies, particularly auditory hallucinations (AHs) and hallucinatory-like experiences (HLEs). Nonetheless, limited research integrates clinical and non-clinical perceptual anomalies to examine these cognitive mechanisms and the connections between them. The present study aimed to investigate the role of three cognitive processes within the perceptual anomalies continuum. Moreover, the study examines the relationship between perceptual anomalies, cognitive processes, self-disturbances, and general functioning.

Methods: Eighty-nine patients with schizophrenia spectrum disorders (SSD) were divided into two groups based on AHs presence - 46 with AHs and 43 - non-hallucinating, 43 matched healthy controls (HC), and a sample selected from the general population of 40 participants with high HLEs and 43 with low HLEs performed three experimental tasks assessing top-down processes (False Perception Task - FPT), source monitoring (Action Memory Task - AMT), and inhibitory control (Go/No-Go Task).

Results: Both patient groups committed significantly more source monitoring errors and more false perceptions (after accounting for response bias) than HC, with no differences between SSD with AH vs SSD without current AH and high HLEs vs low HLEs. No significant group differences were found for false alarms in the Go/No-Go Task. However, there was a significant relationship between perceptual anomalies and all the cognitive processes as well as self-disturbances and functioning in the entire sample.

Conclusions: This study sheds further light on the mechanisms and correlates of perceptual anomalies in clinical and non-clinical populations.

Keywords: hallucination continuum, psychosis**,** psychotic-like experiences**,** cognition, perception

1. Introduction

Perceptual anomalies, particularly hallucinations, are core symptoms for the diagnosis of schizophrenia spectrum disorder (SSD) (Bauer et al., 2011). However, multiple studies have proven that perceptual anomalies are prevalent in the general population (Powers, Kelley, & Corlett, 2017; Sommer et al., 2010). Depending on the types of perceptual anomalies studied and the mode of assessment (interview versus self-report), prevalence rates are estimated from 5% to even 60% in the general population (Beavan, Read, & Cartwright, 2011; Deb, 2015; Linszen et al., 2022). These findings led to a dimensional understanding of psychotic experiences that established the continuum of psychosis hypothesis (Johns & van Os, 2001; van Os, Linscott, Myin-Germeys, Delespaul, & Krabbendam, 2009; Verdoux & van Os, 2002). It has been assumed that hallucinatory-like experiences (HLEs) might share some mechanisms with clinical hallucinations (Waters et al., 2012). Nevertheless, there is ongoing discussion on the nature of the continuum approach (David, 2010; Kaymaz & van Os, 2010; Sommer, 2010). Studies over the perceptual anomalies continuum show mixed findings (Badcock & Hugdahl, 2012; Bell et al., 2024; Moseley et al., 2021, 2022; Toh, Moseley, & Fernyhough, 2022), and there are not many studies combining both clinical and non-clinical populations to compare mechanisms using similar experimental designs. Investigating both populations is crucial to understanding the similarities and differences in their mechanisms. Moreover, studies on the general population circumvent important confounding factors connected to clinical populations (e.g., medications, comorbidity).

Systematic reviews emphasise that no single cognitive mechanism can sufficiently justify perceptual anomalies emergence (Tracy & Shergill, 2013; Waters et al., 2012). Instead, researchers propose that there is an interplay between multiple factors (Gawęda et al., 2024). Recent accounts highlight the role of source monitoring (Brookwell, Bentall, & Varese, 2013), top-down processing (Powers, Kelley, & Corlett, 2016), and inhibitory processes (Waters, Badcock, Michie, & Maybery, 2006) in the formation of perceptual anomalies. The model proposed by Waters et al. (2012) states that misinterpreting the sources of information could cause self-generated information to be perceived as coming from an external source (e.g., misattribution of inner speech to an external source). Moreover, overreliance on top-down processes can result in perceptual priors dominating the formation of perceptual experiences (Corlett et al., 2019). Subsequently, atypical inhibitory processes could explain the uncontrollable element of hallucinations (Waters, Badcock, Maybery, & Michie, 2003). Together, these processes might contribute to the emergence of perceptual anomalies.

Some studies found that source monitoring errors are associated with clinical hallucinations in SSD (Gawęda, Woodward, Moritz, & Kokoszka, 2013; Woodward, Menon, & Whitman, 2007) and HLEs in the general population (Larøi, Van der Linden, & Marczewski, 2004), whereas others showed no such link (Alderson-Day et al., 2019;

Moseley et al., 2021, 2022). Several studies showed a link between HLEs in the general population and top-down processing measured by experimental tasks based on Signal Detection Theory (SDT) (de Boer et al., 2019; Laloyaux, Hirnstein, Specht, Giersch, & Larøi, 2022; Moseley et al., 2021, 2022; Ans Vercammen & Aleman, 2010). However, there are few studies with more mixed findings on patients diagnosed with SSD, especially since there are very little amount of studies with a direct comparison between hallucinating and non-hallucinating patients. These studies demonstrated differences between patients diagnosed with SSD and HC (Gawęda & Moritz, 2021); however, when hallucinating patients were compared with non-hallucinating patients, the findings were not confirmed (Aleman, Böcker, Hijman, de Haan, & Kahn, 2003; Kowalski et al., 2024) or exhibited mixed results (Vercammen, de Haan, & Aleman, 2008). One line of studies showed a potential link between clinical hallucinations and intentional inhibition (Waters et al., 2006). Whereas a recent study investigating a relationship between clinical hallucinations in patients diagnosed with SSD and inhibitory control showed no such link (Aleksandrowicz, Kowalski, Stefaniak, Elert, & Gawęda, 2023), the amount of studies on inhibitory processes are still too small to allow strong inferences

Inconsistencies in findings are usually attributed to differences in (task) design, different procedures in population selection, small sample sizes, and publication bias (Bell et al., 2024). Hence, more research is needed to verify the dimensional approach to perceptual anomalies. Moreover, perceptual anomalies have been linked to social functioning (Buck et al., 2022) and self-disturbances (Rasmussen, Raballo, Preti, Sæbye, & Parnas, 2021). Still, more studies are needed to combine these perspectives in clinical and non-clinical contexts.

Thus, our project aims to investigate mechanisms of perceptual anomalies on the hallucination continuum. To our knowledge, this is the first study that integrates all of the aforementioned cognitive mechanisms – source monitoring, top-down processing, and inhibitory control – within the hallucination continuum. For these purposes, we aimed to recruit patients diagnosed with SSD that would be divided into currently hallucinating and non-hallucinating (study I) and to investigate a sample derived from the general population frequently experiencing HLEs in comparison to the low HLEs group (study II). Additionally, the relationship between perceptual anomalies, cognitive factors, self-disturbances, and functioning (social and occupational) was explored. Together, we aimed to test the theoretical framework of perceptual anomalies proposed by Waters et al. (2012) by combining the range of hallucinatory-like experiences in one model of the hallucination's continuum.

