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Should absolute pitch be considered as a unique kind of absolute sensory judgment in humans? A systematic and theoretical review of the literature

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ABSTRACT

Absolute pitch is the name given to the rare ability to identify a musical note in an automatic and effortless manner without the need for a reference tone. Those individuals with absolute pitch can, for example, name the note they hear, identify all of the tones of a given chord, and/or name the pitches of everyday sounds, such as car horns or sirens. Hence, absolute pitch can be seen as providing a rare example of absolute sensory judgment in audition. Surprisingly, however, the intriguing question of whether such an ability presents unique features in the domain of sensory perception, or whether instead similar perceptual skills also exist in other sensory domains, has not been explicitly addressed previously. In this paper, this question is addressed by systematically reviewing research on absolute pitch using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) method. Thereafter, we compare absolute pitch with two rare types of sensory experience, namely synaesthesia and eidetic memory, to understand if and how these phenomena exhibit similar features to absolute pitch. Furthermore, a common absolute perceptual ability that has been often compared to absolute pitch, namely colour perception, is also discussed. Arguments are provided supporting the notion that none of the examined abilities can be considered like absolute pitch. Therefore, we conclude by suggesting that absolute pitch does indeed appear to constitute a unique kind of absolute sensory judgment in humans, and we discuss some open issues and novel directions for future research in absolute pitch.

1. Introduction

Absolute pitch (AP) has been defined as the ability to identify the chroma (pitch class) of a tone presented in isolation or to produce a specified pitch without external reference (e.g., Deutsch, 2013; Ward, 1999). It is often contrasted to relative pitch, the latter defined as the ability to identify the name of a tone based on a reference tone and the interval that the two tones form. Individuals with AP can, for example, name the note they hear or play it directly without having to search for it with a musical instrument, identify all of the tones of a given chord, or sing a note once given the name. Individuals with AP might also be able to identify and name the fundamental frequency of non-musical sounds, such as car horns or sirens.

AP has long been a popular topic among those researchers working in the field of music perception.[1] In the late nineteenth century, Carl Stumpf provided one of the first scientific descriptions of the phenomenon Stumpf (1882, 1890), while empirical studies started to appear around 1900 (e.g., Baird, 1917; Boggs, 1907; Gough, 1922; Kries, 1892; Meyer, 1899; Weidensall, 1905; and Seashore, 1940; Neu, 1947, for early reviews). Given the common psychological tenet that humans perform poorly in tasks requiring absolute sensory judgments,[2] most of these early researchers viewed AP as a rare ability and attempted to

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[1] The topic of AP is discussed extensively in Watt (1917) *Psychology of Sound* and there is a dedicated chapter in the key reference book for music psychologists edited by Diana Deutsch as early as its first edition in 1982. Interestingly, however, Moore devotes only one page to AP in his *Psychology of Hearing* across all six editions from 1977 to 2012.

[2] "An axiom of perceptual psychology has it that human beings are very poor absolute measuring instruments but are very good at comparing things" (Lawless & Heymann, 1999, p. 301).

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Table 1
List of the relevant notions that have been evoked in the psycho-musicological literature on AP.

Terms	Description	Sources
Absolute pitch	The ability to identify the chroma of a tone presented in isolation using pitch labels or to produce a specified pitch without external reference	Deutsch, 2013; Miyazaki, 2004a; Ward, 1999
Relative pitch	The ability to identify the name of a pitch given an external reference	Deutsch, 2013; Ward, 1999
Pitch memory	The stable and long-term memory for pitch (without the ability to name it)	Schellenberg & Trehub, 2003
Perfect pitch	Extraordinary acuity in the discrimination of the frequency of tones	Parncutt & Levitin, 2001
Quasi-absolute pitch	The ability to identify one pitch and use it as a reference for measuring the intervals	Bachem, 1937, 1955
Tone pitch	Equivalent to absolute pitch	Parncutt & Levitin, 2001
Piece pitch	The ability to recognize whether a familiar piece is played in the correct key (passive), or singing a familiar song in the correct key (active)	Parncutt & Levitin, 2001
(Relatively) absolute tonality	Ability to recognize whether a known melody/piece is played in the original key	Ward, 1999
Instrumental pitch (or piano pitch)	The ability to recognize tones only when produced by a specific instrument, which often turns out to be the piano	Levitin & Rogers, 2005

describe its phenomenology and defining features.[3]

Research on AP has increased a great deal over the recent decades, with more papers published in the last twenty years (2003–2023) than in the previous century (1899–2002) (190 vs. 87, see Table 1 Supplementary material). Such an effort has generated robust insights concerning several key psychophysiological mechanisms underlying the perception of AP in humans (e.g., see Herceg & Szabó, 2023; Hou et al., 2017; Kim & Knösche, 2017; Szyfter & Witt, 2020, for recent reviews). Different related notions have also been introduced to account for the complex phenomenology of AP (see Table 1).

In parallel, comparative research has investigated the perception of AP in several mammals and avian species (see, e.g., Friedrich et al., 2007; Hoeschele, 2017, for a review). However, an important caveat should be made here regarding the meaning of AP in animal studies, which is quite different from its occurrence in human studies. We refer to the distinction between “general AP” and “musical AP” abilities, the latter being related to naming and thus considered exclusively human, while the former are related to discrimination (or production) of pitch without external reference, an ability that can be present in animals, such as songbirds (Weisman et al., 2006).[4] Consequently, the methodology adopted when testing non-human animals is different than that adopted with humans, given the absence of linguistic counterparts of pitch, and is mostly based on pitch discrimination tasks (see also Hulse et al., 1984).

After more than a century of empirical research on the topic, the accumulated evidence has converged on the suggestion that the ability of those individuals with AP to name the pitch of (at least) one tone in an automatic and effortless manner, and without the aid of any external reference, clearly represents a case of reference-free sensory judgments[5] in humans. Surprisingly, however, the intriguing question of whether such auditory ability presents unique features in the domain of sensory perception would never appear to have been explicitly addressed previously. We thoroughly address this question in this paper. In **Section 2**, we provide a systematic review of the multidisciplinary literature on AP perception. We start by providing the details of the way the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines have been implemented (**Section 2.1**). Then, we move on to reviewing the studies investigating the genetic basis of AP (**Section 2.2**) and the neuroscientific (see **Section 2.3**), perceptual (see **Section 2.4.1**), and cognitive (see **Section 2.4.2**) mechanisms underlying AP. **Section 2.5** focuses on the perception of AP in clinical populations, such as Autism Spectrum Disorder (ASD) and Williams syndrome. In **Section 3**, we move on to understanding if and how similar perceptual skills exist in other sensory domains, by comparing AP with three phenomena that share key phenomenological features with AP, namely synaesthesia (see **Section 3.1**), eidetic memory (see **Section 3.2**), and colour perception (see **Section 3.4**). Finally, in **Section 4**, we summarize the main findings of the review (see **Section 4.1**), answer the main question of this paper (see **Section 4.2**), list some open issues (see **Section 4.3**), and suggest some novel directions for future research in AP (see **Section 4.4**).

This systematic theoretical review contributes to the literature on absolute pitch (AP) in several significant ways. First, it provides a comprehensive systematic review of the existing literature on AP. Second, it offers a fresh perspective on AP, by reframing it within the context of sensory skills rather than solely musical abilities and conducting a thorough and illuminating comparison between AP and three related absolute perceptual abilities. Third, it delves into the often-overlooked question of the biological utility of AP, addressing open issues in the field. Finally, five research directions for future studies to further our understanding of AP perception are outlined.

2. Section 2

2.1. PRISMA review

Following the guidelines suggested in the PRISMA method (Moher et al., 2009), we systematically review the research on AP from the first identified article published back in 1899 through to January 2024. The document search was conducted through Scopus and Pubmed databases using the following string: ‘absolute’ AND ‘pitch’ in the title or abstract (and keywords, for Scopus database only). The inclusion criteria were: full text available, written in English, and empirical articles. The exclusion criteria were defined as well: books, commentaries, conference reports, editorials, articles in languages other than English, and grey literature (non-academic reports or documents, or any other material that did not pass the criteria for inclusion).

The initial search yielded a total of 705 records. Of these, 266 records were immediately excluded as duplicates. We then screened the titles and abstracts of the remaining 439 articles. 169 were manually excluded for not being primarily related to AP in humans (e.g., comparative studies), conceiving the terms in a different way (e.g., related to the processing of AP compared to relative pitch instead of individuals with AP), being review or preprint articles, or not being related to the research question. The remaining 270 records were considered fully eligible as meriting further analysis (see Fig. 1). Articles were categorized according to the following categories: studies investigating the genetic dimension of AP ($n = 14$); neuroscientific/psychophysiological studies ($n = 95$); behavioural studies ($n = 131$); studies on clinical population (e.g., ASD, Williams syndrome, blind) ($n = 30$) (see Fig. 2

[3] Interestingly, an often conceptually associated similar phenomenon, namely synaesthesia, has a quite similar historical evolution (e.g., Cytowic, 1997). We will focus on the relationship between AP and synaesthesia in **Section 3.1**.

[4] In this paper, we primarily refer to musical AP, given that the ability to identify pitches verbally or in any other direct way is crucial for AP.

[5] We use the term “sensory judgment” to indicate one of the most prototypical ways AP skills are tested in the empirical literature, that is, by asking participants to verbally identify a musical note (“this sound is a C").

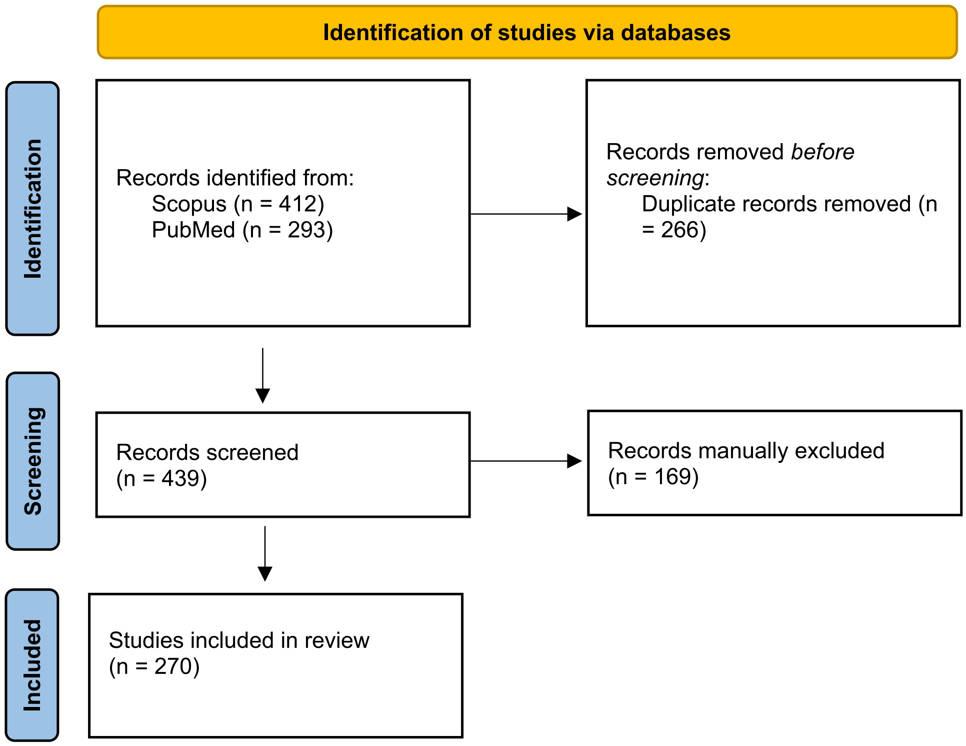

Fig. 1. PRISMA flow diagram.

