

Full Length Article

Absolute pitch and sound-color synesthesia provide for unique learning opportunities

Beat Meier^{a,*}, Solange Glasser^b^a Institute of Psychology, The University of Bern, Fabrikstr. 8, 3012 Bern, Switzerland^b Melbourne Conservatorium of Music, The University of Melbourne, 234 St. Kild Rd., Melbourne, Australia

ARTICLE INFO

Keywords:

Statistical learning

Incidental learning

Tone-color associations

Connectivity

Experiential consequences

ABSTRACT

The goal of this study was to investigate the impact of absolute pitch (AP) on statistical learning and on cross-modal associative learning. Previous studies have demonstrated that compared to non-musicians, musicians have an advantage in statistical learning and that musical expertise leads to a reorganization in the network supporting statistical learning. As the brains of AP possessors show stronger connectivity in this network, we hypothesized that they show a further advantage in statistical learning. We used a paradigm with fixed tone-color pairs presented to participants in a stream of adjacent three-element sequences. We assessed statistical learning by asking participants subsequently to give frequency judgements for presented and not presented sequences. We assessed cross-modal associative learning of tone-color pairs by probing memory for the colors that were presented with each tone. We compared musicians with AP ($N = 24$), musicians without AP ($N = 22$), and a non-musician control group without AP ($N = 20$). The results showed an advantage in statistical learning for both groups of musicians. AP musicians had a long-lasting advantage in the incidental learning of tone-color associations (indicated by follow-up assessments after one week and one month). One third of the musicians with AP also had sound-color synesthesia ($N = 7$), and additional analyses revealed that they had a unique statistical learning advantage. The results indicate that musical expertise, AP, and synesthesia provide specific learning advantages. We suggest that the results can be best explained in a framework that considers for each group of participants the different experiential consequences of the task requirements.

1. Introduction

Absolute pitch (AP) is the ability to label or produce a note of a given pitch in the absence of a reference note, with AP possessors providing pitch labels rapidly and effortlessly learnt through musical training, in which the pitch of a tone is inferred by comparing it to an external reference tone (Theusch et al., 2009). Musical training is a multisensory form of training and like language, music is a highly structured system with regularities that listeners extract implicitly (Tillmann et al., 2000). In fact, previous studies have demonstrated that compared to non-musicians, musicians have an advantage in extracting regularities from streams of information using the statistical learning paradigm (Mandikal Vasuki et al., 2017; Paraskevopoulos et al., 2017; Pesnot Lrousseau & Schon, 2021; Shook et al., 2013). It has been suggested that the neural differences between musicians and non-musicians are functional for extracting the regularities in the stream of information. Musical expertise leads to a reorganization in the network supporting

statistical learning, in particular the pathways that connect bilateral superior temporal and intraparietal areas with the left inferior frontal gyrus (Paraskevopoulos et al., 2018). Compared to musicians without AP, AP possessors have increased connectivity in the superior temporal gyrus (Dohn et al., 2015; Loui et al., 2011). Thus, it is possible that AP musicians have an additional benefit in statistical learning. To investigate this question was the first goal of this study.

Statistical learning is typically investigated by exposing participants to a stream of stimulation, for example, a stream of syllables to test verbal statistical learning. While this stream of information seems random from the perspective of the participant, there is a hidden structure such that some transitions are more frequent than others. Research has shown that even 8-month-old infants are able to extract this kind of frequency information as indicated by their attention allocation (Saffran et al., 1996; Saffran et al., 1999). Using tones, Saffran et al. (1999) exposed adults and infants to a continuous stream consisting of repeated three-tone sequences structured in such a way that

* Corresponding author.

E-mail addresses: beat.meier@unibe.ch (B. Meier), solange.glasser@unimelb.edu.au (S. Glasser).

pairs of tones within triplets occurred more often than pairs between triplets. Both adults and infants were able to distinguish repeatedly presented triplets from new ones. Statistical learning can occur for auditory and visual streams of information as well as for musical timbres (Frost et al., 2019; Tillmann & McAdams, 2004). So far, it is not clear whether musical training improves statistical learning specifically in the auditory domain, or whether musical training and the resulting neuroplastic brain changes in the network supporting statistical learning leads to a more general improvement. Only few studies have addressed this question.

Mandikal Vasuki et al. (2017) presented a group of seventeen musicians and eighteen non-musicians with an auditory (based on tones) and a visual (based on cartoons) stream of information. The results showed better auditory, but not visual, statistical learning for musicians compared to non-musicians. Therefore, they suggested that musical expertise is associated with an enhanced ability to detect statistical regularities specifically in the auditory domain.

Paraskevopoulos et al. (2018) investigated statistical learning of an auditory (based on timbre), a visual (based on color), and an audiovisual stream (based on shape and pitch) of information in a group of twelve musicians and twelve non-musicians. On a behavioral level, they found stronger statistical learning for musicians than for non-musicians, but no differences across modalities. Magnetoencephalography revealed a contribution of Heschl's gyrus for auditory statistical learning and a contribution of medial temporal and visual association areas for visual statistical learning. The cortical network underlying audiovisual statistical learning was partly common and partly distinct from the corresponding unimodal networks, involving right temporal and left inferior frontal sources. Musicians showed enhanced connectivity between these regions and top-down modulation of their activity by the pre-SMA and the superior temporal gyrus, while this neuroplastic effect also showed a cross-modal stability between the auditory and audiovisual domain. Thus, these results indicate both specific and general consequences of musical training on statistical learning.