2. Methods

2.1. Participants

Part of the data was previously analysed (the correlations between source monitoring, top-down processes, inhibitory control and psychotic symptoms, e.g., hallucinations on a sample of patients with SSD) (Aleksandrowicz et al., 2023). Forty-six patients diagnosed with schizophrenia spectrum disorders (SSD) with current auditory hallucinations (SH group), 43 patients without auditory hallucinations (SN group), and 46 healthy controls (HC) were included in the study I. The patient's diagnoses included schizophrenia (n=83), schizoaffective disorder (n=1), schizotypal disorder (n=2), and brief psychotic disorder (n=1). After data inspection, n=1 was excluded from further analyses due to poor performance on multiple tasks. Moreover, experimental data from n=10 has been excluded due to troubles with completing, poor performance or technical errors on one of the three behavioral tasks. One patient did not complete the the Positive and Negative Syndrome Scale (PANSS) interview due to circumstances caused by COVID-19. Some patients did not complete surveys. Forty-three participants with low HLEs and 40 with high HLEs met the inclusion criteria for study II. After data inspection, experimental data from n=1 has been excluded due to poor performance on the Go/No-Go Task. Several participants did not complete surveys. Thus, sample sizes might vary depending on the specific variable.

Patients were recruited via clinical centres, e.g., Institute of Psychiatry and Neurology, Warsaw (Poland), outpatient clinics across Warsaw, as well as via advertisement on social media platforms. For the patients diagnosed with SSD groups, the division was determined by the presence of auditory hallucinations measured by the PANSS (Kay, Fiszbein, & Opler, 1987) P3 item (only auditory hallucinations were considered for this classification). Patients scoring 1 or 2 were classified as currently not hallucinating, and with ≥ 3 were classified as currently hallucinating. Additionally, the inclusion criteria for the hallucinating group were experiencing auditory hallucinations for at least a week prior to the study, and for the non-hallucinating group, a lack of auditory hallucinations for at least one month prior to the study. The control group was matched with the clinical groups regarding gender, age, and education.

In study II, participants from the general population were recruited via a recruitment company and social media platforms. A screening procedure was conducted using the CAWI method. A sample of 3141 individuals was screened in an online survey using the Revised Hallucination Scale (RHS) and demographics questions. The screening procedure was divided into several stages from February 2022 to January 2024. Participants were asked to rate hallucinatory-like experiences during the past month. After each screening stage, 5-10% of participants with the highest scores on RHS and 5-10% with the lowest scores were selected for the telephone interview, where the inclusion criteria were verified. After the preliminary meeting of the inclusion criteria, participants were invited to the Institute of Psychology, Polish Academy of Sciences. The clinical interview was performed using a structured interview with the Neuropsychiatric Interview (MINI 5.0) (Lecrubier et al., 1997) in study

I and study II. Additionally, in study I, the symptom severity of patient groups was assessed using the PANSS interview.

The inclusion criteria for the clinical groups included: age between 18 and 45 years old, stable state (i.e., no agitation, able to make contact with the person administering the experiment) and medication (the same dosage for at least two weeks), and lack of severe formal thought disorders. The inclusion criteria for the healthy participants were age between 18 and 45 years old, lack of current mental health disorders (or a history of any psychotic disorders, bipolar disorder, or a diagnosis of borderline personality disorder). The exclusion criteria for all the groups included alcohol or other substance dependence in the past 12 months, the presence of severe neurological disorders, intellectual disability, or hearing impairments. Before the study, all participants received written and verbal information about the study and provided written informed consent. All participants received financial reimbursement for participation (117.5 PLN – approximately 27.5 USD). The study was approved by the local ethics committee at the Institute of Psychology, Polish Academy of Sciences.

2.2. Psychopathology Assessment

All participants were assessed with a clinical interview - MINI (Lecrubier et al., 1997) to screen for major psychiatric problems. Patients diagnosed with SSD were assessed using PANSS (Kay et al., 1987; Kay & Sevy, 1990; Kay, 1991). PANSS scores were calculated based on the five-factor model: Positive (α = 0.61), Negative (α = 0.86), Disorganized (α = 0.58), Excited (α = 0.43), and Depressed (α = 0.59) symptoms. Cronbach's α for the total PANSS was 0.79. Additionally, The Examination of Anomalous Experiences (EASE) (Parnas et al., 2005) was performed in both Study I and II. The EASE interview allows for an in-depth evaluation of self-disturbances, including a wide range of different perceptual abnormalities. For the purposes of the current study, we assessed the parts from the domains: (1) Cognition and Stream of Consciousness (that domain involves a typical sense of consciousness that is perceived as continuous, fluid, occupied by a single subject, and introspectively transparent in a nonspatial manner) and (4) Demarcation/Transitivism (that domain investigates loss or transmittance of self-world boundaries). These particular parts were chosen to expand the characteristics of different perceptual disturbances, especially those connected to self-world boundaries, discriminating between self and others (similar to self-monitoring), or giving a more detailed examination of thought processes. In addition, basic demographic information was collected such as age at illness onset, duration of the illness, number of inpatient and outpatient hospitalisations, as well as chlorpromazine equivalent.

2.3. Experimental tasks

2.3.1. The Action Memory Task (AMT)

The AMT (Gawęda, Moritz, & Kokoszka, 2012; Gawęda et al., 2013; Moritz, Ruhe, Jelinek, & Naber, 2009) assesses source monitoring errors. In this task, verbal instructions or nonverbal pictograms of actions were presented. Participants were instructed to perform actions presented in the green frame (if the instructions do not state precisely, actions can be performed with the chosen arm/leg/foot) and imagine actions presented in the red frame. During the instruction phase, participants were asked to memorise the presented actions as there would be a recollection after the experiment. Then, during the practice trial, participants were familiarised with the experiment. In the main task, 18 verbal and 18 nonverbal actions were presented on the computer screen. Each included 9 actions to be performed and 9 to be imagined. Instructions were displayed for 10s for each trial, then a button press was required to continue to the next action. Participants were asked to either perform or image each action for the entire trial display. Before the recollection, the Go/No-Go task was performed, which took approximately 10 min. Then, 36 verbal instructions for all the actions were presented together with 20 new actions (the recognition items were displayed in a different font from the items in the primary task to prevent physical matching). Participants were asked three questions: 1) whether the corresponding instruction was presented either verbally or nonverbally or was not presented at all (presentation type differentiation); 2) to rate their confidence in their answer on a four-point scale ranging from 100% certain (response 1) to extremely uncertain (response 4); and 3) to choose whether the action had been performed or imagined (self-monitoring), graded for confidence (1 – *certain imagined*; 2 – *not certain imagined*; 3 – *certain performed*; 4 – *not certain performed*; 5 – *new action*). All items were randomised (both in the learning and recognition phases).