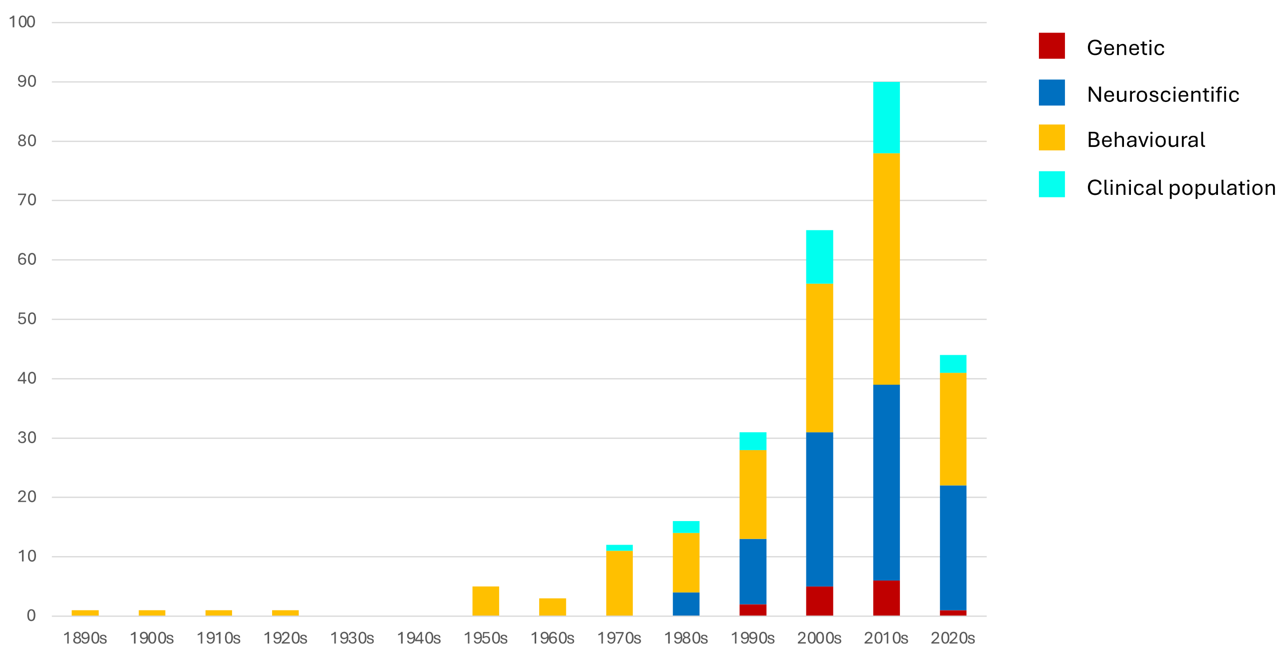

Fig. 2. Academic papers published on the topic of AP per decade and category.

below and Table 1 in Supplementary material). The main findings for each category are reviewed in the following **Sections 2.2–2.5**.

2.2. *Genetic and ethnicity studies*

While the prevalence of AP in the general population has been estimated at about 0.01–1% (Bachem, 1955; Levitin & Rogers, 2005; Ward, 1999),[6] these numbers increase significantly in specific cultures and populations, thus suggesting that there might be genetic predispositions toward certain of the underlying traits necessary for the development of AP. Several studies have been conducted to investigate

[6] The reliability of these values has been questioned by Carden and Cline (2019) given that the data on which the estimate is based is not available in the original source of Bachem (1955).

the familial or ethnic predispositions or advantages in AP perception. One of the earliest was a segregation study conducted by Profita et al. (1988), who reported significant familial incidence in 35 AP probands from 19 families. A subsequent familial aggregation study yielded a sibling recurrence risk-ratio estimate of 20, meaning that siblings of AP possessors are approximately 20 times more likely to possess AP relative to the general population (Gregersen & Kumar, 1996). Further studies by Gregersen et al. (1999, 2001) obtained lower, though still significantly higher than normal, values (i.e., of 8.3 and 12.2, respectively, see also Baharloo et al., 1998; Baharloo et al., 2000). A recent study by Bairnsfather, Ullén, Osborne, Wilson, & Mosing (2022) documented a significant correlation between pitch-naming scores for monozygotic ($r = 0.27$, $p < .001$) but not dizygotic twin pairs ($r = -0.04$, $p = .63$), with the age of onset no longer being a significant predictor once practice was considered in twins. These findings are in line with the notion that the pitch-naming ability is associated with both genetic factors and the amount of early practice, rather than just age of onset per se.

Inconsistencies among familial studies might be explained, as observed by Tan et al. (2014), by noting that familial aggregation does not distinguish between genetic and environmental contributions to a trait, making it possible that the high familial aggregation estimates stem from environmental influences such as early music training, which has been identified as a key environmental determinant of AP (Miyazaki, 1988; Profita & Bidder, 1998; Sergeant, 1969; Wilson et al., 2009). At the same time, those children who excel at pitch-naming may have an increased tendency to practice, thus partially explaining the higher percentage of AP possessors in this samples.

Other evidence relates to an ethnicity cluster for AP; namely that a higher rate of AP has been documented among Asian students as compared to Caucasian students (47.5% vs 9%, respectively, see Gregersen et al., 2000; though see Schellenberg & Trehub, 2008). Note that this is not attributable to sociocultural variables, because the elevated rate has also been documented in North Americans of Asian descent (cf. Levitin & Rogers, 2005) or to early exposure to tonal languages, given that the sample included people from Korea and Japan. Miyazaki (2004a, 2004b) estimated that in Japan the proportion of individuals with AP is approximately 30% for university students of music education and 50% or more for music students (see also Gregersen et al., 1999, 2000). More recently, Miyazaki et al. (2018) investigated AP abilities in a sample of music students from East Asian and Western countries (Japan, China, Poland, Germany, and the USA). The conservatory-level Japanese students showed the highest AP performance and more than half of them were classified as accurate AP possessors. In contrast, only a small percentage of the participants from Poland, Germany, and the USA were identified as accurate AP possessors, with participants from China intermediate on AP measures (see Chavarria-Soley, 2016, on listeners from Costa Rica).

However, as observed earlier, ethnic differences might be explained by observing that people with AP tend to take music education or training courses more likely than normal perceivers. Different pedagogical traditions might partially account for these differences, given that Asians are significantly more likely to receive ‘fixed pitch training’ (i.e., reinforcing tone/name associations), such as embodied by the Suzuki method, as compared with Caucasians (29% of Asians vs. 6% of Caucasians, $p = .001$, in the sample examined by Gregersen et al., 2000; see also Gregersen et al., 1999).

Possible ethnicity effects for AP can also be observed from a genome-wide linkage study of 73 families of European, East Asian, Jewish, and Indian descent in the United States and Canada (Theusch, Basu, & Gitschier, 2009) and a similar study of AP families (in which multiple family members have AP) and with synaesthetic families (in which multiple family members have synaesthesia; Gregersen et al., 2013).

2.3. The neuroscience of AP

Several studies have investigated the neuroscience of AP perception, leading to the identification of the neurological, structural, and functional correlates of AP (e.g., Dohn et al., 2015; Elmer et al., 2015; Itoh et al., 2005; Oechslin, Meyer and Jäncke, 2010; Ohnishi et al., 2001; Loui et al., 2011; Keenan et al., 2001; Jäncke et al., 2012; Schlaug et al., 1995; Wilson et al., 2009; Zatorre, 2003) see also Hou et al., 2017; Kim & Knösche, 2017; Loui, 2017, for reviews). The accumulated evidence has led to the identification of two brain regions that are prominently involved in the processing of pitch by individuals with AP, namely the left posterior dorsolateral frontal cortex (DLFC) and the planum temporale (PT).

The role of the DLFC during pitch naming was suggested by an early study by Zatorre et al. (1998) and later confirmed by a number of other studies (Bermudez & Zatorre, 2005; Ohnishi et al., 2001; Schulze et al., 2009; Wengenroth et al., 2014). Known to be involved in tasks that require working memory (e.g., Blumenfeld & Ranganath, 2006; Petrides, 2000), the DLFC should facilitate AP musicians’ ability to retrieve the learned associations between pitch and verbal labels. The results from a recent Stroop-like task with AP musicians confirmed the causal relationship between the left DLFC and pitch labelling, the latter emerging as an automatic and largely irrepressible process triggered by the exposure to musical tones (Rogenmoser et al., 2021).[7]

Another important region for AP ability is the PT, located in the posterior portion of the superior temporal gyrus (STG) (Clark et al., 2010). The involvement of the PT in pitch processing has been consistently implicated in a large number of studies (see Griffiths & Warren, 2002, for a review). Functional neuroimaging studies yielded positive correlations between the left PT activation and AP proficiency among AP musicians during pitch naming (Wilson et al., 2009; Zatorre et al., 1998), with some evidence suggesting that pitch chroma and pitch height are processed separately in the anterior and posterior parts of the superior temporal planes, respectively (Warren et al., 2003).[8]

A recent MEG study by Benner et al. (2023) confirmed the activation of PT induced by complex harmonic tones and provided original insights into the temporal dynamics of brain responses at the location of corresponding fMRI activations. In the AP group, the auditory evoked P2 onset occurred ~25 *ms* earlier in the right as compared to the left PT and ~ 15 *ms* earlier in the right as compared with the left anterior STG. This effect was consistent at the individual level and correlated with AP proficiency. Based on the combined application of MEG and fMRI measurements, the authors were for the first time able to demonstrate a characteristic temporal hierarchy – they called it “chronotopy” – of human auditory regions in relation to specific auditory abilities, reflecting the prediction for serial processing from nonhuman studies. Shorter latencies of N100 responses in AP musicians compared to non-AP musicians and non-musicians have been also recently confirmed by Sharma et al. (2023) using high-density electroencephalographic recording.