So far, no study has tested statistical learning in musicians with AP. However, there is evidence for enhanced connectivity of structures involved in statistical learning in AP possessors. Using diffusion tensor imaging and tractography, Loui et al. (2011) observed hyperconnectivity in bilateral superior temporal lobe structures. These hyperconnected regions included the posterior superior and middle temporal gyri in both left and right hemispheres. AP possessors had significantly higher tract volume than Non-AP individuals. Similarly, Dohn et al. (2015) found structural differences in brains of musicians with and without AP with increased cortical thickness in the bilateral superior temporal gyrus, the left inferior frontal gyrus, and the right supra-marginal gyrus. Furthermore, they found higher fractional anisotropy in APs within the inferior fronto-occipital fasciculus, the uncinate fasciculus, and the inferior longitudinal fasciculus. Kim and Knosche (2017) investigated the intracortical myelo-architecture in musicians with and without AP using quantitative mapping of the longitudinal relaxation rates with ultra-high-field magnetic resonance imaging. Most importantly, they found greater intracortical myelination for AP musicians in the anterior region of the supratemporal plane, a region on the dorsal surface of the superior temporal gyrus, which contains key auditory areas such as Heschl's gyrus (primary auditory cortex) and the planum temporale. Using diffusion tensor imaging in a sample of musicians with different degrees of AP, Burkhard et al. (2020) found a positive correlation between degree of AP and white matter density in the planum temporale. Thus, there is evidence for enhanced connectivity in brain areas which are also involved in statistical learning, and it is possible that these differences translate into more efficient extraction of frequency information and, as a result, in an additional benefit in statistical learning for AP possessors.

Moreover, AP possessors excel in tasks involving pitch identification, labeling, and auditory working memory (Bachem, 1954; Deutsch & Dooley, 2013; Dooley & Deutsch, 2010, 2011; Zatorre & Beckett,

1989). It is possible that these advantages can also contribute to statistical learning. The representation of pitch-pitch name relations can be considered as a knowledge structure in semantic memory. It is thought that AP is based on a pitch template that represents pitches across octaves in a unitary way integrated with the verbal code (Levitin & Rogers, 2005). This template is not completely rigid but can be transposed according to concurrent experience (Van Hedger et al., 2013). The fast and accurate retrieval of tone labels from the template in response to a particular pitch is typically used to assess AP (Bairnsfather et al., 2025). As the semantic memory is organized in networks of related concepts, it is likely that it can be used for establishing novel associations between pitch and other information. In the present study, we used a statistical learning paradigm that involved a stream of fixed tone-color pairs in order to test whether the AP template provides for an advantage in incidental learning pitch-color associations. We reasoned that AP possessors should have an advantage in learning these associations. Thus, the second goal of this study was to assess whether AP musicians have a specific advantage in incidental associative learning of pitch-color associations.

AP is typically acquired by predisposition and musical training during a critical period in early childhood. However, it seems to be possible that this critical period can be reopened pharmacologically (Gervain et al., 2013) and that some adults can acquire AP in adulthood by training (Van Hedger et al., 2019; Zatorre, 2003). The evidence for a genetic contribution comes from genome-wide linkage studies (Gregersen et al., 2013; Theusch et al., 2009), familial aggregation studies (Baharloo et al., 2000), and twin observations (Gregersen, 1998; Theusch & Gitschier, 2011). AP is a rare ability and has been estimated to occur in less than one in 10,000, or 0.01% of the general population (Profita & Bidder, 1988; Takeuchi & Hulse, 1993). It should be noted, however, that despite the prevalence of its citations, this figure lacks substantiation and further research into the prevalence of AP in the general population is needed. The prevalence rate of AP is significantly higher in professional musicians as indicated by a survey of musicians, in which the frequency of self-reported AP was 15% (Baharloo et al., 1998b). Interestingly, there seems to be a relationship between AP and synesthesia (Di Stefano & Spence, 2024).

Synesthesia is also a rare condition with a prevalence of approximately 4%, in which a stimulus in one sensory domain (the inducer, e.g., a certain tone) can elicit a sensation in another sensory domain (the concurrent, e.g., a color experience; see Meier (2021); Ward (2013), for overviews). Gregersen et al. (2013) reported that the occurrence of synesthesia in a sample of 768 musicians with documented AP was 20.1%. Moreover, a family linkage analysis revealed a close phenotypic and genetic relationship between absolute pitch and synesthesia. Both phenomena are associated with enhanced brain connectivity (Brauchli et al., 2019; Loui et al., 2011; Loui et al., 2012; Rouw & Scholte, 2007; Ward et al., 2024). Like the unique relation between pitch and pitch label in AP, in synesthesia unique associations between inducers and concurrents exist (Chiou & Rich, 2014; Meier, 2013). Given these relationships between AP and synesthesia, a further goal of this study was to assess the proportion of synesthesia in our sample of AP possessors. Moreover, given the possibility that the brains of AP possessors with synesthesia are characterized by even stronger connectivity including areas involved in statistical learning, these people may show an additional benefit in statistical learning.

To summarize, the primary goal of the present study was to test whether AP musicians have an advantage in statistical learning compared to musicians without AP. Fixed tone-color pairs were initially presented to participants in a stream of adjacent three-element sequences. Participants were instructed to attend to the visual color sequence while the exposure to the auditory stream was incidental. Subsequently, they gave frequency judgements for presented and not presented sequences to assess statistical learning. If AP leads to a more efficient extraction of frequency information than musical expertise per se, we expected enhanced statistical learning, that is, better

discrimination between presented (i.e., old) and not presented (i.e., new) triplets in AP possessors. We complemented the design with a non-musician control group and we expected that both musicians with and without AP show better statistical learning. Moreover, in an exploratory analysis we compared those AP musicians with synesthesia with those without synesthesia.

The second goal was to test incidental learning of tone-color associations. Specifically, we predicted that musicians with AP have better memory for these associations because they can integrate the color associations into their existing knowledge structures. In contrast, musicians without AP lack these knowledge structures (i.e., the pitch template), and thus they may not even learn more than the non-musician control group. We also conducted follow-up tests after one week and after one month to assess the longevity of this supposed memory advantage in AP.