2.3.2. False Perception Task (FPT)

In the FPT (Gawęda & Moritz, 2021), participants were instructed that they would hear words embedded in the "street noise" through stereo headphones. Words were presented with different levels of audibility: 60% were audible and 40% were nonaudible. Participants were asked to press a button on the keyboard to decide whether or not they had heard the word (yes/no forced choice response). The words were presented in three expectancy conditions. In the low expectancy condition, the target stimulus was not preceded by any cue. In the intermediate expectancy condition, the target stimulus was introduced in the form of text on the computer screen (the same word as the target stimulus) before the presentation of the target stimulus. In the high expectancy condition, after the text presentation, an integrated audio and a video recording of an actor mouthing the word was presented. In all cases, the cues were consistent with the audible stimuli. The stimuli included 60 neutral words from the Polish version of the Berlin Affective Word List Reloaded. Stimuli were categorised into blocks of six words. Three different blocks (three conditions) were repeated five times. Stimuli within the block were pseudorandomised and the block order was randomised. There were three repetitions of each word for each expectancy condition, which resulted in 180 trials. Each target stimulus was present for 2s, and then an additional 3s were given to respond after the stimulus had occurred. Inter-stimulus intervals ranged between 750 and 1500 ms, and inter-block intervals ranged between 1500 and 2500 ms. The task was designed using Psychopy (Peirce et al., 2019). Before the task, participants could adjust the volume to a comfortable level. To adjust the volume, street noise was played starting from the system maximum (100%) and reduced every 10pp until a comfortable loudness level was achieved. Then, participants could re-adjust the volume levels after the practice trial.

2.3.3. Go/No-Go task

This task was based on the previously designed auditory Go/No-Go task (Weisbrod, Kiefer, Marzinzik, & Spitzer, 2000). During the task, four blocks of 40 infrequent high-pitched tones were presented. Tones were pseudorandomly distributed between 160 frequent low-pitched tones and presented binaurally for 40 ms. The interstimulus interval randomly varied, ranging from 1.3 to 1.7 s. The instruction stated to press the space key on the keyboard using a dominant hand when the frequent tone was presented and to refrain from responding when the rare tone was presented. The frequent tone was displayed at 1000 Hz, and the infrequent tone at 2000 Hz. Tones order was randomised between the participants. The practice trial consisted of 12 trials that provided feedback after each trial. Participants could continue with the main task after understanding the instructions and performing correctly on the majority of the practice trial. The primary task did not include feedback information.

2.4. Questionnaires

2.4.1. Revised Hallucination Scale (RHS)

The RHS (Morrison, Wells, & Nothard, 2002) is a 24-item self-report scale that measures the frequency of a wide range of hallucinatory-like experiences. RHS was adapted by our group into Polish (Gaweda & Kokoszka, 2011). For the purposes of the current study, only a total score was included. Cronbach's alpha for this scale was 0.95.

2.4.2. Cardiff Anomalous Perceptions Scale (CAPS)

The CAPS (Bell, Halligan, & Ellis, 2006) is an assessment of hallucinatory experiences. It consists of 32 items (e.g., "Do you ever hear noises or sounds when there is nothing about to explain them?") with "yes" and "no". If responded with a ''yes'' to the initial question, participants are asked to rate the item for distress, intrusiveness, and frequency of occurrence on a 5-point (1–5). For the purposes of the current study, three subscales were included: Sensory Flooding, Thought Echo, and Hearing Thoughts Out Loud, Temporal Lobe subscales. The outcome variable included the total number of items. Further subscales on distress, intrusiveness, and frequency were not included in the current analysis. Cronbach's alpha for the sum of three subscales was 0.78.

2.4.3. Multi-Modality Unusual Sensory Experiences Questionnaire (MUSEQ)

The MUSEQ (Mitchell et al., 2017) is a 43-item self-report measure that assesses perceptual anomalies in six modalities: auditory, visual, olfactory, gustatory, bodily sensations, and sensed presence. The MUSEQ shows good reliability and construct validity. Moreover, can discriminate between non-clinical and clinical populations. MUSEQ was adapted by our group into Polish (Kowalski et al., 2024). Cronbach's alpha for this scale was 0.97.

2.4.4. Social and Occupational Functioning Assessment Scale (SOFAS)

SOFAS (Goldman, Skodol, & Lave, 1992) is a global rating of current functioning ranging from 0 to 100, where higher scores indicate higher functioning. The SOFAS focuses on social and occupational functioning independent of the overall severity of the individual's psychological symptoms.

2.5. Data preparation

Analyses were conducted using Python software version 3.10 (Pilgrim, 2010). The parameters of the experimental tasks were calculated. For AMT the primary variable of interest was the number of imagined actions misattributed as performed as well as performed actions misattributed as imagined (internal source monitoring errors). For the FPT task, the primary variable of interest was the false perception ratio (The ratio of the number of false perceptions to the number of nonaudible trials with the exclusion of omissions). Additionally, Signal Detection Theory (SDT) parameters (Stanislaw & Todorov, 1999) were calculated: task sensitivity, d' (how well the participant could distinguish signal from noise), calculated as standardised False Alarm Rate (FA) subtracted from the Hit Rate (H); and response bias measures: β and c - criterion (the tendency of biased responses on the task or the criterion the participant uses to decide on the presence of a stimulus). The primary variable of interest for the Go/No-Go was false alarms.

2.6. Data analysis

Firstly, for the FPT unreliable responses were removed from the analyses blind to results (reaction time below 500ms). Single missing data responses were handled using the imputation method replacing missing responses with a mean (van Buuren, 2018). It was implemented in the case of PANSS (8 missing responses), RHS (1 missing response), and MUSEQ (1 missing response). Then, z-scores were calculated for all tasks for correct response parameters. The exclusion criteria were z-scores of -3 or more for one or more tasks. Data analysis was conducted according to the parametric test assumptions, and nonparametric tests were performed when parametric test assumptions were violated. For the study I, group differences were calculated using Kruskal-Wallis ANOVA. Post hoc tests were calculated using Dunn's Test with the Holm correction. For the FPT (study I and study II), group differences with the expectancy conditions as factors were calculated with repeated measures ANOVA with a Greenhouse-Geisser correction. Then, for additional analysis, response bias parameter - c (the tendency to be biased in yes/no responses on the task or the criteria participants use to determine the presence of a stimulus); $c=-\frac{1}{2}(Z(\text{Hit Rate})+Z(\text{False Alarm Rate}))$ was added as a covariate. For study II, group differences were calculated with repeated measures ANOVA accounting for age (due to statistical differences in age between high HLEs and low HLEs groups). Then, for the additional analysis, response bias was added as a covariant. Post hoc tests were calculated using Bonferroni correction. Next, associations between all primary measurements from three experimental tasks (FPT, AMT, Go-No/Go), HLEs measurements (RHS, MUSEQ, CAPS), self-disturbances (EASE), and social and occupational functioning (SOFAS) were examined with Spearman's rho correlations. Holm correction for multiple comparisons was applied with a 5% false discovery ratio to control for false positives (Rice, Schork, & Rao, 2008). Then, a hierarchical regression model was created to search for possible predictors of perceptual anomalies measured by CAPS (sum of three subscales). A logarithmic transformation was implemented since the CAPS was positively skewed.