Neuroanatomical studies demonstrated stronger left surface/volume asymmetry in PT among AP musicians associated with increased AP accuracy (Griffiths & Warren, 2002; Schlaug et al., 1995). It has been observed that this asymmetry may be driven by a smaller right PT surface rather than a larger left surface (Keenan et al., 2001; Loui et al., 2011; Schlaug et al., 1995; Wilson et al., 2009). However, the role of PT asymmetry in AP remains somewhat controversial, given Zatorre’s (1989) findings that AP ability was unchanged after surgical excision of the left PT (which implies that the right PT may play a role in AP ability).

Putting together evidence on DLFC and PT, Hou et al. (2017) suggested that the bilateral PT and the left posterior DLFC may form a

[7] The role of the left posterior DLFC in associative learning and memory has also been verified in nonhuman primate studies (Bermudez & Zatorre, 2005; Katsuki et al., 2022; Qi et al., 2010).

[8] More generally, the PT is implicated in auditory language processing, including perception of phonemes (units of speech; Griffiths & Warren, 2002). Phonemic categories of speech might be held similar to musical pitch categories, which are, of course, crucial for AP ability.

functional pathway that is implicated in AP ability, which might result in part from the interactions between the PT/posterior DLFC and a network of other brain regions that are implicated in the retrieval and manipulation of various types of associations with pitch (Zatorre et al., 1998), including verbal-tonal associations (Ohnishi et al., 2001; Petrides & Pandya, 1988, for relevant findings in primates).

The early case report of epileptic patients with AP by Zatorre (1989) poses interesting questions about the hemispheric specialization in AP. In that study, AP recognition in the patient was intact after anterior temporal lobectomy of the left hemisphere, a result which led the author to suggest the right-hemispheric domination in AP (Zatorre, 1989). More recently, Wengenroth et al. (2014) identified a right hemisphere network for AP perception, including the right premotor and secondary somatosensory cortices, the right inferior frontal gyrus, and the right middle temporal gyrus. These function together with the right PT, the left posterior DLFC, and the left Broca's area – regions that are involved in conditional association pitch memory and motor aspects of speech performance, respectively (Bermudez & Zatorre, 2005; Zatorre et al., 1998) – instrumental for pitch labelling.

However, studies also indicate that hemispheric dominance might be influenced by the different AP skills of individuals. For example, while reporting the engagement of the right hemisphere in individuals with lower AP skill, the study by Wilson et al. (2009) showed a left hemisphere advantage among AP musicians, thus indicating that AP and quasi-AP or lower AP possessors might use different strategies (i.e., working memory) and thus recruit different neural circuitries.[9] Indeed, several ERP studies showing decreased P300 amplitudes and latencies among AP musicians (Crummer, Walton, Wayman, Hantz, & Frisina, 1994; Klein, Coles, & Donchin, 1984; Wayman et al., 1992; see also Itoh et al., 2005) have been interpreted as indicating less working memory involvement during pitch naming by AP due to their reliance on tonal templates (Berti & Roeber, 2013; Ruhnau et al., 2010; Schomaker & Meeter, 2014; though see Hirose et al., 2002 for null findings on P300).

Overall, the literature reviewed here suggests that AP is associated with integration across multiple brain regions that together form a complex, functionally interconnected network. Other neuroimaging studies have demonstrated the involvement of a number of brain areas in AP musicians during naming, including the superior temporal gyrus (Zarate & Zatorre, 2008) and the middle frontal gyrus (Wilson et al., 2009). Both the right inferior frontal and right occipital gyri are also activated (Zatorre et al., 1998). The superior temporal gyrus is implicated in auditory processing, including in the perception of phonemes (units of speech; Griffiths & Warren, 2002; Oechslin, Imfeld, et al., 2010). Superior temporal gyrus activation during pitch naming has been shown to be positively correlated with AP proficiency (Ohnishi et al., 2001; Wilson et al., 2009; Zatorre et al., 1998). The inferior frontal gyrus subserves semantic functions (Platel et al., 2003), the middle frontal gyrus is implicated in sensorimotor functions with auditory signals (Wan & Schlaug, 2010), and the occipital gyrus subserves vision and visual imagery functions (Schmithorst, 2005). This suggests a potential functional network including the left posterior DLFC and additional regions, since the DLFC is linked to other implicated brain regions, and lesions to it impair acquisition of arbitrary associations between stimuli and responses (Petrides, 2000).

The literature that has been reviewed here also highlighted some inconsistent results. For instance, regarding P300 brain responses (Klein, Coles, & Donchin, 1984; Hirose et al., 2002), and the involvement of working memory in AP labelling. Assuming that AP ability emerges from two separate processing stages – the first being an early phase of pitch encoding, the second being the associative mechanism that categorizes pitches with verbal labels (or any other abstract coding) – the inconsistencies might depend on the fact that AP possessors use different strategies to associate pitch with labels and each strategy might, in turn, recruit different neural circuitries (e.g., verbal coding, semantic memory, auditory, kinesthetic, visual, and spatial imagery). For instance, Siegel (1974) found that AP musicians retained pitch information by using verbal labels to remember tone information, while Zatorre and Beckett (1989) found that AP musicians can encode music pitches verbally. This explanation would receive support by results showing no group difference between AP and non-AP musicians in neurophysiological indicators of early sensory processing while passively listening of tones (Elmer et al., 2013).

2.4. *The behavioural evidence*

2.4.1. AP perception. AP is often reported to be an automatic 'perceptual expertise' among those who possess it (e.g., Bachem, 1937; Ward, 1999), and one that those who have it are unaware of the way in which it functions exactly. The former claim is supported by the wide body of evidence showing that individuals with AP identify pitches effortlessly and immediately (e.g., Bachem, 1940; Profita et al., 1988; Revesz, 1953; Rogenmoser et al., 2021) and report having made no special effort to develop AP (Baird, 1917; Boggs, 1907; Levitin & Rogers, 2005, for a review).

Research in humans suggests that AP turns out to be the result of an allegedly innate individual predisposition, although a few cases have been demonstrated of the acquisition of AP by adults (e.g., see Van Hedger et al., 2019; Wong et al., 2020). The literature suggests that AP emerges early in human development, typically between 3 and 6 years of age, and is strongly correlated with musical education (Miyazaki, 2004a; Takeuchi & Hulse, 1993). Such an ability tends to remain throughout life, although it might shift a little in tuning (e.g., see, Vernon, 1977).[10] However, it might also be lost due to traumatic neurological events. The study by Katsuki et al. (2022) reported the case of a 68-year-old musician who lost AP due to a *hemorrhage edematous* lesion under the posterior insular cortex. Remarkably, as the hematoma was absorbed, her AP ability recovered. Moreover, studies have shown that AP can be temporarily affected by certain drugs, such as carbamazepine (Braun & Chaloupka, 2005; Fujimoto, Enomoto, Takano, & Nose, 2004; Konno, Yamazaki, Kudoh, Abe, & Tohgi, 2003).

Often presented as an ability individuals either are or are not endowed with, AP is thus likely best seen as a spectrum of skills, a distributed and multifaceted ability rather than a static and dichotomous one. The manifestations of AP significantly vary across those individuals who possess it in terms of accuracy, response time, preferred timbre, and means of identification of the pitch (e.g., verbal or playing). The perception of AP is often considered as categorical, with different responses to differences within a category (of, say, C) and to transition into a new one (C#).

The most prominent manifestation of AP is the ability to name the pitch immediately after hearing it. The literature shows that the percentage of correct identifications varies widely in the literature, between 70% and 99% (Takeuchi & Hulse, 1993).[11] This variability might be attributable to individual factors, the nature of the stimuli, and the experimental

[9] However, Suriadi et al. (2015) showed intact AP abilities after selective amygdalohippocampectomy of the right hemisphere, thus suggesting that AP might be relatively independent of medio-temporal structures, particularly the hippocampus.

[10] Explanations for this effect have been formulated, highlighting the impact of age on the mechanical properties of the basilar membrane (e.g., elasticity), with cascading effects on pitch processing (Ward & Burns, 1982).

[11] Baharloo et al., 1998 distinguished between four groups of AP possessors. The first group includes those individuals who were able to label any pitch regardless of its timbre and spectral region. Individuals who performed at a level that was significantly above-chance, but who performed at progressively lower levels for pure tone labelling than the first group, formed the remaining three groups, depending on their scores. Similarly, Miyazaki (1990) arbitrarily classified those individuals with AP into three subgroups according to the following values of accuracy in AP tests: > 90%, 70–90%, < 70% (and apparently with a minimum threshold of 30%, see Miyazaki, 1990, Fig. 1, p. 179). Importantly, all individuals were considered AP possessors.

protocols used. For example, individuals with AP are typically more accurate in identifying the names of pitches (pitch classes) rather than the exact octave, thus suggesting that they adopt a two-stage process in which they identify the pitch class of the presented tone and then locate its octave position (Miyazaki, 2004a). However, the percentage of correct identifications is far higher than chance in all of the experiments that have been reported to date, with the most accurate identifications being the fastest, both within and across participants (Baird, 1917; Carroll, 1975; Miyazaki, 1988, 1989; Whipple, 1903). Individuals with AP might also be able to sing or reproduce the tone they have heard on an instrument, or identify the key of a piece (Deutsch, 2013; Ward, 1999).

AP can be enhanced by association or integration with other perceptual or cognitive parameters (Siegel, 1974; Zatorre & Beckett, 1989). For example, AP is enhanced as a result of linking pitches to colours, a phenomenon that might be related to chromaesthesia or coloured hearing, although the latter are associations that occur involuntarily and automatically (Peacock, 1985; Rogers, 1987; Spence & Di Stefano, 2022, for a review). Timbre might also facilitate, or at least affect, AP perception, with musicians tending to identify the tones of their main instrument more reliably and more rapidly than other timbres (Lockhead & Byrd, 1981; Marvin & Brinkman, 2000). When the preferred timbre is that of the piano, the AP has been labelled as piano-pitch (Levitin & Rogers, 2005). Intriguingly, among pianists, the identification of tones corresponding to the black keys on the keyboard is typically less accurate than white-key notes (Miyazaki, 2004a, 2004b see also, Dohn et al., 2012).[12]

Surprising as it may sound, AP possessors and non-possessors have equivalent acuity and perceptual thresholds for pitch differences (see Levitin, 2004). However, AP has often been considered a clear sign of musical talent, and many musical geniuses were endowed with this particular ability. Mozart was one such gifted composer. He displayed this ability when he was 7 years old, as reported in the following passage from an anonymous letter: “I saw and heard how, when he was made to listen in another room, they would give him notes, now high, now low, not only on the pianoforte but on every other imaginable instrument as well, and he came out with the letter of the name of the note in an instant. Indeed, on hearing a bell toll or a clock, even a pocket-watch, strike, he was able at the same moment to name the note of the bell or timepiece.” (Augsburgischer Intelligenz-Zettel, 1763, cited in Deutsch, 1990, p. 21). Other great composers, such as Beethoven, Bach, and Handel also possessed AP (Deutsch, 2002), thus contributing to the notion that such an ability is often a hallmark of extraordinary musical ability.