2. Method

2.1. Participants

To determine sample size, we consulted previous studies that have investigated whether musicians and non-musicians differ in their statistical learning abilities (Mandikal Vasuki et al., 2016; Mandikal Vasuki et al., 2017; Paraskevopoulos et al., 2018). Mandikal Vasouki et al. tested 17 musicians and control participants; Paraskevopoulos et al. tested 12 musicians and control participants. Based on these studies, we planned to include 20 participants per group. As we were successful in recruiting a few more musicians, we included all of them in the study. Musicians were students enrolled at the Conservatorium of Music at the University of Melbourne. Depending on their score on a pitch identification task (see below), they were further classified as having absolute pitch ($N = 24$, age between 18 and 31 years, $M = 22.75$, 11 females) or not ($N = 22$, age between 18 and 29 years, $M = 19.5$, 19 females). As all the musicians were enrolled at a music conservatorium and exercises in relative pitch are part of the curriculum, it is mandatory that all of them possess this ability, although this was not specifically tested in this study. The control group consisted of 20 students (age between 21 and 31 years, $M = 23.5$, 11 females) from the University of Bern. All participants were recruited by word of mouth and were not financially compensated. After the experiment, the participants were screened for the presence of synesthesia. It turned out that seven out of the 24 musicians with absolute pitch (i.e., about 30%) also reported to have sound color-synesthesia, which was further confirmed with the corresponding consistency test of the Eagleman-Battery (Eagleman et al., 2007), see Supplementary Materials Consistency-test. The study was approved by the Ethics committees of both the University of Melbourne and the University of Bern in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants.

2.2. Materials

2.2.1. Pitch identification task

The pitch identification task was modelled on previous tests (Baharloo et al., 1998; Deutsch et al., 2009; Wilson et al., 2012). It was composed of two blocks, the first with piano tones and the second with pure tones. Each block consisted of the presentation of three sequences composed of twelve tones between C3 and B5. All 12 pitch classes were presented an equal number of times, and their presentation order was randomized (e.g., B3, D5, C#4, F5, C4, E5, F3, F#4, D3, A#5, D4, C#3). Each tone was presented for 0.5 s with 2.5 s response time between tones, during which participants named each tone on a prepared sheet of paper. After twelve tones, there was a four-seconds break to allow participants to move to the next line. As participants were required to respond to pitch-class only, octave errors were not possible. Two scoring methods were applied. A strict criterion considered correct responses only and a lenient criterion also considered half tone deviations. For

those participants who indicated to have AP, mean correct responses scores were 0.92 and 0.97, for strict and lenient scoring, respectively. Of the other musicians, 9 were willing to try the test, resulting in mean scores of 0.10 and 0.23. for strict and lenient scoring, respectively.

2.2.2. Statistical learning task

The stimuli for the statistical learning task consisted of a unique combination of a color and a tone (i.e., white – C3, cyan – C#3, red – D3, light red – D#3, yellow – E3, olive – F3, orange – F#3, green – G3, lime – G#3, purple – A3, magenta – A#3, navy – B3). Color assignments were informed by qualitative observations from interview data collected during the second author's doctoral research (Glasser, 2018), in which individual participants reported idiosyncratic pitch-color associations. These observations were used as an initial guide and were subsequently refined iteratively to ensure adequate perceptual differentiation across stimuli and a balanced color palette.

The colors were presented for one second on a computer screen and spanned the whole screen. The tones were piano tones, synthesized to a duration of one second and all the tones were drawn from C3 to B3. These compound stimuli were used to create eight color-tone sequences containing distinct three-seconds tone-color triplets with unique transitions (e.g., white – C3, orange – F#3, light red – D#3; see Fig. 1A for an illustration; Appendix A for the full list). For the study phase, the eight triplets were randomized to create a familiarization stream that contained 208 triplets (i.e., 26 repetitions of each triplet). There were no breaks between triplets during the stream. The only constraint in the

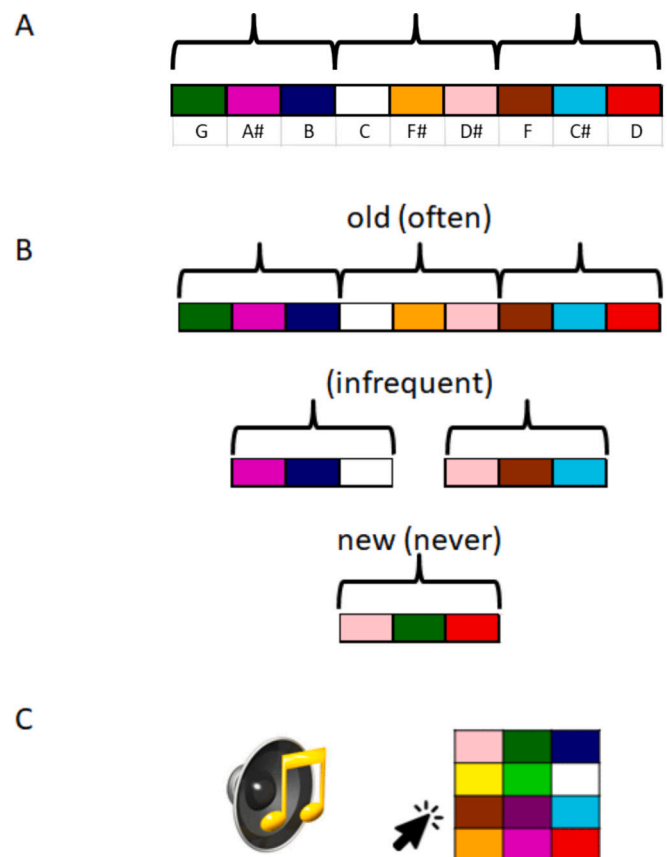


Fig. 1. Experimental procedure. A) Exemplary extract of the statistical learning familiarization phase. B) Examples of the three categories of test triplets that were presented for frequency judgements: “Old” triplets were presented repeatedly in the familiarization phase. “Infrequent” triplets emerged infrequently in the familiarization phase by the random combination of triplets. “New” triplets were never presented during the familiarization phase. C) Depiction of the tone-color association test in which participants had to select the color that was paired with a particular tone in the statistical learning task.

Table 1
Ordering of the experimental procedure.