3. Results

3.1. <u>Study I: Patients with SSD with hallucinations and without hallucinations compared to the control group</u>

3.1.1. Sample characteristics

There were no group differences in any demographic variables. SH and SN groups did not differ in the number of in and out-patient hospitalisations and illness duration. There were significant differences in the age of onset and chlorpromazine equivalent. Clinical groups differed on the total score and positive subscale of PANSS. Moreover, there were significant differences in self-report measures. Detailed patient characteristics are presented in Table 1.

3.1.2. Between-group differences

3.1.2.1. Source monitoring

There was a significant effect of group in imagined actions misattributed as performed $H(2,130) = 17.97$, $p < 0.001$, $\eta p^2 = 0.12$. Post hoc analysis revealed that both clinical groups significantly more often misattributed imagined actions as being performed than the HC ($p<0.01$), with no significant differences between the clinical groups.

3.1.2.2. Top-down processing

There were no group differences in volume levels $H(2,126) = 3.03$, $p = 0.22$, $\eta p^2 = 0.01$ (SH: M = 37.8, SD=20.5, range: 5 – 90; SN: M = 44.3, SD=18.9, range: 20 – 100; HC: M = 43.0, SD=20.7, range: 15 – 100).

There was a significant effect of condition in false perceptions ratio $F(1.48, 191.90) = 9.14$, $p < 0.001$, $\eta p^2 = 0.07$, with the low expectancy condition eliciting the smallest number of false percepts and the high expectancy eliciting the greatest amount. Moreover, there was a significant between-groups effect, $F(2,130) = 7.71$, $p < 0.001$, $\eta p^2 = 0.11$, with post hoc tests indicating that the SN group committed significantly more false perception errors than the HC (no significant differences between the SH and HC groups). The difference between SN and SH groups was on the verge of statistical significance ($p = 0.053$; SN > SH). The condition x group interaction was not significant $F(2.95,191.90) = 1.99$, $p = 0.118$, $\eta p^2 = 0.03$. However, when response bias (criterion) was added as a covariate, there were significant differences between both clinical groups and HC ($p < 0.05$), but not between the SH and SN groups ($p = 0.970$). The figure after accounting for the criterion can be found in the Supplementary materials.

3.1.2.3. Inhibitory control

There were no significant differences among groups for false alarms in the Go/NoGo Task $H(2,130) = 1.58$, $p = 0.45$, $\eta p^2 = 0.06$.

3.2. <u>Study II: Participants with high HLEs compared to low HLEs</u>

3.2.1. Sample characteristics

There were significant differences in age between the two groups. Thus, group differences were calculated by accounting for age. There were no significant differences in any of the remaining demographic characteristics. Groups differed significantly on perceptual anomalies measurements. Details are presented in Table 1.

[Table 1]

3.2.2. Between-group differences

3.2.2.1. Source monitoring

There were no significant differences between groups for imagined actions misattributed as performed $F(1,81) = 1.997$, $p = 0.161$, $\eta p\ 2 = 0.01$ when controlling for age.

[Figure 1]

Top-down processing

There were no group differences in volume levels $F(1,79) = 2.66$, $p = 0.107$, $\eta p\ 2 = 0.02$ (high HLEs: M = 41.5, SD = 20.3, range: 5 – 90; low HLEs: M = 38.5, SD = 16.5, range: 7 – 80).

There was no significant effect of condition in false perception ratio $F(1.59,127.25) = 0.58$, $p = 0.53$, $\eta p\ 2 = 0.01$. The group effect was insignificant, $F(1,80) = 0.96$, $p = 0.33$, $\eta p\ 2 = 0.01$. The condition x group interaction was not significant $F(1.59,127.25) = 1.60$, $p = 0.21$, $\eta p\ 2 = 0.02$. Subsequently, the criterion was added as a covariate alongside age, which did not significantly alter the results. The figure after accounting for the criterion can be found in the Supplementary materials.

[Figure 2]

3.2.2.2. Inhibitory control

There were no significant differences between groups for false alarms in the Go/NoGo Task $F(1,80) = 0.46$, $p = 0.50$, $\eta p\ 2 = -0.01$.

[Figure 3]

3.3. Continuous model

3.3.1. Correlation matrix

Correlational analyses were performed for the total sample (Table 2).

[Table 2]

3.3.2. Hierarchical regression analysis

Table 3 shows a summary of the regression analyses. All models were statistically significant at all three steps. At step one, imagined as performed errors were a significant predictor: $F(1,201) = 20.243$, $p < 0.001$, $R2 = 0.095$ of CAPS subscales. At step two, the false perception ratio in the FPT explained an additional 8.1% of the variation in the CAPS score, and the change in R2 was significant: $F(2,200) = 20.803$, $p < 0.001$. Adding false alarms in Go/No-Go explained an additional 1.9%, and the change in R2 was significant $F(3,199) = 15.906$, $p < 0.001$. Together, all variables accounted for 19.4% of the variance in the CAPS score.

[Table 3]

4. Discussion

The aim of these two studies was to investigate the extended cognitive model of hallucinations (Waters et al., 2012), positing the role of source monitoring, top-down processes, and inhibitory control across the continuum of hallucinations. In the first study, patients experiencing AHs (SH) and non-hallucinating (SN) patients were compared to the HC. In the second study, we compared people without current diagnoses of psychological disorders who had high HLEs and low HLEs. Additionally, we aimed to further verify the hallucination continuum hypothesis by investigating the relationship between perceptual anomalies measured by self-reports and cognitive processes as well as self-disturbances and social functioning in the entire sample.

4.1. Source monitoring

Results in the clinical sample regarding source monitoring (SM) are contrary to the models of AHs (Brookwell et al., 2013; Waters et al., 2012). Findings revealed significant differences between both clinical groups and HC, but no differences between SH and SN groups were found. For many years, SM has been a cognitive process most often associated with mechanisms of hallucinations (Brookwell et al., 2013), but so far, the evidence is mixed (Gawęda et al., 2024; Kowalski, Aleksandrowicz, Dąbkowska, & Gawęda, 2021). Some previous research showed an atypical performance in SM tasks in hallucinating patients in comparison to the non-hallucinating population (Allen et al., 2007; Gawęda et al., 2013). Moreover, there is a line of research showing that SM could be connected to other symptoms of schizophrenia, such as delusions (Brodeur, Pelletier, & Lepage, 2009) or disorganization (Docherty, 2012; Nienow & Docherty, 2004).