The ability to perceive pitch absolutely, though, negatively impacts some musical tasks, such as producing transpositions in pitch (Miyazaki, 2004b; Revesz, 1953; Ward, 1999; Wilson, 1911). An individual with AP who reads G4 in a musical score but is asked to transpose (i.e., sing or play) it one tone higher will have to produce A4, with conflicting information between the written and sounded pitches. There is evidence of a Stroop-like interference effect in those individuals with AP when asked to identify pitches. For instance, Zakay et al. (1984) demonstrated that participants were slower and more prone to error when identifying tones sung with an incongruent pitch name (e.g., the pitch D4 sung on the syllable “do”) than when identifying pitches sung on a neutral syllable. This strengthens the notion that absolute perception occurs immediately and involuntarily and, in certain situations, can interfere with the perception of pitch relations.[13]

[12] This might depend on the fact that tones corresponding to black keys are relatively less frequent in the exercises or excerpts individuals practice when they start learning how to play the piano.

[13] Regarding the importance of relative versus absolute processing of pitch in music, it might be worth going back to an observation made more than a century ago by Henry Watt, a Scottish experimental psychologist: “Absolute ears emerges when the natural absoluteness of tonal orders maintains its efficiency is spite of the tremendous emphasis laid on relativity or proportion in music" (Watt, 1917, p. 200).

Although AP has a clear perceptual basis, there are reasons to doubt that the perceptual system directly and simply maps physical frequencies onto pitch categories. If there were such a system of direct mapping, the only variability in note identification performance would arise from differences in the perception of frequency, but this is not the case. For example, although two people might both perform well enough on a musical note identification task to be considered to have AP, they can show significant differences in performance with specific timbres, notes, or frequency ranges (e.g., see Bahr et al., 2005).

Moreover, cases of individuals who can identify the frequency of a tone but cannot name it suggest that having perceptual and discrimination skills as refined as those of AP possessors is not sufficient to give rise to AP. For instance, Halpern (1989) found that those adults without AP consistently sang familiar melodies starting on the same pitch. The starting pitch varied from song to song and varied across participants but was consistent within individuals over several repetitions of the same song, even when the repetitions were separated by a couple of days. In a similar way, Schellenberg and Trehub (2003) demonstrated that adults with little musical training can remember the pitch level of familiar instrumental recordings, as reflected in their ability to distinguish the correct version from versions that have been shifted upward or downward by 1 (58% correct answers, $p < .001$) or 2 semitones (70% correct answers, $p < .001$). Together with other findings (Levitin, 1994; Terhardt & Seewann, 1983; Terhardt & Ward, 1982), these results suggest that normal perceivers can accurately encode a specific starting pitch for melodies and can retrieve this starting pitch reliably. Should those individuals be able to name the starting pitch, they would satisfy one of the requisites of quasi-AP, i.e., the ability to identify a pitch (Bachem, 1937, 1955).

Finally, if the ability to directly identify the pitch of a tone relies on an extraordinary perceptual skill that allows individuals to exactly match frequency with pitch, why is this ability restricted to the tuning of the scale system to which the particular listener is accustomed? In other words, why does an extraordinary perceiver with AP recognize only those qualities represented by the twelve pitches of our tempered tuning system, given that normal perceivers can discriminate very small changes in frequency along the audible range (i.e., few *Hz* in the range 1000–4000 *Hz*, see Fastl & Hesse, 1984)? These questions lead us to assume that the mapping between frequency and pitch class cannot be fully explained in perceptual terms, given that pitch naming does not merely translate the fine-grained discreteness of frequency discrimination. In what follows, we consider the cognitive dimensions that allegedly play a role in prompting the mapping, focusing especially on the role of memory.

2.4.2. The cognitive mechanisms underlying AP: learning and memory. Levitin (1994) suggested that AP consists of two distinct component abilities: (1) the ability to maintain stable, long-term representations of specific pitches in memory, and to access them when required, namely pitch memory; and (2) the ability to attach meaningful labels to these pitches, such as A to 440 Hz, namely pitch labelling. Levitin and Rogers (2005) subsequently observed that AP, conceived of as the ability to name pitches, is probably acquired just like other perceptual labels in the developing child’s vocabulary. The acquisition of pitch categories might parallel that of colour categories, for both of which the child must learn to distinguish one perceptual quality (pitch chroma, or hue) from several other perceptual attributes as a prerequisite to creating the correct mappings between tone (or colour) and its linguistic label.

Although it is unclear how and why the pitch-name associations are formed in a relatively automatic manner in certain individuals, it should be noted that most children are not taught pitch labels. Given that individuals with AP report having had musical training, one of the most parsimonious ways in which to explain the perception of AP would therefore seem to assume that individuals have learned the association during development through musical training. Such an explanation is consistent with evidence showing that AP possessors and normal perceivers have equivalent acuity and perceptual thresholds for pitch differences and that timbre-dependent AP is often piano-dependent, given that the piano is one of the most frequent timbres that listeners are exposed to during the development and one of the most popular instruments present at home (see Levitin, 2004; Levitin & Rogers, 2005). Hence, AP would be essentially mediated by two key interrelated factors, namely perceptual learning and memory.

Interesting evidence comes from those studies, though relatively scarce, proving that some adults with no AP have been trained and eventually learned AP. For instance, Wong et al. (2020) trained adult participants, mostly Cantonese speakers, to learn the names of pitches through a series of experiments that included a computerized, gamified, and personalized training protocol for 12 to 40 h. The results demonstrated that AP learning showed classic characteristics of perceptual learning, with 14% of the participants (6 out of 43) being able to name twelve pitches with an accuracy of 90% or above, comparable to that defined in the literature for individuals with AP (see also Van Hedger et al., 2019, for similar results obtained on a smaller number of participants). Such a high level of accuracy is even more surprising, considering that the participants' training lasted between 12 and 40 h in total, which is significantly shorter time of exposure and training compared to the time a child devotes to musical training in the first years. Additionally, Van Hedger et al. (2015) have demonstrated that auditory working memory capacity predicts the efficacy of learning AP note categories, thus supporting the idea that a larger auditory short-term memory might underlie the formation of AP categories.

The role of learning is also suggested by the fact that AP is a language-mediated ability, and that the critical period for the acquisition of AP is thought to be similar to that of language development (Chin, 2003; Deutsch et al., 2009). This would thus imply that the genetic predisposition might be necessary but is clearly not sufficient: tone labels must still somehow be learned.[14] Further support for the mediating role of memory might be undirectedly provided by findings showing that individuals with AP perform better on certain pitch memory tasks (Bachem, 1954; Rakowski & Rogowski, 2007; Siegel, 1974), such as being able to indicate, after a 1-week interval, whether a standard tone and a comparison tone are the same or different (Bachem, 1954). This likely demonstrates that they can assign verbal labels to pitch classes, due to their refined abilities to apply a verbal encoding strategy, and easily recall them after a relatively long time.[15]

Given the prominent role of memory and perceptual learning, however, it might be surprising that only a small fraction of musicians possesses AP (ranging between 4 and 18% in Westerners, see Carden & Cline, 2019), given that for many years these individuals are exposed to the association between pitches and pitch labels. It would be similarly difficult to explain why the incidence increases to 50–60% among Asian musicians (e.g., Chinese or Japanese) (Deutsch, 2006; Miyazaki, Makomaska, & Rakowski, 2012). Moreover, after years of practicing, most musicians naturally learn by heart a number of musical compositions, to the point that they can write the exact score from memory; however, this ability does not lead to AP, not even limited to the notes of the learned score. In contrast, most musicians develop a refined ability to recognize other important auditory properties, such as timbre. Timbre identification is such a sophisticated ability that musicians (but occasionally also non-musicians) might be able to identify not only the instrument or the voice they hear, but also the instrumentalist or the singer. For instance, when hearing Bach's *Chaconne* for violin, they can recognize whether Heifetz or Vengerov is playing, or when hearing Verdi's aria *Questa o quella*, they can recognize the voice of Domingo or Pavarotti. These considerations strengthen the idea that exposure and learning are critical in the acquisition of AP but cannot in themselves account for this ability.

To summarize, the ability of those individuals who possess AP seemingly rests on an auditory-semantic correlation, namely between tone names (i.e., scale steps) and their usual approximate pitches. This rare ability may thus be seen as resulting from the combination of various components, namely memory, a particular (genetic) predisposition, and formal and explicit musical training. To delve deeper into the biological and acquired factors of AP, in the next section, the evidence indicating a purportedly higher prevalence of AP skills among individuals with neurodevelopmental disorders and visual impairment is reviewed.

2.5. *AP in clinical populations*

Several studies have investigated the relationship between extraordinary perceptual skills, including AP, and neurodevelopmental disorders such as ASD and Williams syndrome (e.g., Bonnel et al., 2003; Heaton, 2003; Heaton et al., 1998; Lenhoff et al., 2001; Masataka, 2017; Meilleur et al., 2015). These studies are motivated by the observation that these perceptual skills are more often prevalent among individuals with those disorders than among control participants. For instance, the prevalence of AP has been estimated as about 0.01–1% in typical populations (see §2.2) but has been reported to vary between 5% and 11% in individuals with ASD (Bonnel et al., 2010; Romani et al., 2021; Kupferstein & Walsh, 2016, reports much higher values, i.e., 97% in people with autism, though the same study reports about 50% of neurotypicals to manifest AP-like abilities).

The participants tested in a study of ASD and typically-developing children reported by Masataka (2017) heard 36 pure sine wave tones, presented in pseudo-randomized order, which ranged from A3 to A5, with each tone being presented once. The participants had to answer the tonal label after hearing the accordant tone. In a sample of 19 ASD children, 15 exceeded the chance level in a test of AP ability, while the accuracy of all of the typically-developing children remained indistinguishable from chance.