Type of activity	Kind of task/test	# of Trials
Practice Phase		
(1) Familiarization 1	Statistical Learning and Exposure to Color-Tone Associations	208 Triplets
(2) Practice Test	Frequency judgements of Color Triplets	24 Triplets
(3) Familiarization 2	Statistical Learning and Exposure to Color-Tone Associations	208 Triplets
Test Phase		
(4) Test (Colors)	Frequency judgements of Color Triplets	24 Triplets
(5) Test (Tones)	Frequency judgements of Tone Triplets	24 Triplets
(6) Test (Color-Tones)	Frequency judgements of Color-Tone Triplets	24 Triplets
(7) Color-Tone Association Test	Test of Color-Tone Associations	2 × 12 Trials

randomization order of the stream was that the same triplet could not be repeated twice in a row.

For the test phase, the same color-tone combinations were used to form three kinds of triplets (see Fig. 1B). “Old” triplets, that is, those which were used to create the familiarization stream of the study phase. “Infrequent” triplets, which consisted of the second and third color-tone combination of one of the familiarization triplets and the first element of another one of these triplets. Thus, these latter color-tone combinations occurred during familiarization but only occasionally. They were included to provide some variation in the frequency of occurrence among the test items but were not used for analysis. “New” triplets were created in such a way that the first two elements were the same as the “old” triplets, but the third element of the triplet was different and never occurred in a triplet sequence during familiarization. A statistical learning score was calculated as difference between the frequency judgements for old and new triplets. Separate tests were composed such that either colors, tones, or both tones and colors were presented, and accordingly, separate learning scores were calculated for the statistical learning of color-, tone-, and tone-color triplets.

2.2.3. Color-tone test

For the color-tone test, a 3 × 4 grid of the twelve colors was composed such that the color patches were randomly positioned within

the grid for each trial (i.e., twelve trials in total). On each trial, a different tone was presented, and the corresponding color had to be selected by mouse-click (see Fig. 1C).

2.3. Procedure

2.3.1. Main experimental procedure

Participants were tested individually. After arrival in the laboratory, they were seated in front of a computer and gave informed consent. Then the experimental procedure began. The ordering of the activities for the statistical learning task and for the color-tone test is presented in Table 1.

For the study phase, participants were told that they would see a series of colors on the screen and that some successions would be more frequent than others. They were told that afterwards, they would be tested on their ability to discriminate between successions that have been presented more or less frequently. They were instructed to pay attention to the colors even if by and by the task may become a bit monotonous.

For the subsequent practice test, participants were informed that they would see a series of colors as before, but that they had to judge after each triplet how often they thought that this triplet had occurred in the study phase on a 5-point rating scale ranging from 1 (= never) to 5 (= often). They were instructed to enter their judgements using the number keys of the keyboard. They had the opportunity to repeat the test triplet if they wanted to see it again by pressing the “enter” key. Three kinds of color triplets (old, new, infrequent) were presented in random order for a total of 24 trials (8 old, 8 infrequent, 8 new). The purpose of the practice test was to make sure that participants focused on the sequence of the colors such that the sequence of tones would be learned incidentally. Next, the familiarization task was repeated (see Table 1).

The critical test phase was similar to the practice test. First, only triplets of colors were presented. Second, only triplets of tones were presented. Third, triplets consisting of both colors and tones were presented. Each test consisted of 24 trials (i.e., 8 old, 8 infrequent, 8 new). As in the practice test, participants were instructed to judge after each triplet how often they thought that it had occurred on a 5-point rating scale ranging from 1 (= never) to 5 (= often) by using the number keys of the keyboard. Again, participants had the opportunity to repeat a test

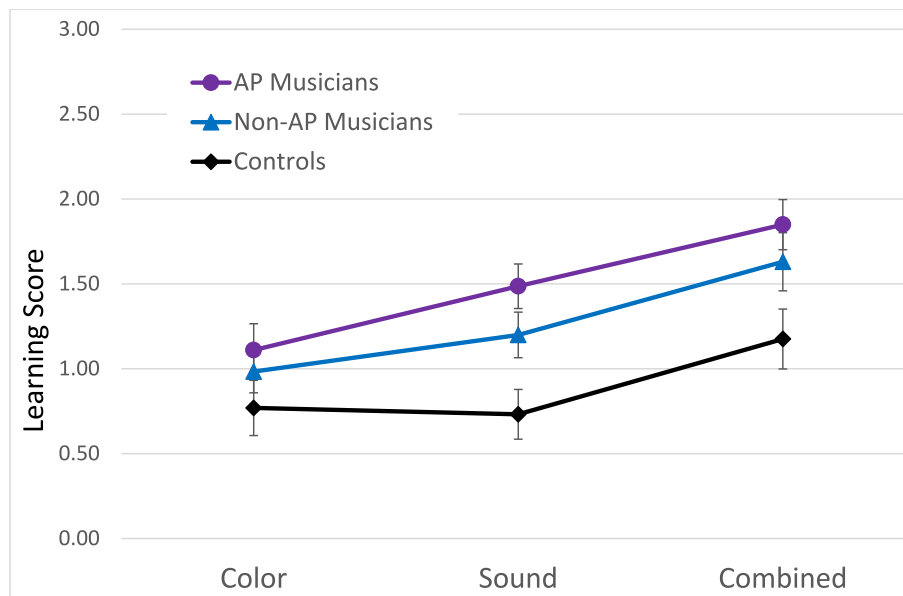


Fig. 2. Statistical learning scores for color triplets, tone triplets and triplets consisting of both colors and tones, separately for AP Musicians, Non-AP Musicians, and Controls. Learning scores represent the difference between frequency judgements for old and new triplets. Error bars represent standard errors.