Additionally, non-clinical participants with various levels of HLEs did not differ significantly in the amount of SM errors. Studies regarding SM in the non-clinical populations are still scarce. One study showed an association between SM and proneness to hallucinations (Larøi et al., 2004). However, the current results align with more recent studies on non-clinical voice-hearers (Moseley et al., 2022) and a large sample from the general population (Moseley et al., 2021), where associations between perceptual anomalies and SM were not found. Another study on hallucination-prone participants displayed no differences between high and low hallucination proneness groups in externalising bias as well as internal SM (Garrison et al., 2017). Alternatively, studies on ultra-high risk (UHR) populations demonstrated increased SM errors compared to HC (Gawęda et al., 2018; Nelson et al., 2020), indicating that the closer one gets to the clinical symptoms, the more pronounced the deficit, although it may not be symptom-specific. Hence, growing evidence suggests that source monitoring deficits might not be a key cognitive process associated with HLEs but rather non-specifically connected to the symptomatology of psychosis.

4.2. Top-down processes

Similarly, contemporary models indicate that top-down processes play an important role in perceptual anomalies formation (Corlett et al., 2019; Powers et al., 2016). However, the current study's results are mixed, showing that top-down errors were generally linked to schizophrenia symptoms rather than specifically to AHs. These findings align with previous research comparing patients with SSD to HC (Gawęda & Moritz, 2021). Contrary to our hypothesis, patients with SSD who experienced hallucinations reported fewer false perceptions than non-hallucinating patients. However, after accounting for response bias, both groups had similar false perception ratios, suggesting that a more liberal response style might interfere with the observed effect. It is worth noting that only a few studies directly compared hallucinating with non-hallucinating patients on false perception, often with mixed results (Aleman et al., 2003; Kowalski et al., 2024; Vercammen et al., 2008). Additionally, no significant differences were found between participants with high and low HLEs. One explanation could be a study population. We recruited participants with the highest scores on a questionnaire measuring different perceptual anomalies, following previous studies on the general population (Laloyaux et al., 2022; Vercammen & Aleman, 2010) This resulted in obtaining a sample with more diverse and time-fluctuating experiences. Therefore, the current lack of group effects compared to previous studies (de Boer et al., 2019; Moseley et al., 2021, 2022) could be due to the severity and type of hallucinatory experiences. Still, it is worth highlighting that a non-clinical sample was selected from a general population based on detailed inclusion criteria and was screened with a clinical interview for the presence of current mental disorders to exclude false positive effects - as studies show that hallucinations are prevalent across different disorders such as depression or bipolar disorder (Toh, Thomas, & Rossell, 2015). Another explanation for the lack of significant results compared to previous studies might be due to differences in task designs, such as the type of stimuli or noise implemented (Barkus, Stirling, Hopkins, McKie, & Lewis, 2007; Laloyaux et al., 2022; Ans Vercammen & Aleman, 2010).

Our study measured expectancy-dependent top-down errors, hypothesising that higher expectancy levels would lead to more errors, as shown in a previous study (Gawęda & Moritz, 2021). We expected false perceptions to increase gradually, most pronounced in clinical samples, particularly among hallucinating patients compared to non-hallucinating patients and in high HLEs compared to low HLEs. Results showed a significant effect of condition in patient groups but no interaction between groups and conditions. No significant effects were found in non-clinical samples. Sensitivity analysis (after accounting for response bias) revealed the SSD group was slightly more liberal in decision-making (more likely to say yes when making a decision). After controlling for response bias, both patient groups showed similar false perception errors, increasing linearly with expectancy levels. Non-clinical samples exhibited a V-shaped effect (more false perception errors in the low expectancy condition than in the medium condition and similar in the high expectancy condition), though this effect was insignificant. Future studies should investigate how expectancy differences influence clinical and non-clinical groups experiencing perceptual anomalies.

4.3. Inhibitory processes

Another core mechanism in the model proposed by Waters et al. are inhibitory processes. Several studies highlight the significance of these processes in the development of hallucinations (Sun et al., 2021; Waters et al., 2003; Waters et al., 2006). Likewise, research shows a link between hallucinatory experiences in the general population and intentional inhibition deficits (Alderson-Day et al., 2019; Paulik, Badcock, & Maybery, 2007). However, we did not find significant differences between clinical and non-clinical groups. One possible explanation pertains to the type of inhibitory control investigated in the current study. Previous studies that found a significant association with perceptual anomalies implemented different components of inhibitory control processes, especially intentional/unintentional inhibition (Waters et al., 2003; Waters et al., 2006) and inhibition of irrelevant memories (Badcock, Waters, Maybery, & Michie, 2005; Paulik, Badcock, & Maybery, 2008). In the current study, we investigated immediate/momentary inhibitory control processes as this component has been less frequently explored. One study (Sun et al., 2021) on patients with SSD who were divided into hallucinating and non-hallucinating groups showed differences between both patient groups and HC, but not within the clinical groups. Perhaps immediate inhibitory processes are not specific to those experiencing hallucinations. Our previous results indicated that inhibitory control might be more connected to negative and disorganised symptoms of schizophrenia rather than specific to hallucinations (Aleksandrowicz et al., 2023). However, there is no evidence to draw certain conclusions, as immediate inhibitory control processes in the context of perceptual anomalies are still understudied. To our knowledge, this is the first study to directly compare immediate/momentary inhibitory control processes between clinical and non-clinical samples. This area of research remains understudied, and further investigation is required to draw more definitive conclusions.

4.4. Continuous model

Finally, we examined the entire sample to explore the continuous model of perceptual anomalies. Results showed the strongest associations between SM errors and social functioning and significant correlations among all measures of perceptual anomalies and self-disturbances. For top-down processes, false perception errors had the strongest relationship with self-disturbances and perceptual anomalies (measured by CAPS). Inhibitory processes were weakly connected to perceptual anomalies and social functioning, but these results did not survive correction for multiple comparisons. Hence, the only associations between all cognitive domains were significant for parts of the CAPS scale measuring various perceptual experiences (e.g., thought echo, hearing thoughts out loud or sensory flooding - feeling overwhelmed by sensory information), possibly indicating that these experiences could be most strongly associated with tested cognitive processes.

Furthermore, we hypothesised that there would be relationships between source monitoring errors, top-down processes, and inhibitory processes, but we found no correlations for primary outcome variables. Those results contradict contemporary cognitive models of perceptual anomalies (Waters et al., 2012), suggesting joint interaction between these processes contributes to perceptual anomalies. However, our previous study found correlations between SM and correct responses and response bias in the top-down task in patients with SSD (Aleksandrowicz et al., 2023), but the results were opposite from expected—more SM errors required more evidence to confirm the presence of auditory stimuli. These findings suggest a complex interplay between cognitive processes, thought processes, self-disturbances, and social functioning. The complexity of investigating perceptual anomalies might involve multiple continua (Waters & Fernyhough, 2019), including factors like functioning, other perceptual disturbances, distress, cognitive control, associated dysfunction, and neurodevelopmental brain changes (Garrison, Fernyhough, McCarthy-Jones, Simons, & Sommer, 2019; Powers, van Dyck, Garrison, & Corlett, 2020). Larger-scale studies with complex designs accounting for potential confounding variables are needed to answer these questions.