A number of studies have revealed a heightened pitch discrimination and identification ability in those with ASD as compared to controls (Bonnel et al., 2003; DePape, Hall, Tillmann, & Trainor, 2012; Heaton, 2003; Heaton et al., 1998; Meilleur et al., 2015).[16] Additionally, children with ASD demonstrated a superior pitch discrimination ability in the melodic context and stronger long-term memory for melody (Stanutz et al., 2014). However, when it comes to vocal imitation, individuals with ASD have shown inferior performance to controls on AP and duration matching for speech and song imitation, while performing as well as controls on relative pitch and duration matching (Wang, Pfordresher, Jiang, & Liu, 2021).

To date, fewer studies have explored the correlation between AP skills and Williams syndrome. Lenhoff et al. (2001) demonstrated that

[14] This might suggest a further parallel with language acquisition, given that human infants are equipped at birth to learn any language and can perceive and discriminate between differences in all human speech sounds. For example, 4-month-old Japanese infants can distinguish the /r/ and /l/ sounds in English as reliably as 4-month-olds raised in English-speaking households. Later on, however, infants tend to exhibit a preference for phonemes in their native language over those in foreign languages and by the end of their first year no longer respond to phonetic elements peculiar to non-native languages. In accordance with the idea of a critical period for AP acquisition, the ability to perceive these phonemic contrasts evidently persists for several more years, until about the age of 7 or 8 years. After this point, similar to AP ability, performance gradually declines no matter what the extent of practice or exposure (Purves et al., 2001).

[15] Here it might be worth mentioning that motor memory could have a role in certain occurrences of AP, such as quasi-AP or pseudo-AP. For instance, a singer might have motor memory about the way they produce a specific pitch, and use it as reference tone (e.g., Levitin, 1994).

[16] Furthermore, several single case reports have been published on this, such as Brenton et al. (2008), Heaton et al. (2008), Mottron et al. (1999), and O'Connell (1974).

the five individuals they tested, who have Williams syndrome, exhibited near-ceiling levels of AP. However, these findings contrast with those of Martínez-Castilla, Sotillo, & Campos (2013), who conducted two experiments involving a total of 34 individuals with Williams syndrome and compared them to 58 typically-developing participants. Using a traditional assessment of AP, they observed that individuals with Williams syndrome and their controls achieved low results in the AP task. Their responses showed an arbitrary pattern, and their performance fell significantly below that of musicians with AP, suggesting that AP is also rare in individuals with Williams syndrome.

The prevalence of AP skills has also been investigated in blind people (Gaab, Schulze, Ozdemir, & Schlaug, 2006; Hamilton et al., 2004; Welch, 1988; see also Pring et al., 2008). In an early observation by Welch (1988), the incidence of AP in early blind individuals (i.e., either congenitally blind or due to an accident occurring in the first days following birth) was much higher than in sighted individuals, with 64.7% of blind participants (22 out of 34) showing AP skills. Similar values were later obtained by Hamilton et al. (2004) on a sample of 21 early blind participants who received musical training, 12 of whom (57.1%) reported having AP, reflecting markedly increased prevalence compared to sighted musicians. Additionally, magnetic resonance images acquired in a subset of blind AP musicians revealed greater variability in PT asymmetry compared with the increased left-sided asymmetry previously described in sighted individuals with AP (see **Section 2.3**), suggesting that the neural mechanisms underlying AP in blind individuals could differ from those in the sighted. The difference in neural correlates of AP has been confirmed by Gaab and colleagues (2006), who demonstrated that the brains of blind musicians exhibited significantly more activation in bihemispheric visual association areas, the lingual gyrus, and parietal and frontal areas compared to sighted musicians. Conversely, sighted musicians displayed more activation in the right primary auditory cortex and the cerebellum when compared with blind musicians (Gaab et al., 2006).

3. AP and synaesthesia, extraordinary memory, and colour perception

In the previous sections, the various elements that contribute to making AP, at least in its prototypical manifestation, a rare example of reference-free sensory judgment in audition have been thoroughly reviewed. However, it remains unclear whether this auditory ability is not only statistically rare among individuals, but also rare or unique in the spectrum of sensory/perceptual abilities. In the following sections, we will take a closer look at three occurrences of sensory judgments that have been occasionally, and often anecdotally, related to AP, namely synaesthesia (see **Section 3.1**), eidetic memory (see **Section 3.2**), and colour perception (see **Section 3.4**), in the attempt to understand if and how these phenomena exhibit similar features to the phenomenon of absolute pitch.

3.1. Synaesthesia and AP

Synaesthesia is the rare neurological condition in which specific inducing stimuli give rise to an additional idiosyncratic concurrent experience in either the same or different sensory modality; these synaesthetic experiences are involuntarily and automatically triggered, highly-specific, and consistent over time (Cytowic, 1997; Grossenbacher & Lovelace, 2001). Over the years, several different theories have been put forward to explain the existence of synaesthesia (see Simner & Hubbard, 2013, for a review). Here, we will mainly consider those cases of synaesthesia in which an inducer in one sensory modality gives rise to a concurrent in a different sense. For our purposes, we will focus on music-colour synaesthesia, in which a musical stimulus (the inducer) elicits a colour perception (the concurrent).[17] Such synaesthetic experiences are typically reported by individuals with absolute, reference-free sensory judgments such as “The sound of the trumpet is scarlet” or “F is green”.

Synaesthesia is considered as a genuine sensory phenomenon and not merely a high-level cognitively-mediated (e.g., mnemonic) association (Ramachandran & Hubbard, 2001). For example, an individual with number-colour synaesthesia is not just ‘imagining the colour’ nor is s/he associating it to numbers based on childhood memories. For example, if several 2’s are scattered among a matrix of randomly placed 5’s, the global shape formed by the embedded 2’s is very hard to discern; normal participants take several seconds to find the shape. However, a grapheme–colour synaesthete might look at it and very quickly see the global shape as a red triangle or square against a background of green 2’s (Ramachandran & Hubbard, 2001; though note that only a subset of synaesthetes has been shown to experience such pop-out phenomena). Such results show that, at least in certain cases, synaesthesia is a low-level sensory phenomenon; the induced colour can lead to pop-out and segregation and only perceptual features processed early in visual processing can lead to segregation (Beck, 1966; Treisman, 1982).[18]

Several potential links between AP and synaesthesia have been suggested over the last decades (see Carroll & Greenberg, 1961; Glasser, 2021). The most simple and direct link would be to conceiving of AP as a case of synaesthesia in which the pitch inducer directly triggers a verbal concurrent; however, the intersubjective agreement regarding the inducer-concurrent associations seemingly goes against the idiosyncratic nature of synaesthetic matchings. Another possibility would be to conceive forms of synaesthesia induced by pitch as mediated by AP. Findings from Itoh et al. (2017) support this idea, demonstrating that the associations between pitch class and colour in synaesthetes with AP are mediated by the name of the note (i.e., C, D, E…), so that there turn out to be two associations: pitch-pitch class (via AP) and pitch class-colour (via synaesthesia). Alternatively, one could suggest a more indirect and cognitively mediated link, in which the synaesthesia allows the perceiver to directly move from pitch to colour and then use colours to deduce pitches via a deliberate matching between colours and pitch names. For this latter possibility to be valid, several conditions must hold, such as that notes a semitone apart must have perceivable differences in colour; the induced colour percept must be indifferent to timbre; stored perceptual differences can acquire linguistic labels (Ward et al., 2006). This phenomenology has anecdotally been supported by a single-case report of a professional musician with AP who used her tone-colour synaesthesia to identify the pitch of a tone (Hänggi et al., 2008, see also Bouvet et al., 2014; Haack & Radocy, 1981; and Lebeau et al., 2020, for reports on single-case, and also Petrovic et al., 2012; Zdzinski et al., 2019, on chromaesthesia and AP).

The link between synaesthesia and AP might also be established on a merely statistical basis, with the literature showing that there is a significantly higher prevalence of synaesthesia among those individuals who have been identified as having AP. For instance, Gregersen et al. (2013) found that out of 768 individuals with AP, 151 (20.1%) reported being synaesthetes with colour being the most common concurrent.

[17] Estimates of the prevalence of music-colour synaesthesia within the synaesthete population vary between studies, but were reported at 41% in a study by Niccolai et al. (2012). It might not be easy to establish when synaesthesia appears during human development given that it might take time for individuals to become aware they are synaesthetes.

[18] As observed by Spence and Di Stefano (2023), the link between the inducer and the concurrent in synaesthesia can be conceived of in terms of “synonymity” or “identity”: Rather than being associated or cognitively-linked, the inducer and the concurrent are simply part of one and same perceptual experience. Hence, for a synaesthete, the sound of the trumpet and the colour scarlet are always co-experienced (though note that some early reports showed that colours were only sometimes induced by musical sounds; see MacDougal, 1898).

Moreover, at least according to certain sources, AP may be much less frequent among the population than synaesthesia (e.g., 0.01–1% vs. 1–4%, respectively, see Levitin & Rogers, 2005 and Simner et al., 2006, although both values are subject to variability depending on the specific inclusion/selection criteria). This would be consistent with the fact that only a fraction of synaesthetes are pitch-name synaesthetes. Finally, and importantly, results from Gregersen et al. (2013) demonstrated a close phenotypic and genetic relationship between AP and synaesthesia. That being said, however, the literature also demonstrates that AP is by no means necessary for pitch class-colour synaesthesia (Itoh et al., 2017).

The linkage between AP and synaesthesia is further supported by neurophysiological findings. Hänggi et al. (2008) compared magnetic resonance images of the brain of a pitch-taste and pitch-colour synaesthete with AP and a control group (musicians and non-musicians). The results highlighted increased volumetric white and grey matter in the synaesthete's auditory and gustatory areas, which might be associated to the interval-taste synaesthesia as well as volumetric white and grey matter alterations in visual areas, which might represent the neuroarchitectural foundation of the tone-colour synaesthesia (see also Dohn et al., 2015 for white matter anatomy in individuals with AP). FMRI studies by Loui et al. (2011, 2012) found enhanced activity in the superior temporal gyrus associated with auditory associations in those individuals with coloured-music synaesthesia and AP. This led researchers to claim that AP and synaesthesia are "two sides of the same coin" (Loui et al., 2013), meaning that the same general mechanism of enhanced sensory activation allegedly feeds into auditory experience in AP and visual experience in synesthetes.