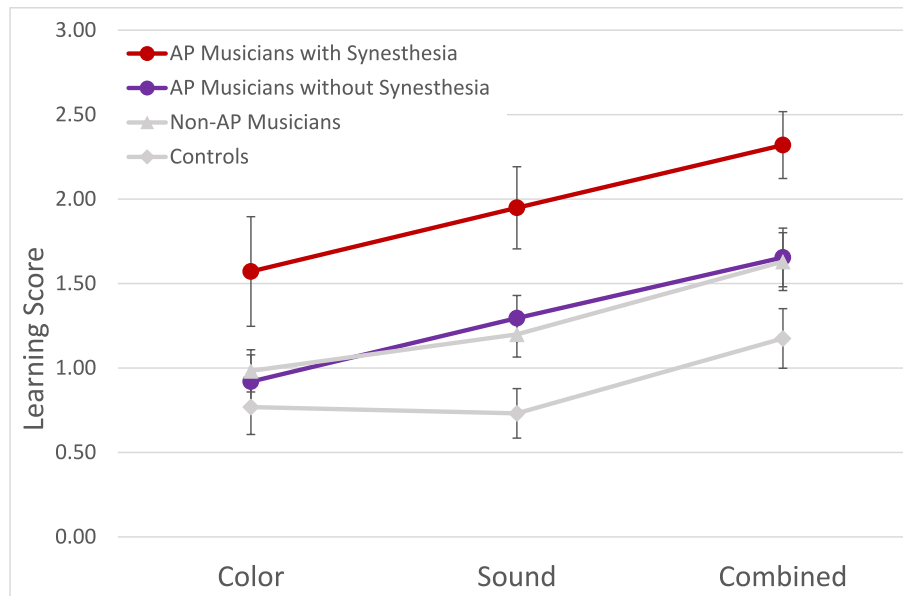


Fig. 3. Statistical learning scores for color triplets, tone triplets and triplets consisting of both colors and tones, separately for AP Musicians with and without synesthesia (Non-AP Musicians, and Controls are included in grey for illustration). Learning scores represent the difference between frequency judgements for old and new triplets. Error bars indicate standard errors.

triplet if they wanted to see/hear it again by pressing the “enter” key on the keyboard. It is noteworthy that our measure of statistical learning slightly differs from previous studies which typically used a two alternative forced choice (2AFC) decision task, during which participants had to decide which one of two elements was presented or which was presented more often during the initial exposure of the stimulus stream. To increase the sensitivity of the measure, we asked participants to rate the frequency with which they thought a particular element occurred.

Finally, we tested whether participants were able to learn the tone-color associations. They were instructed that they would hear a tone and see a palette of colors on the screen and that the task was to use the mouse and to click on the color that has been presented with that tone during the experiment. They were encouraged to make their best guess if they were not sure. For each trial, a 3×4 grid of the twelve colors from tone-color combinations was composed such that the color patches were randomly positioned within the grid. There were two blocks, each consisting of twelve trials (i.e., all the 12 tones used in the experiment).

After the experiment, the participants were screened for the presence of synesthesia. It turned out that seven out of the 24 musicians with absolute pitch (i.e., about 30%) also reported to have sound color-

synesthesia, which was further confirmed with the corresponding consistency test of the Eagleman-Battery. They were then further questioned about their experiences during the exposure phase, in particular, when their synesthetic experience and the experimental sound-color associations were incongruent. The responses are included in the *Supplementary Materials*. Participants in the control group filled out the German version of the Goldsmith Musical Sophistication Scale (Mullensiefen et al., 2014) in order to control for their musical experience. Moreover, they filled out the Synesthesia-Check in order to identify potential synesthetes (Meier et al., 2014). To summarize these results, no participant of the control group qualified as a musician or as a sound-color synesthete.

2.3.2. Follow-up assessment

After one week and after one month, participants with AP were contacted again by email to assess their memory for tone-color combinations. Participants were specifically asked to recall the colors that were presented with the twelve notes during the statistical learning procedure (Glasser, 2018). The responses are also included in the *Supplementary Materials*. After one-month, those participants who recalled at least eight of the twelve colors in the one week test were further

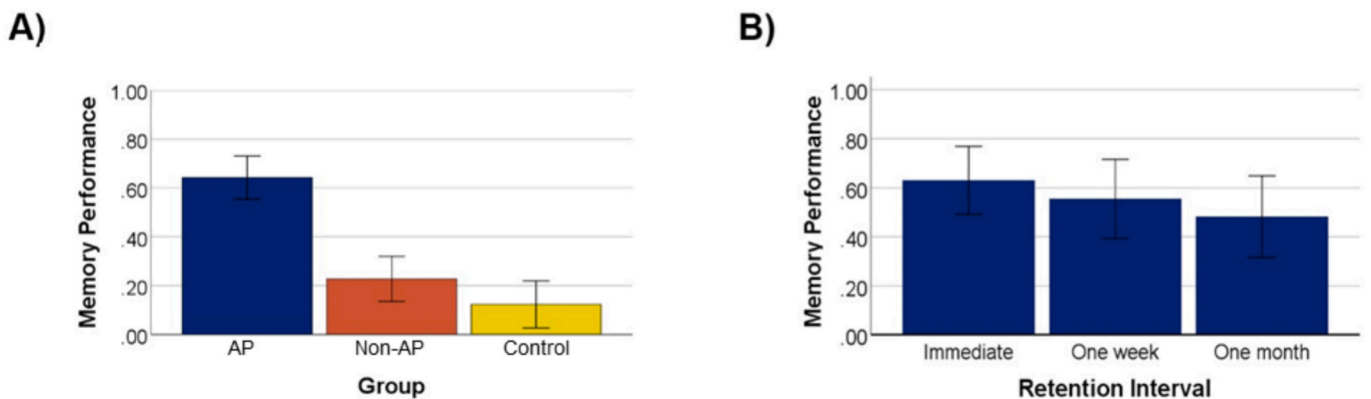


Fig. 4. Memory for tone-color associations (proportion remembered colors when a particular tone was given as a retrieval cue). A) Immediate Memory for AP musicians, Non-AP musicians, and controls. B) Immediate memory, after one week, after one month (AP musicians only). Error bars indicate 95% confidence intervals.