4.5. Limitations

The two studies face several limitations. Firstly, the severity of the symptoms in the clinical sample was relatively low (including hallucinations) compared to some previous studies (Powers, Mathys, & Corlett, 2017; Varese, Barkus, & Bentall, 2012). Similarly, most of our sample of high HLEs did not experience hearing voices. Phantom phone ringing/vibrations or hearing their names or sounds, such as footsteps, doorbells, etc., were more prevalent in this group. Thus, future studies should consider whether frequency and severity of the symptoms might play a role in the lack of group differences in the current study, as well as focus more on comparisons between populations with specific perceptual anomalies to look more closely at the differences in mechanisms across various phenomenological experiences. Secondly, various experimental task designs make generalising the results and comparing the studies difficult. In the current investigation, we implemented an internal source monitoring paradigm as it showed specificity for hallucinations in the previous studies (Franck et al., 2000; Gawęda et al., 2013). However, the majority of previous findings highlight the role of the reality monitoring paradigm (Gawęda et al., 2024). Although theoretical models highlight the role of the investigated processes as of key importance (Waters et al., 2012), the mechanisms of perceptual anomalies represent a more complex phenomenon. Future research should consider other studied processes, e.g., attentional control, intentional inhibition, working memory, or language functions (Bell et al., 2024; Toh et al., 2022). Perhaps different perceptual features are associated with specific cognitive markers. Lastly, the study design does not allow the determination of causal relationships. Thus, future research should implement longitudinal designs and use more methods to capture the time-variability of perceptual experiences.

4.6. Conclusions

Our results add another layer to the discussion on the continuities and discontinuities in the contemporary models of AHs and bring a new direction to search for other factors that might mediate the relationship between perceptual anomalies and cognitive functions. Our studies revealed some discrepancies between the theoretical framework of Waters et al. (2012) and empirical evidence. Thus, more studies are needed to verify the model further. Future research should compare the various task designs discussed to identify the effects observed in current and past studies. It should also consider the severity of symptoms and differentiate types of perceptual experiences to investigate the mechanisms behind various perceptual anomalies more precisely. Additionally, researchers should examine whether broader perceptual experiences, such as self-disturbances or thought processes, contribute to the observed effects.

Funding

This study was supported by the PRELUDIUM BIS grant from the National Science Centre, Poland (ŁG, 2019/35/O/HS6/02982) and the NAWA travel grant (PPN/STA/2021/1/00016/U/00001).

Ethical standards

The authors assert that all procedures used in this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

CRediT authorship contribution statement

Adrianna Aleksandrowicz: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft. Joachim Kowalski: Methodology, Investigation, Writing – review & editing. Steffen Moritz: Methodology, Writing – review & editing. Izabela Stefaniak: Investigation, Writing – review & editing. Łukasz Gawęda: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Conflicts of Interest

The author(s) declare that there were no conflicts of interest with respect to the authorship or the publication of this article.

Acknowledgements

We would like to thank Katarzyna Elert, dr Michał Jarkiewicz, dr Justyna Sędek, Joanna Gruhn-Devantier, Małgorzata Kostka, Alicja Fidler and Martyna Tomczyk for help with the assessment of the participants. Moreover, we would like to thank all the participant for their involvement in the study.

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Table 1. Descriptive characteristics for study I and study II

	SH (n=46)	SN (n=43)	HC (n=46)	Statistical Test (F/T/χ²)	p-value	high HLEs (n=40)	low HLEs (n=43)	Statistical Test (T/χ²)	p-value
age	32.65 (7.37)	33.70 (8.53)	31.80 (7.53)	1.18	0.554	28.45 (8.01)	32.79 (8.03)	-2.46	0.016
gender	48% female	49% female	63% female	2.65	0.265	63% female	56% female	0.16	0.692
education	44% higher	37% higher	48% higher	7.22	0.513	58% higher	60% higher	1.39	0.709
number of inpatient hospitalizations	5.84 (5.01)	4.45 (4.98)	-	1.31	0.195	-	-	-	-
number of outpatient hospitalizations	1.29 (1.67)	1.64 (3.73)	-	-0.57	0.568	-	-	-	-
illness duration year	12.33 (7.88)	9.79 (6.75)	-	1.60	0.114	-	-	-	-
age of onset year	20.26 (5.18)	23.91 (7.89)	-	-2.51	0.014	-	-	-	-
Chlorpromazine eqv. (mg)	708.52 (302.48)	506.96 (257.53)	-	3.05	0.003	-	-	-	-
PANSS total	61.15 (10.30)	51.88 (12.71)	-	3.77	<0.001	-	-	-	-
PANSS positive	14.72 (4.15)	9.10 (3.83)	-	6.58	<0.001	-	-	-	-
PANSS P3	4.28 (0.72)	1.10 (0.30)	-	26.69	<0.001				
PANSS negative	14.28 (6.05)	12.48 (6.12)	-	1.39	0.168	-	-	-	-
PANSS disorganized	6.09 (3.01)	5.29 (1.67)	-	1.52	0.131	-	-	-	-
PANSS excited	5.33 (1.83)	4.88 (1.42)	-	1.27	0.208	-	-	-	-
PANSS depressed	8.43 (2.80)	8.74 (2.85)	-	-0.50	0.616	-	-	-	-
RHS total	46.46 (13.87)	41.13 (11.61)	30.12 (3.72)	120.28	<0.001	46.73 (9.76)	25.53 (1.68)	14.02	<0.001
MUSEQ total	98.59 (40.14)	83.79 (33.18)	53.90 (9.53)	98.96	<0.001	89.22 (32.98)	47.05 (5.62)	8.26	<0.001
MUSEQ Auditory	20.80 (7.34)	17.00 (6.17)	11.30 (3.39)	33.80	<0.001	20.38 (6.09)	9.02 (3.15)	10.77	<0.001
CAPS total	3.11 (2.05)	2.79 (1.79)	0.25 (0.61)	118.04	<0.001	2.05 (1.77)	0.00 (0.00)	7.61	<0.001
SOFAS	56.60 (15.32)	69.10 (16.45)	89.11 (7.80)	94.54	<0.001	88.40 (8.13)	86.44 (10.75)	0.93	0.355
EASE total	4.56 (2.83)	4.26 (3.37)	0.37 (0.53)	113.29	<0.001	2.33 (2.06)	0.19 (0.45)	6.66	<0.001