3.2. Extraordinary memory and AP

In the psychological literature, cases are reported of individuals who have the extraordinary ability to memorize a huge number of sensory stimuli and are able to recall these memories even after long time (e.g., years). Intriguingly, this ability is often considered as linked to synaesthesia (Rothen et al., 2012). Anecdotal reports of this go back to the case of Solomon Shereshevskii studied by Luria (1968), who famously said that his memory "had no distinct limits […] there was no limit either to the capacity of Shereshevskii's memory or the durability of the traces retained" (p. 11). For instance, he could recall long meaningless lists of nonsense syllables and written nonsense equations both immediately and after 4 and 8 years or remember matrices of 50 digits after only a few minutes of inspection. Moreover, he was able to effortlessly recall them when retested 15 or 16 years later. Shereshevskii had multiple forms of synaesthesia (e.g., sound-colour synaesthesia, phoneme-colour synaesthesia, phoneme-taste synaesthesia); however, the extent to which his memory ability was attributable to his synaesthesia is unclear.

Another case is reported of a man who has memorized over 6000 books and has encyclopaedic knowledge of several disciplines, such as geography, literature, history, sports, and music. He was able to name all the US area codes and major city zip codes. He also has the ability to read extremely rapidly, simultaneously scanning one page with the left eye and the other page with the right eye (Peek & Hanson, 2007).

Intriguingly, similar extraordinary mnemonic abilities, occasionally also referred to as "savant syndrome" (Treffert, 2009), have been related to AP (Birbaumer, 1999; Snyder & Mitchell, 1999). Both AP and eidetic memory have been often considered as fast, low-level, sensory-rooted operations. Commentators have occasionally described the experience of musical savants with AP in terms of the direct access to lower levels of "raw" auditory information which are normally integrated into holistic information content in normal perceivers (Heaton et al., 1998; Miller, 1989). However, cognitive mediation must be recognized in those extraordinary mnemonic abilities that require some form of mathematical or computational skills.

Considering all the abilities in the human repertoire, it might be interesting to observe that music is one of those extraordinary skills that are most consistently present among savants, with AP being one of its most prevalent manifestations. It is interesting as well to note that unusual sensory discrimination in smell, touch, or vision including synaesthesia are among the other skills that have been reported, although less often, together with a prodigious facility for language. Last but not least, these special skills are always accompanied by prodigious memory abilities (Treffert, 2009). Conversely, typical synaesthetes have moderately enhanced long-term episodic memory and, to a lesser extent, also short-term, working memory (Rothen et al., 2012; Ward et al., 2019).

Mottron et al. (2009) proposed that many savant abilities involve a one-to-one mapping process between two isomorphic series of elements, a mapping between different codes involving the detection of structural similarity between the two series of units (see Di Stefano & Spence, 2023, on issues related to similarity across the senses). Importantly, the mastering of these mappings is implicit, both in the way in which they are learned and in the frequent difficulty or impossibility that savants have in verbalizing the strategies that they use to produce answers relying on these mappings. According to this view, therefore, AP could be explained in terms of the mapping between two discretized dimensions, pitch labels and pitches of the chromatic scale.

Such a one-to-one mapping ability might be considered as a consequence of another ability that is often associated with savants, namely, enhanced pattern detection, which allows for the stabilizing of associations between labels and precise values within continuous dimensions (e.g., frequency; Mottron et al., 2009; Treffert, 2009). For most savant abilities, the equivalent ability in normal individuals is only poorly or rarely, if at all, represented; this may be because one series of representations cannot be anchored on the other, as in the example of AP.

3.3. Interim summary

The comparison between AP, extraordinary memory, and synaesthesia has evidenced some interesting similarities and potential links between these rare phenomena. First, all these abilities seem to be automatically executed by the participant, without any cognitive effort. Such phenomenology might suggest describing the perception of AP in terms of pitch-label couples that form unique percepts. Just like the colour and shape of Lego blocks, individuals with AP would perceive an auditory-verbal unity when perceiving a tone, such as '440 Hz-A'.[19] Second, the key role played by associative mechanisms mediated by memory has been highlighted: in all cases, the subjects seem to be able to manifest their extraordinary skill thanks to an implicit or explicit association between stimuli from different domains, such as numbers and colours, pitch and labels, or calendar dates and days of the week. However, and interestingly, some associations are more easily recalled than others, with some preferred sensory directions emerging clearly in synaesthetes and those individuals with AP, namely, auditory-visual, for the former, and auditory-verbal/semantic for the latter (see Fig. 3 for a comparison between the perception of a musical note in individuals without AP, with AP and in pitch-colour synaesthetes).

Some differences emerge when it comes to the innate or acquired nature of these abilities. Although musical training is not sufficient in

[19] However, different from the simultaneous perception of the colour and shape of blocks, in AP the information related to pitch name is sensorily absent. Thus, it might be more properly considered as a case of amodal completion, that is, an occurrence of perceptual completion in which the observer integrates the information to generate a perceptual unity (see, e.g., Gerbino, 2020 and Spence & Di Stefano, 2024, for a recent review). In the case of AP, the subject would be completing the lacking verbal/semantic information based on the available auditory information (like when by hearing the bark of a dog one recognizes the breed). If this is a reliable description of how AP perception works, it further supports the role of associative learning.

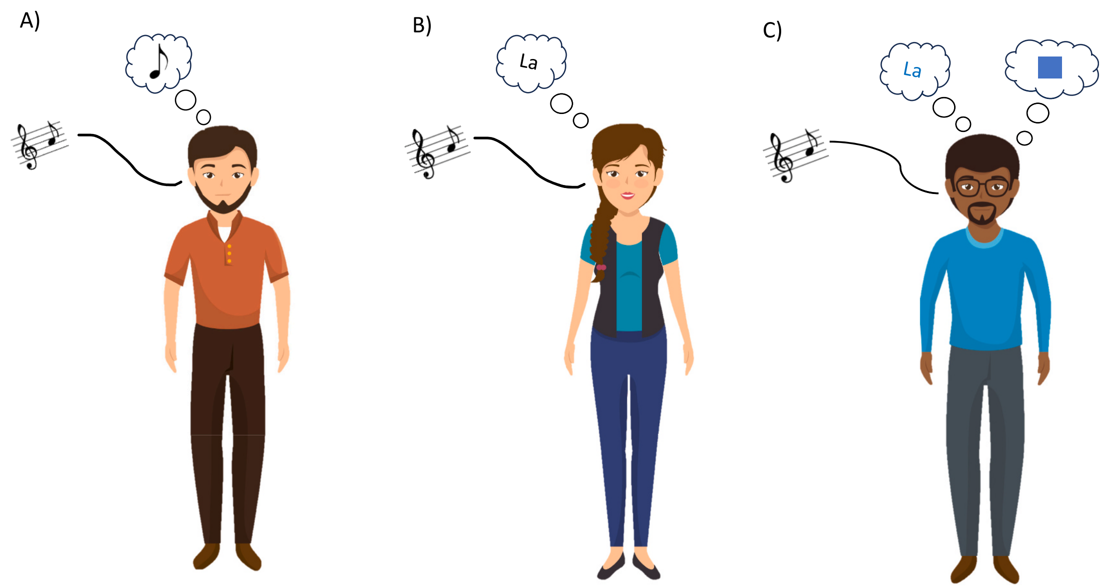

Fig. 3. Conceptual representation of the perception of a musical tone by normal perceivers (A), individuals with AP (B), and pitch-colour synesthetes with AP (C). All human figures designed by studiogstock/Freepik.

itself, it is clear from the literature that AP needs musical training to develop. Something similar can be said of those individuals with extraordinary mnemonic abilities, who must have been exposed to the information they demonstrate to recall with accuracy and precision even after long time. In contrast, synaesthetes do not seem to have gone through any explicit form of learning that led to the acquisition of synaesthetic experiences.

Finally, and intriguingly, none of these abilities seem to have any biological value or, at the very least, it is unclear how they represent an advantage for the rare individuals who are endowed with them. While each of them might facilitate individuals in specific tasks, such as the memorization of a sequence of visual stimuli or the transcription of melodies, these tasks are seemingly unrelated to survival needs and do not broadly affect human life as one would expect from sensory abilities which have a clear biological value (e.g., smelling spoiled food). Additionally, while synaesthesia is more prevalent in females, "savant syndrome" affects more males than females. Somewhat surprisingly, the same sex ratio is reported for both phenomena, 6:1 (Baron-Cohen et al., 1996; Treffert, 2009) while, to our knowledge, no study found any gender differences in the prevalence of AP, which might suggest that the ability is equally present in males and females.

To summarize, despite some prominent and intriguing similarities in the phenomenology of synaesthesia, eidetic memory, and AP, the automatic, sensory, intersubjective, and consensual nature of AP judgments seemingly makes such an ability unique with respect to both pitch-induced forms of synaesthesia (that are idiosyncratic) and extraordinary mnemonic abilities (that appear to be conscious rather than automatic). We now move on to examining a more common occurrence of absolute sensory judgments, namely colour perception.

3.4. *Colour perception and AP perception*

Influential scholars have often highlighted the parallel between AP perception and colour perception (e.g., Deutsch, 2002; Lewis, 1939). The analogy between pitch and colour perception was evoked very early in the literature on AP as an attempt to provide an intuitive explanation for a very rare perceptual phenomenon through a common one. Lewis (1939) observed: "Pitch arises as an attribute of auditory experience when the ear is stimulated in appropriate ways, just as color arises as an attribute of visual experience when the eye is appropriately stimulated" (p. 121) (see also Caivano, 1994). Based on Stevens' (1957) classification of perceptual dimensions, an analogy exists between auditory pitch and hue both considered as metathetic sensory dimensions (as well as both being circular dimensions; Spence & Di Stefano, 2023).[20] Here, we delve deeper into the comparison between colour perception and AP perception, drawing attention to a few important aspects that limit the validity of such comparison, thus supporting the uniqueness of AP in the domain of sensory perception.

First, different physiological mechanisms underly colour and pitch perception. Information about colour is separated into discrete streams by cones in the retina (Kolb, 2003), and remains separated up to the level of the cortex, thus allowing the human visual system to categorize colours (Siuda-Krzywicka et al., 2019; Zeki, 1993). In contrast, the cochlea and peripheral auditory system processes the frequency of sounds continuously between about 20 Hz and 20 KHz thus apparently preventing the discrete mapping between excitation patterns and percepts (Evans, 1992; Julesz & Hirsh, 1972; Warren, 2013).[21] Moreover, much of what we call music perception deals with the combination of different tones simultaneously perceived (i.e., harmony); this is not the case for colours, which are typically perceived as discretized entities.[22] Therefore, the fact that some individuals can categorize pitches into discrete

[20] Note that metathetic dimensions obey a well-structured organization without necessarily having a 'more than' or 'less than' end. In contrast, prothetic dimensions are quantitative perceptual continua (i.e., having to do with how much) with ratio properties with a clear 'more than' and 'less than' end. Examples of these dimensions are loudness, brightness, visual lightness, heaviness, duration, and roughness (Stevens, 1957, 1971).