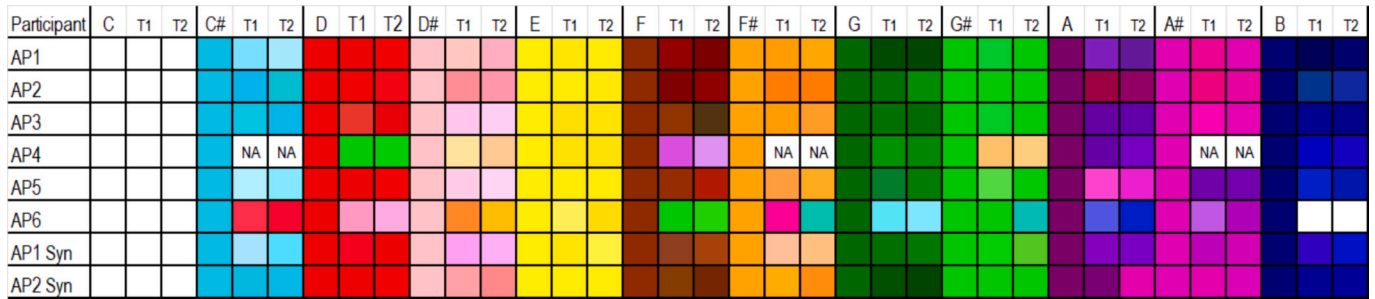


Fig. 5. Color Memory after one month for the eight AP musicians who had ceiling memory performance after one week. Colors were adjusted by the participants with a color wheel similar to what is typically used in a synesthesia consistency test. For each tone, the three colors represent the presented color and the colors selected by the participant in each of the two trials (T1 and T2). NA indicates that no color was selected.

invited to complete a more fine-grained color memory test by using a color wheel similar to the color picker tests that are used to assess consistency in synesthesia (Eagleman et al., 2007; Meier, 2021). Specifically, they were asked to indicate as precisely as possible which color was presented with a particular tone. The task consisted of two blocks with twelve trials each, that is, the twelve original tones were presented once in each block.

2.4. Analysis

Statistical learning was measured by calculating the difference between frequency judgements for old and new triplets. Higher positive values reflect better discrimination because of statistical learning. To analyze performance in incidental associative learning of color-tone associations, we counted the number of correct responses on the tone-color association test and compared memory performance across groups. For those participants who scored high in the initial test, we explored the trajectory of color memory after one week and one month. Alpha level was set to 0.05. All *t*-tests are two-sided.

3. Results

3.1. Statistical learning

The results of the statistical learning score (i.e., the difference between frequency judgements for old and new triplets) are presented in Fig. 2. We conducted an analysis of variance (ANOVA) with the between-subjects factor group (AP musicians, Non-AP musicians, Controls) and the within-subjects factor test type (colors, tones, combined). The results revealed a main effect of group, $F(2, 63) = 5.465, p = .006, \eta_p^2 = 0.148$, and of test type, $F(2, 126) = 27.993, p < .001, \eta_p^2 = 0.308$. The group $\times$ test type interaction failed to reach significance, $F(4, 126) = 1.226, p = .303, \eta_p^2 = 0.037$. Post-hoc tests indicated that both AP musicians and Non-AP musicians had superior statistical learning compared to controls ($p < .002$, and $p < .043$, respectively), while AP-musicians and Non-AP musicians did not differ ($p = .233$). Moreover, pairwise comparisons indicated that multimodal statistical learning was superior to both visual and auditory statistical learning ($ps < 0.001$), and auditory was superior to visual statistical learning ($p < .036$).

3.1.1. Exploratory analysis on the impact of synesthesia

As noted above, in the sample of AP musicians, seven participants also had synesthesia. To test whether this condition affected statistical learning, we compared AP musicians with and without synesthesia. The descriptive results are depicted in Fig. 3. An ANOVA with the between-subjects factor group and the within-subjects factor test type (colors, tones, combined) revealed a main effect of group, $F(1,22) = 7.289, p = .013, \eta_p^2 = 0.249$, indicating that the presence of synesthesia boosted statistical learning. The main effect of test type was also significant, $F(2, 44) = 13.195, p < .001, \eta_p^2 = 0.375$. The group $\times$ test type interaction was

not significant, $F(1, 44) = 0.001, p = .999, \eta_p^2 < 0.001$. The results indicate that the numerical advantage of AP musicians compared to Non-AP musicians (as depicted in Fig. 2) has been caused entirely by the sub-sample of synesthetes in the AP musician group. This analysis corroborates the conclusion that AP per se does not provide an additional advantage in statistical learning. However, it indicates that the combination of absolute pitch and synesthesia in musicians provides a unique advantage in statistical learning over and above the general advantage of musicians.

3.2. Memory for tone-color associations

To test the incidental learning of tone color-associations, we conducted an ANOVA with the between-subjects factor group (AP musicians, Non-AP musicians, Controls) and the within-subjects factor block (block 1, block 2). The results revealed a main effect of group, $F(2, 63) = 36.509, p < .001, \eta_p^2 = 0.537$. No other effect was significant, with $F(1, 63) = 0.235, p = .629, \eta_p^2 = 0.004$, for the main effect of block and $F(2, 63) = 0.002, p = .998, \eta_p^2 < 0.001$, for the group $\times$ block interaction, respectively. In Fig. 4A, the results are presented summarized across blocks. Post-hoc *t*-tests revealed that AP musicians outperformed the other two groups, $t(44) = 5.565, p < .001$ compared to Non-AP musicians, and $t(42) = 7.075, p < .001$ compared to controls, while memory performance for Non-AP musicians was not significantly different from controls, $t(41) = 2.741, p = .122$.

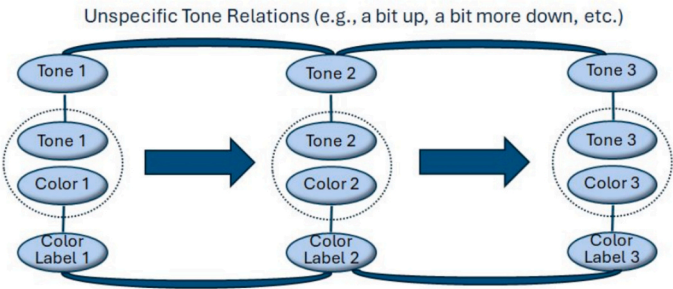
To ascertain that the advantage of the musicians with absolute pitch was not solely caused by the seven participants with synesthesia, we compared AP musicians with and without synesthesia. Both groups had a memory score of 0.642 ($SE = 0.317$ for AP with synesthesia, $SE = 0.329$ for AP without), and accordingly a *t*-test gave no significant result, $t(22) < 0.001, p = .999$, thus ruling out the possibility that the advantage of AP musicians was caused by synesthesia.