Note: n = 3 patients did not take antipsychotic meditation during the study and, for n = 8, it was impossible to calculate the chlorpromazine equivalent. Missing data for total sample: education, number of hospitalizations (n=1); illness duration (n=4); PANSS (n=1); RHS (n=19); MUSEQ (n=23); CAPS (n=3); SOFAS (n=33)

Table 2. Spearman's correlations on the total sample (study I and study II)

Variable	1	2	3	4	5	6	7	8	9
1. Imagined as performed	—								
2. False perceptions ratio	0.100	—							
3. GNG false alarms	0.101	0.109	—						
4. CAPS total	**0.312** ***	**0.265** ***	0.161 *	—					
5. MUSEQ total	**0.283** ***	0.206 **	0.140	**0.728** ***	—				
6. MUSEQ Auditory	**0.270** ***	0.191 **	0.104	**0.651** ***	**0.935** ***	—			
7. RHS total	**0.235** ***	0.204 **	0.094	**0.712** ***	**0.860** ***	**0.806** ***	—		
8. EASE total	**0.217** **	**0.328** ***	0.110	**0.760** ***	**0.695** ***	**0.658** ***	**0.669** ***	—	
9. SOFAS	**-0.405** ***	-0.182 *	-0.171 *	**-0.481** ***	**-0.277** ***	-0.215 **	-0.244 **	**-0.423** ***	—

* p < .05, ** p < .01, *** p < .001

Note: Computed correlation used spearman-method with listwise-deletion. Bold values are significant after Holm correction for multiple comparisons.

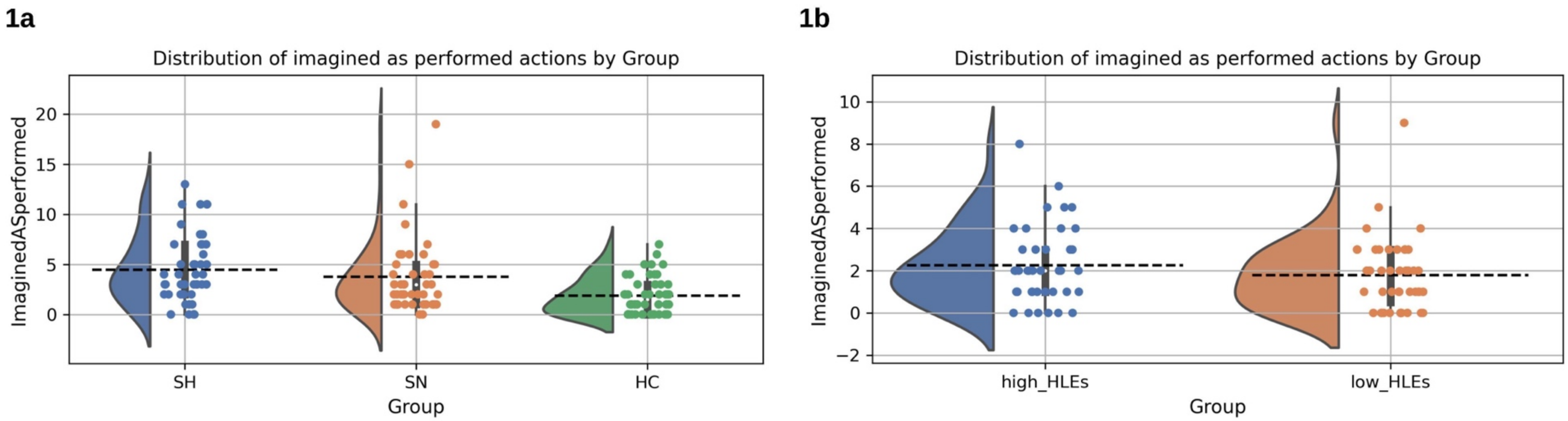
Table 3. Regression results using log transformed CAPS as the criterion

Predictor	*b*	*b* 95% CI [LL, UL]	*beta*	*beta* 95% CI [LL, UL]	sr^2	sr^2 95% CI [LL, UL]	*r*	Fit	Difference
(Intercept)	0.47**	[0.33, 0.60]							
Imagined as performed	0.09**	[0.05, 0.12]	0.31	[0.18, 0.44]	.09	[.03, .18]	.31**		
								R^2 = .095** 95% CI[.03,.18]	
(Intercept)	0.34**	[0.20, 0.48]							
Imagined as performed	0.09**	[0.05, 0.12]	0.30	[0.18, 0.43]	.09	[.02, .17]	.31**		
False perception ratio	1.00**	[0.55, 1.45]	0.28	[0.16, 0.41]	.08	[.01, .15]	.29**		
								R^2 = .176** 95% CI[.09,.26]	ΔR^2 = .081** 95% CI[.01, .15]
(Intercept)	0.27**	[0.12, 0.43]							
Imagined as performed	0.08**	[0.05, 0.12]	0.29	[0.16, 0.42]	.08	[.01, .15]	.31**		
False perception ratio	0.97**	[0.52, 1.41]	0.28	[0.15, 0.40]	.08	[.01, .14]	.29**		
GNG false alarms	0.02*	[0.00, 0.04]	0.14	[0.01, 0.26]	.02	[-.01, .05]	.19**		
								R^2 = .194** 95% CI[.10,.28]	ΔR^2 = .019* 95% CI[-.01, .05]

Note. A significant *b*-weight indicates the beta-weight and semi-partial correlation are also significant. *b* represents unstandardized regression weights. *beta* indicates the standardized regression weights. sr^2 represents the semi-partial correlation squared. *r* represents the zero-order correlation. *LL* and *UL* indicate the lower and upper limits of a confidence interval, respectively.