[21] If this holds true for the way in which auditory information is processed, one must acknowledge that in musical practice, a small range of frequencies surrounding one specific frequency is often accepted as corresponding to the particular musical pitch. This is seemingly similar to what happens with colours, leaving the question on the many/one-to-one mapping of colours and pitch open.

[22] See Kubovy and Van Valkenburg (2001) and Kubovy and Schutz (2010) for a reflection on the duality of vision and audition and of their underlying mechanisms (e.g., colour constancy in vision).

categories requires an explanation of what is different about these individuals in terms of their perceptual and/or neural architecture (see also Ross et al., 2005).

Moreover, the variability in the way in which AP impacts tone perception might make the comparison between AP and hue perception only partially valid. For example, studies have shown that some individuals with AP can identify the label of tones produced by only one particular instrument, thus suggesting that other factors, such as timbre, might impact AP perception (Reymore & Hansen, 2020). Other individuals, meanwhile, have AP for only a single tone which allegedly acts as an internal referent for the calculation of other pitches (this case is often referred to as 'quasi-AP'); what is more, these individuals typically have slower reactions in discrimination/perception tasks (e.g., Bachem, 1937; Levitin & Rogers, 2005, and Ward, 1999, for reviews).[23] Taken together, therefore, these studies demonstrate that AP is not exclusively dependent on pitch.

Beyond psychophysical and physiological differences, there are some fundamental differences in the way in which AP and colour labels emerge in humans. While it is well-established that the development of both abilities needs repetitive exposure to the perceptual stimuli and memory (see **Section 2** for AP and Pitchford & Mullen, 2006, for the acquisition of colour terms), it should also be pointed out that the mnemonic skills required for storing the matches between colour hues and colour labels seem much less demanding and more common than the mnemonic ability required for creating consistent pitch-labels associations. This is reflected by the fact that most infants develop the ability to name colours between the age of 3 and 6 years (at least with a similar accuracy of identification of individuals with AP in labelling pitches), with most children associating at least the basic colours and their names correctly and consistently after 4–5 years of age (Bornstein, 1985). In contrast, AP needs more time to be fully developed (between 5 and 9 years of age, Levitin & Rogers, 2005; Ward, 1999). Moreover, while only a small fraction of children exposed to musical stimuli develop AP, the large majority of (typically developing) children end up in mastering colour names within a few years. This might be even more surprising, given that the children who receive musical training are likely exposed longer to pitch labelling than to colour labelling and, nevertheless, they acquire colours names first.

One explanation for the developmental delay, the additional effort, and the relatively higher training of AP, is that colours are environmentally frequent, if not ubiquitous, features of objects. In contrast, very few objects have pitch as one of their perceptual features. Children interact every day with coloured objects and use colour names when playing; but they rarely, if ever, use pitch labels. Moreover, colour is a highly salient perceptual dimension for children which allows them to classify and sort objects they interact with; in contrast, children will hardly classify objects, not even musical instruments, according to the exact pitch they produce. In contrast, one might observe that pitch is a less perceptually salient feature of objects, and likely even of sounding objects. Thus, pitch processing, not to say AP, likely needs a stronger contribution of cognitive components which might develop both later and more slowly. Finally, and more generally, it is also worth noting that humans are visually dominant creatures, with larger neural resources in the sensory cortex devoted to the processing of sight rather than sound (e.g., Gallace et al., 2012; Hutmacher, 2019).

The different phenomenal qualities of pitch and hue might also play a role here. While categorizing the hue of colours is quite intuitive (e.g., 'Red' or 'Blue'), perceiving pitch chroma as a salient and consistent perceptual category of sounds (e.g., 'C' or 'D') seems much more difficult for those individuals without AP. Thus, for instance, it would make sense to make intramodal comparison, by asking, for example, whether red is more similar to brown or black, but it would make much less sense to ask whether C is more similar to A or F# (see Di Stefano & Spence, 2023, on issues arising from perceptual similarity).[24]

To summarize, the parallel between colour perception and AP perception could not be taken literally and could not help in understanding the nature of AP perception. Although colour and pitch perception share several surface properties, at deeper examination crucial differences emerge that make the comparison inadequate. This provides further support to the idea that AP represents a unique kind of absolute sensory judgment in humans.

4. Conclusions

4.1. Main findings

The evidence reviewed here provides insights into the genetic and ethnic factors influencing the development of AP, with an emphasis on familial studies, ethnic clusters, and the role of early music training (e.g., Gregersen et al., 1999; Gregersen et al., 1999, Gregersen et al., 2000; Profita et al., 1988). Familial aggregation studies suggest a higher likelihood of AP in siblings of AP possessors, with the age of onset, combined with genetic factors and early practice, considered as a factor strongly influencing pitch-naming ability. Ethnic clusters for AP are observed, with higher rates among Asian students compared to Caucasian students, and significant differences in prevalence across countries (Miyazaki, 2004a, 2004b; Miyazaki et al., 2018). Early exposure to tonal languages does not fully explain the higher prevalence among Asians, with the Suzuki method and other pedagogical traditions (fixed pitch training) likely contributing to ethnic differences.

The neuroscientific literature has revealed the intricate neural mechanisms associated with AP perception, emphasizing the involvement of multiple brain regions and potential variations in processing strategies among individuals with AP skills. In particular, studies suggest a functional pathway involving bilateral PT and the left posterior DLFC, forming a network implicated in AP ability (e.g., Bermudez & Zatorre, 2005; Ohnishi et al., 2001; Schulze et al., 2009; Wengenroth et al., 2014; Wilson et al., 2009; Zatorre et al., 1998). The DLFC, implicated in those tasks that require working memory, likely mediates AP musicians' ability to associate pitch with verbal labels. The PT, located in the superior temporal gyrus, plays a vital role in pitch processing. Positive correlations between left PT activation and AP proficiency are observed. Neuroanatomical studies show stronger left surface/volume asymmetry in PT among AP musicians, associated with increased AP accuracy (Benner et al., 2023). Early findings on right-hemispheric domination in AP processing need further empirical confirmation, given some controversial findings.

The behavioural literature shows that AP emerges early in development, typically between 3 and 6 years, and is strongly correlated with musical education (Bachem, 1937; Levitin & Rogers, 2005; Miyazaki, 2004a; Ward, 1999). AP is considered an automatic perceptual expertise, effortless for those who possess it, with individuals often unaware of its exact functioning. While it can persist throughout life, traumatic events or certain drugs may temporarily affect it (e.g., carbamazepine, see Braun & Chaloupka, 2005). AP manifests as a spectrum of skills,

[23] For example, those individuals with quasi-AP typically take more time to identify the key that has been struck on a piano keyboard than those with AP (Bachem, 1937).

[24] It is perhaps worth going back to Helmholtz regarding this point. The early psychophysicist once wrote that: "The distinctions among sensations which belong to different modalities, such as the differences among blue, warm, sweet, and high-pitched, are so fundamental as to exclude any possible transition from one modality to another and any relationship of greater or less similarity. For example, one cannot ask whether sweet is more like red or more like blue. Comparisons are possible only within each modality; we can cross over from blue through violet and carmine to scarlet, for example, and we can say that yellow is more like orange than like blue!" (Von Helmholtz, 1878/1971, p. 77).

varying in accuracy, response time, and means of identification. The primary manifestation is immediate pitch naming, with accuracy ranging between 70% and 99% (Takeuchi & Hulse, 1993).

Surprisingly, AP possessors and non-possessors exhibit equivalent acuity for pitch differences (Levitin, 2004). While often seen as a sign of musical talent, AP may negatively impact some musical tasks involving pitch transpositions (e.g., Miyazaki, 2004b; Revesz, 1953; Ward, 1999). Cases of individuals who can identify the frequency but not the name of the pitch suggest that refined perceptual skills alone are insufficient for AP, challenging the idea of a direct mapping of physical frequencies onto pitch categories. The complexity of the phenomenon is underscored by the nuanced differences in performance with specific timbres, notes, or frequency ranges.

The prevalence of AP has been studied in relation to neurodevelopmental disorders such as ASD and Williams syndrome (Bonnel et al., 2003; Heaton, 2003; Heaton et al., 1998; Lenhoff et al., 2001; Masataka, 2017; Meilleur et al., 2015). Individuals with ASD often exhibit heightened pitch discrimination and memory for melody, but may struggle with vocal imitation tasks. In Williams syndrome, studies yield conflicting results, with some indicating near-ceiling levels of AP, while others suggest low performance compared to controls. Finally, blind individuals, particularly those who received musical training, show a higher incidence of AP, with neural correlates differing from sighted AP individuals (Hamilton et al., 2004; Gaab et al. 2006; Welch, 1988).

4.2. Is AP a unique kind of absolute sensory judgment in humans?

Returning, then, to the main question of this paper, we can answer by observing that AP is a unique kind of absolute sensory judgment in humans: individuals with AP can recall the names of pitches in a quick, automatic, consensual, and, apparently, effortless manner, without the need of a reference. We have supported this claim by comparing, for the first time, AP with phenomenologically similar rare and common phenomena in which perceivers formulate absolute sensory judgments, such as synaesthesia and colour perception. The idiosyncratic nature of the inducer-concurrent matchings in synaesthesia is incompatible with the consensual associations between auditory-verbal stimuli in AP perceivers. Moreover, from a developmental perspective, there is no learning period associated to synaesthesia and people typically report having it from as early as a child can remember, while most people with AP date it back to the years of musical training. At the same time, the psychophysical, physiological, and perceptual differences between colour perception and AP prevent us from considering these two occurrences of reference-free sensory judgments as similar.[25] Thus, in contrast with extraordinary memory, synaesthesia, and colour perception, we can conclude by affirming that AP emerges as the only ability that is, at the same time, sensory, automatic, and based on non-idiosyncratic mappings (see Table 2).

The uniqueness of AP is apparent even when contrasted with a related perceptual phenomenon—absolute tempo. Conceived of as the rhythmic counterpart of AP, absolute tempo involves the capability to recognize or recall the tempo of musical compositions without external cues. Despite the extensive scientific interest in AP over the past century, resulting in hundreds of published papers on the subject, the equivalent rhythmic skill has received limited attention. Only one study, conducted by Gratton, Brandimonte, & Bruno (2016), has systematically explored absolute tempo, highlighting a significant gap in research compared to the comprehensive investigation of AP.