3.2.1. Follow-up assessment

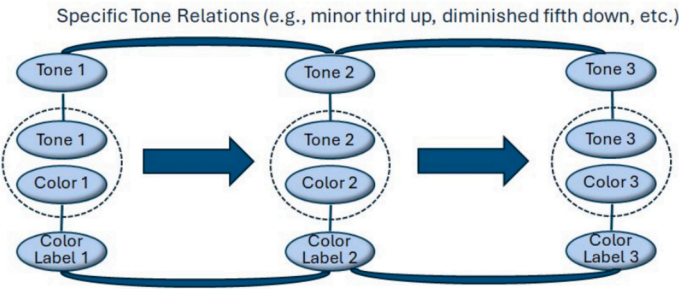
After one week and after one month, musicians with absolute pitch were contacted again by email to assess their long-term memory for tone-color associations. Participants were specifically asked to recall the colors presented with the twelve notes during the statistical learning procedure. The proportion of recalled colors together with immediate test performance are depicted in Fig. 4B. A repeated measures ANOVA revealed a decline across intervals $F(2, 44) = 6.554, p = .003, \eta_p^2 = 0.230$. However, on average AP musicians still remembered about half of the original tone-color pairings after one month.

Moreover, eight participants (two of them with synesthesia) still remembered ten or more of the twelve color-tone associations after one month. These participants had scored at ceiling after one week. To further probe the fidelity of their color memory representations, these participants were invited to indicate as precisely as possible which color was presented with a particular tone by using a color wheel, as is typically used in synesthesia color consistency tests. In Fig. 5, the results are

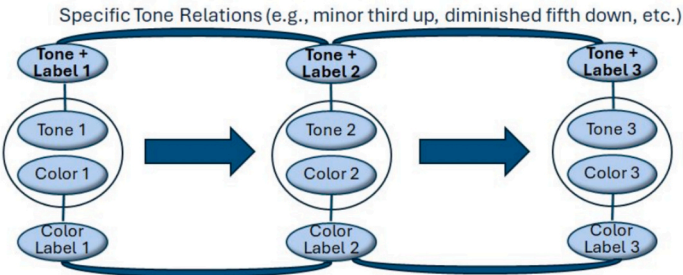
Non-Musicians



Musicians



AP Musicians



AP Musicians with Synesthesia

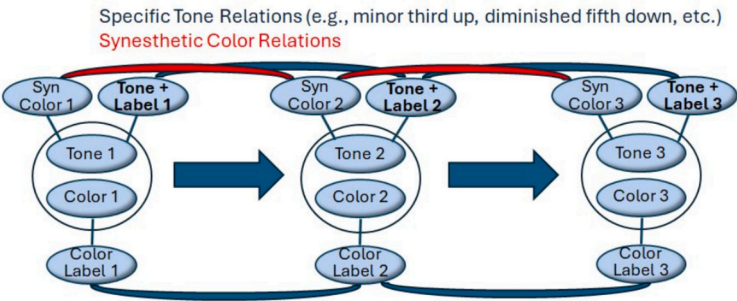


Fig. 6. A schematic depiction of the different opportunities for creating associations for the different groups of participants. A) Controls, B) Non-AP musicians, C) AP musicians, D) AP musicians with synesthesia.

presented for each participant together with the original color. They indicate an impressive precision of color representation. For the sake of completeness, we would like to add that among these participants, two also had synesthesia, however, a visual inspection of the results does not suggest that the fidelity of their color representation was different from the other participants. To quantify the fidelity of the representation, the colors were coded in LUV space and Euclidian distances were calculated between the remembered and the original colors. The mean distance scores were between 16 and 98 ($M = 39$, $SD = 33$), indicating a very accurate color representation after a one-month retention interval.

4. Discussion

The first goal of this study was to investigate whether AP would facilitate statistical learning of sequences of tones and sequences of colors, and the second goal was to investigate whether AP would facilitate incidental learning of tone-color associations. The results showed that musical expertise improved statistical learning. Musicians with and without AP outperformed non-musician controls, however, there was no additional advantage for AP musicians. In contrast, the results showed a unique memory advantage for musicians with AP for incidental learning of tone-color associations.

It turned out that seven out of the twenty-four musicians with AP also had sound-color synesthesia. Exploratory analyses revealed that for statistical learning, this subgroup outperformed the AP musicians without synesthesia, indicating that AP together with sound-color synesthesia, but not AP alone, provides for a unique learning advantage. In contrast, for incidental learning of tone-color associations, sound-color synesthesia did not further boost the memory benefit of the AP musicians. Notably, musicians with AP initially remembered on average nearly two thirds of the tone-color associations and despite a decline across time after one month, they still remembered more than half of the colors that were associated with the tones. Interestingly, one third of the AP musicians still performed at ceiling after one week and one month. A follow-up assessment with a color picker task, as typically used in synesthesia consistency tests, revealed an astonishing precision of their color representation. On the other hand, memory performance of musicians with relative pitch and the control group was low from the beginning and probably reflected mainly memory of the color of the highest and lowest tones of the statistical learning task.