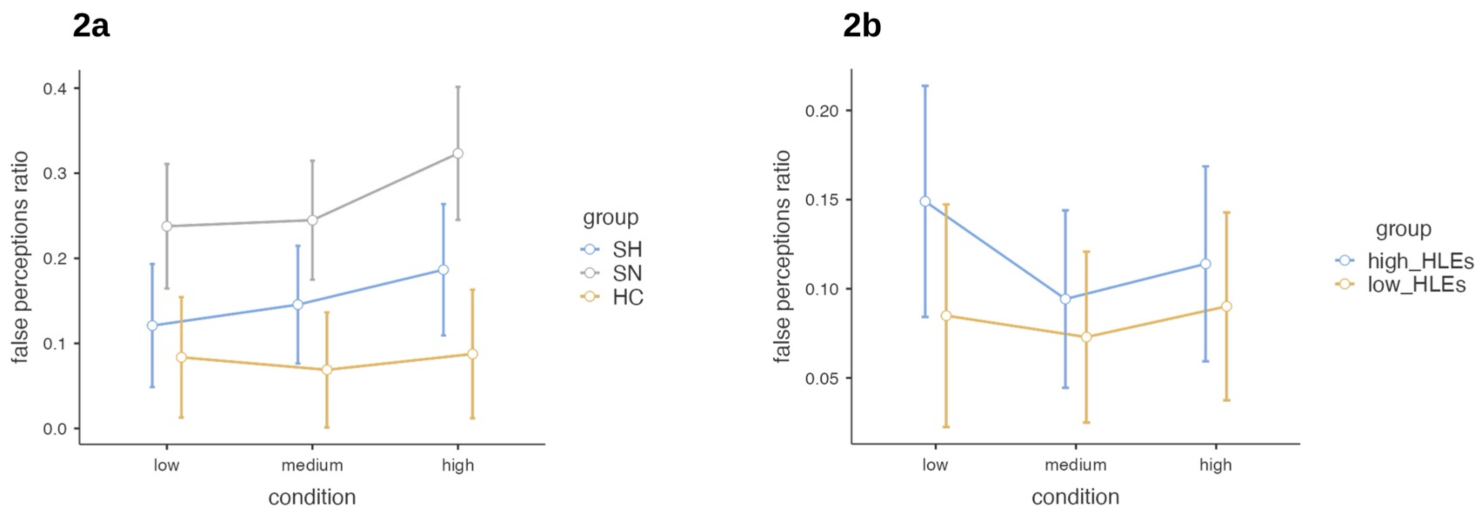
* indicates $p < .05$. ** indicates $p < .01$.

Figure 1. Results of the Action Memory Task. 1a. Results for imagined as performed errors for Study I, 1b. Results for imagined as performed errors for Study II.



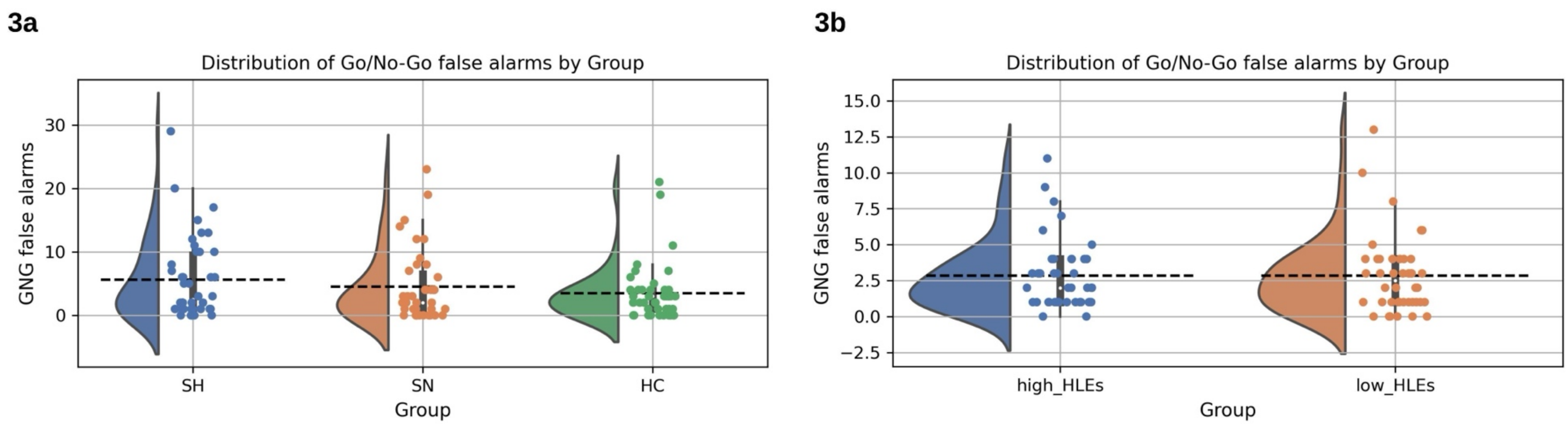
Note: Coloured dots represent individual data points. The probability distributions are represented by the shaded areas.

Figure 2. Results of the False Perception Task. 2a. Results for false perception ratio for Study I, 2b. Results for false perception ratio for Study II.



Note: Error bars represent standard errors.

Figure 3. Results of the Go/No-Go Task. 3a. Results for false alarms for Study I, 3b. Results for false alarms for Study II



Note: Coloured dots represent individual data points. The probability distributions are represented by the shaded areas.]

Supplementary materials

Sensitivity Analysis

Figure 1. Study I (SH vs SN vs HC) - Repeated measures ANOVA for FPT task after accounting for criterion.

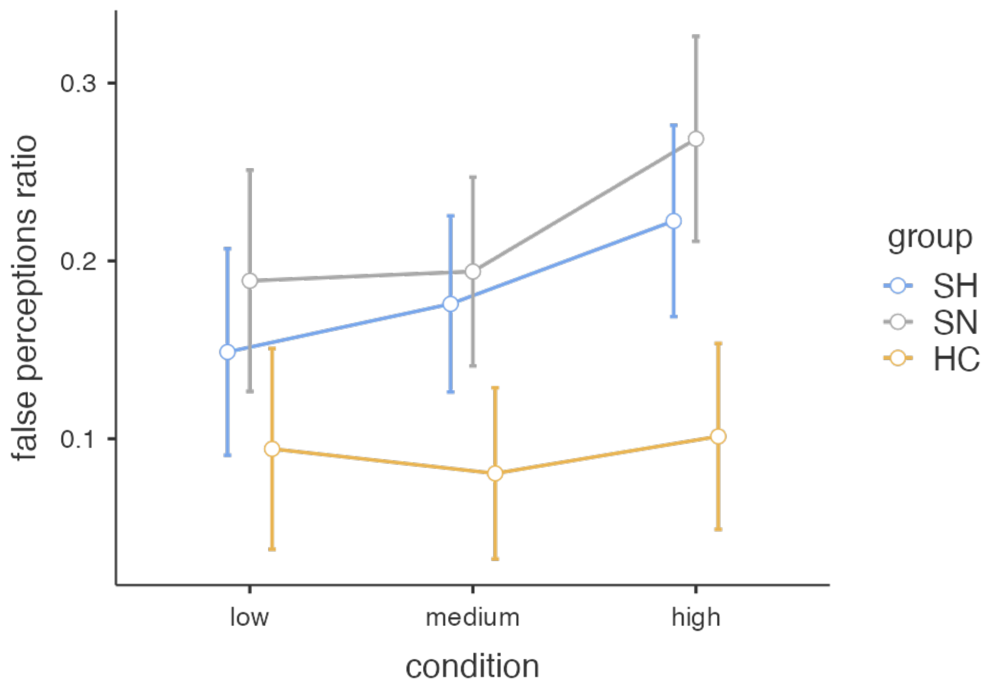


Figure 2. Study I (high HLEs vs low HLEs) - Repeated measures ANOVA for FPT task after accounting for age and criterion.