An apparently overlooked aspect in the literature is the directionality of AP. Most tests used to assess AP expose individuals to auditory stimuli first (often isolated pitches) asking them to verbally identify or reproduce them on a musical instrument. This leaves at least partially unclear whether AP has a privileged direction, namely, from auditory to verbal/semantic. Based on the reviewed literature, it seems unlikely that individuals with AP hear a tone when presented with the name of the pitch, for at least two reasons. First, because the pitch chroma does not necessarily identify an octave, and octave errors are frequent in AP perception. Thus, while linking the tone to the label should be unambiguous, the reverse path would admit different answers. For example, the label "A" might be correctly associated with 220 Hz, 440 Hz; 880 Hz. Second, because an auditory image triggered by a pitch label would probably classify as a form of synaesthesia, namely, the association between the semantic inducer and the auditory concurrent.[26]

Table 2
A comparison among AP, extraordinary memory, synaesthesia, and colour perception.

	Extraordinary memory	Synaesthesia	Colour perception	Absolute pitch
Dichotomous/ Continuous	Dichotomous	Dichotomous	Continuous	Continuous
Cognitive/ Sensory	Cognitive & sensory	Sensory	Cognitive & sensory	Sensory
Automatic/ Conscious	Conscious	Automatic	Conscious	Automatic
Evolutionary benefit	None	None	Yes	None
Idiosyncratic mapping	No	Yes	No	No
Learnability	No	No	Yes	To some extent
Categorical	Yes	Yes (?)	Yes	Yes
Language-mediation	Yes	No	Yes	Yes

4.3. Open issues

The role of learning and language in mediating AP perception remains somewhat obscure. The literature has distinguished between musical AP and general AP, demonstrating that AP-like memory for pitch is widespread among those individuals who do not possess AP (Halpern, 1989; Levitin, 1994; Schellenberg & Trehub, 2003; Terhardt & Seewann, 1983; Terhardt & Ward, 1982). Why, then, should AP-like pitch-label matching be so rare among individuals? The reason behind the inability to name pitch class cannot be the mere ignorance of tone names, because a person without this knowledge could presumably invent his/her own names for the few tones that they are able to distinguish. However, as observed by one of the reviewers of this paper, the fact that listeners could invent their own names does not imply that they would do so in any particular setting. It can be argued that labelling is a process that is either cognitively or perceptually more demanding than merely associating a percept with a tag, and that language/verbalization plays a constitutive role in AP perception.

The reviewed evidence converged on the suggestion that AP does not appear to confer any evident advantage to those individuals who possess it, even in the case of musicians (Levitin, 2004; Miyazaki, 2004b). However, given the abundance of studies highlighting the existence of a genetic component of AP (e.g., Gregersen et al., 1999, 2000), an intriguing question emerges regarding the utility, or biological value, of AP. In other words, one must ask what such putative genes would code for, and what the possible evolutionary value might be.

In contrast with the ability to perceive other acoustic features, such as timbre (e.g., Di Stefano & Spence, 2022, on roughness) or harmony (e.

[25] Regarding the distinction between musical AP and general AP, our conclusions explicitly refer to "musical" AP and "general" AP as categorically distinct perceptual phenomena.

[26] This case would be even more problematic given the unidirectional nature of synaesthesia.

g., Bowling & Purves, 2015, and Di Stefano et al., 2022, on consonance), pitch labelling does not seem to play any evolutionary role.[27] Thus, it has been suggested that AP might be a maladaptive trait, that is, an unfortunate side effect of early and intense musical training (Weisman et al., 2006). However, if this were to be the case, one would expect that natural selection should progressively reduce its occurrence in the population.

Considering AP as a maladaptive trait would partially address an argument based on the similarity between colour perception and pitch perception. The argument is as follows: we are exposed to colours and their names since birth, and this exposure leads all healthy individuals to master colour names in few years, with the exception of the rare individuals affected by colour anomia.[28] Similarly, with many people studying music across the world, why do most people have "pitch anomia"? As Diana Deutsch (2006, p. 11) puts it: "So the real mystery of AP is not why some people possess this ability, but instead why it is so rare?"[29] Besides stressing the biological irrelevance of AP as a maladaptive trait, contrasted with the allegedly biologically useful ability of mastering colour names (Jacobs, 2009; Matthen, 1988), one might also underscore that, although the prevalence of AP in the population is very low, it increases a lot when we narrow down the sample to musicians only. However, one has to acknowledge that, despite the consistent exposure to pitch naming since a very young age, most musicians do not develop AP, while most of them develop refined relative pitch ability.

The idea of AP as a maladaptive trait might receive support from the speculative idea that most, if not all, infants possess AP at birth, but such an ability is inhibited in the first year with the onset of language acquisition (Saffran, 2003; Saffran & Griepentrog, 2001; see also Levitin, 1994). According to this hypothesis, also known as the "savant's hypothesis", the loss of AP might be explained in biological or cognitive terms, given that a common strategy at work in the human brain is reducing the complexity of information to improve efficiency by creating higher-level concepts which discard low-level detail and reduce the number of items one has to manipulate. In this view, processing pitch in an absolute way, instead of relatively, reduces the generalizability of pitch perception based, for example, on octave similarity and transpositions, thus resulting in a less efficient and more demanding process.[30] Thus, most perceivers might lose such an ability to enhance their abilities to process pitch. In line with the savant's hypothesis, Bossomaier and Snyder (2004) have argued that AP is latent within everyone and that it can be switched on by turning off those parts of the brain that are responsible for the inhibition. However, this claim did not receive empirical confirmation, together with a similar hypothesis about the origins of synaesthesia which lacks empirical support (Deroy & Spence, 2013).

Finally, the above reflection leads to a more general observation on the way the issue of AP (as well as many other rare perceptual skills) is approached, namely the idea that the ability is either innate (i.e., biologically or genetically determined) or learned/acquired (i.e., developed thanks to contextual and cultural factors). We argue that such a dichotomic alternative is misconceived and misleading, given that most fundamental abilities that are typically considered as innate have to be eventually learned. Thus, it is probably better to reshape the conceptual approach and focus on the nature of the learning trajectory: when the acquisition of a skill is successful and easy for most individuals, the skill might be considered as more hardwired into the biology of human beings (and thus 'innate'); when the mastering of a skill is hard to achieve, and the learning trajectory highly variable across individuals and often unsuccessful, that ability is not innate, or "less innate"/"acquired", and hence likely determined by individual factors. Examples of the former abilities can be walking or speaking a language, while examples of the latter can be mastering painting or violin playing (see Table 2 for a summarizing comparison between AP, extraordinary memory, and synaesthesia).

4.4. *Future directions*

A first line of investigation would provide further insights into the perceptual aspects that characterize AP, particularly referring to the directionality of AP. Experiments might be conducted to assess whether individuals with AP hear a tone when presented with the name of the pitch or read the note on the score. Similarly, one might also test whether the corresponding auditory pitch is evoked by the mere sight of keys being pressed on a piano or any other way of producing musical tones with instruments. This could be especially tested in piano or instrumental pitch possessors. In all of these experiments, it would be interesting to know more about the timbral quality of the pitch that is evoked (if any) by abstract referents (e.g., notes on the score or pitch labels) or instrument-related ones (e.g., piano keys or guitar frets). Should empirical findings confirm such a reverse sensory path among AP listeners, or a subset of them, it would be difficult to distinguish such sensory experiences from synaesthesia, apart from the fact that AP experience is intersubjective and non-idiosyncratic (i.e., the verbal label triggered by the same pitch is consistent across individuals).

Second, given the evidence showing that crossmodal correspondences involving auditory pitch are mostly based on relative pitch (Spence, 2019), it would most certainly be interesting in future research to investigate how those individuals with AP perform in those tasks on crossmodal correspondences involving auditory pitch (such as, for example, Brunetti et al.'s, 2018, speeded classification task). One would expect those listeners to be more accurate, fast, and consistent when tasks require auditory discrimination abilities.

Third, it would be interesting to assess whether such an absolute perception of auditory parameters exists beyond the domain of pitch. For instance, experiments might be carried out to examine the perception of absolute loudness or absolute tempo (see Gratton et al., 2016). Different approaches might be taken in this case, such as enrolling primarily those subjects who demonstrated extraordinary ability in AP perception or rather musicians specifically trained in rhythmic skills (e.g., drummers, percussionists). Similar findings might also shed light on the role of learning in the acquisition of AP-like skills, as neither loudness nor tempo are normally taught in the same manner as pitch (i.e., involving the association of verbal labels with metronome/loudness values). However, given that tonality and harmony are fixed parameters compared to tempo/loudness in music composition and production (i.e., the tempo of Beethoven's Overture "Leonore" could vary across different interpretations, but its harmonic and melodic structure remains unaltered), one could be perplexed about the musical relevance or utility of such abilities.

Beyond the auditory domain, one might wonder whether, given the similar nature of vibratory phenomena in touch and audition, perceivers exist who exhibit a tactile equivalent of AP. Experiments designed in an attempt to investigate AP in touch should carefully consider the different sensation thresholds of tactile receptors in the human body.

Finally, the development of technological devices that can provide normal perceivers with AP-like experience is also an intriguing area for future development. Along such lines, it is worth mentioning the recent

[27] AP plays no role in the authoritative reviews recently published in *Behavioural and Brain Sciences* about the origins and functions of music (Mehr et al., 2021; Savage et al., 2021).

[28] People with colour anomia can recognize that two objects are of the same colour, and can discriminate between different colours, but simply cannot label them.

[29] A similar question is raised by Levitin (1994): "The proper question might not be the one often asked, 'Why do so few people have AP' but rather, 'Why doesn't *everybody*?'" (p. 414). Levitin grounds his question on properties of the auditory system: given that cells that respond to particular frequency bands are found at every level of the auditory system, information about the AP of a stimulus is therefore potentially available throughout the auditory system.

[30] Notably, pitch processing in an absolute way is more frequent in non-human animals than in humans (Hoeschele, 2017).

conference paper by Oka and Kurihara (2022) in which the authors present a multimodal augmented reality system that allows normal perceivers to have auditory and visual feedback of note names that can simulate the experience of individuals with AP. Sensory substitution devices might also translate auditory pitch into colours and thus provide absolute (visual) perception of auditory pitch (see Spence & Di Stefano, 2023, on translating between audition and vision). Similar devices might be used for training purposes, especially with kids in the AP "critical period".

CRediT authorship contribution statement

Nicola Di Stefano: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Charles Spence:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2024.105805.

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