The statistical learning results replicate previous studies that have shown an advantage for musicians. Moreover, our results indicate stronger learning effects when both colors and tones were present at test compared to when only a single modality stream was present. In addition, statistical learning was higher for auditory stimuli than visual stimuli and this effect was consistent across groups. Thus, musical training and the resulting neuro-plastic brain changes in the network supporting statistical learning seemed to lead to a more general improvement, in line with the study of [Paraskevopoulos et al. \(2018\)](#). However, we would like to note that in the present study the difference between musicians and non-musicians was numerically larger for auditory (and cross-modal) statistical learning. As [Mandikal Vasuki et al. \(2016\)](#); [Mandikal Vasuki et al. \(2017\)](#) also found better auditory, but not visual, statistical learning for musicians compared to non-musicians, this latter finding would be consistent with their interpretation that musical expertise is associated with an enhanced ability to detect statistical regularities specifically in the auditory domain. It must be noted, however, that the present study examines cross-modal associative learning rather than purely auditory statistical learning. Therefore, further studies with larger samples are necessary to non-equivocally resolve this question.

Importantly, we had expected that due to the hyperconnectivity of the brains of AP musicians, particularly, brain areas involved in statistical learning, AP musicians would show an additional statistical learning benefit compared to Non-AP musicians. There are different possibilities, why this was not the case. First, it might be that previous

studies of the effects of musicianship and absolute pitch on brain connectivity are not as reliable as suggested. In fact, [Leipold et al. \(2021\)](#) argued that the studies on large-scale brain networks are heterogeneous regarding the methods, the localization and direction of the effects and based on small samples. In their own study, in which they included samples of more than fifty Non-AP and AP musicians, they found robust effects of musicianship in inter-hemispheric and intra-hemispheric connectivity in both structural and functional networks, but they did not find evidence for an AP effect on functional or structural connectivity. They concluded that the effects of AP on neural networks might be more subtle to be detected. Another possibility is that connectivity differences in the brains of AP musicians are not functional for statistical learning in general, the statistical learning paradigm that we used in the present study, or that musical expertise per se may have already boosted statistical learning towards ceiling. At least the latter explanation can be rejected as the AP musicians with synesthesia showed a significant advantage in our study.

How then can the pattern of our results be explained? Rather than focusing on supposed differences in brain connectivity and their behavioral consequences, we considered the experiential consequences of the task requirements. We analyzed how participants may have experienced the stream of information in the familiarization phase of the statistical learning task. For illustration, in [Fig. 6](#) a triplet of this stream and the supposed experiences are presented separately for each group of participants.

For non-musicians, such a triplet may be experienced as a series of higher/lower tones, each tone accompanied by a certain color ([Fig. 6A](#)). As they lack expertise in dealing with musical stimuli and accordingly pitch information, their tone representations are unspecific. However, the structure of repeated up-down patterns as well as the accompanying specific color sequences enable them to acquire some frequency knowledge about the statistical properties of the stream of tones and colors. Therefore, statistical learning is possible and subsequent test performance beyond chance. However, as they cannot form tone-color associations in a consistent way, incidental learning of tone-color associations is minimal and subsequent associative memory performance is low.

For Non-AP musicians, such a triplet may be experienced as a more sophisticated sequence of higher – lower tone compositions in the sense of, for example, “a minor third up, a diminished fifth down, etc.”, accompanied by a series of certain colors ([Fig. 6B](#)). Given the specific relation of tone intervals, they have an advantage in extracting frequency information compared to non-musicians, and they outperform non-musicians in statistical learning. However, like non-musicians, they cannot form consistent tone-color associations and accordingly, incidental learning of tone-color associations is minimal and subsequent associative memory performance is low.

For AP musicians, the series of tones is as sophisticated as for musicians, but in addition, they have labels for each tone, which enables them to create specific tone-name-color associations ([Fig. 6C](#)). The latter is expressed in the successful creation of associative memory for tone-color pairs. As for statistical learning the frequency of specific tone relations is sufficient, an ability that is present in Non-AP musicians as well, so there is no additional boost in statistical learning despite potential brain connectivity differences. In contrast, as AP musicians can build specific tone-name-color associations, they outperform Non-AP musicians in the incidental learning task.

For AP-musicians with synesthesia, the additional synesthetic experience contributes to the sequence of tones and colors and creates an additional stream of information (i.e., the synesthetic color triggered by the tones; [Fig. 6D](#)). As this stream is correlated with the series of tones and physical colors, AP-musicians with synesthesia can profit from this additional stream in the statistical learning task compared to AP musicians and Non-AP musicians without synesthesia. However, this information is redundant to the tone-name-color associations, and thus there is no additional boost in incidental learning the associations between

tones and physical colors. In fact, in the case of a mismatch between the physical tone-color pairing and the idiosyncratic synesthetic tone-color association perceived by synesthetes, incidental learning of tone-color may even suffer. However, informal reports indicated that this was not the case.

Although some participants reported that they initially struggled when the test colors did not match their synesthetic colors for the presented tones, they could easily distinguish their synesthetic experiences from the presented colors and ultimately, the test-colors did not interfere with their synesthetic colors (see *Supplementary Materials*). This was primarily because their synesthetic colors were “weak” in comparison to the highly vivid colors they were seeing on the screen, which “drowned out” their synesthetic colors.

Together, this experiential analysis of task requirements can provide a comprehensive explanation of the results of the present study without direct reference to supposed differences in brain connectivity. However, we acknowledge that this explanation was conducted post-hoc and requires further empirical verification.

Beyond the results of the cognitive tasks, our study is informative regarding the link between synesthesia and AP. First, it provides further evidence that the prevalence of synesthesia is higher among AP possessors with a probability of about 30% in the present study in comparison to a probability in the normal population of about 4% (Carmichael et al., 2019; Gregersen et al., 2013; Rothen & Meier, 2010; Simmer et al., 2006). This is consistent with previous research that reported a comparable prevalence rate of about 30% with a similar sample size and demographic (Glasser, 2018). Second, our results indicate that the combination of sound-color synesthesia and AP provide for a unique learning opportunity for the extraction of statistical information. Interestingly, the group of participants with both conditions showed a consistent and comparable advantage in each of the three different tests. Notably, this finding aligns with a domain-general account of statistical learning as proposed by Paraskevopoulos et al. (2018). It seems that the presence of sound-color synesthesia in musicians with AP provides for a comprehensive mechanism to extract regularities from sequences of both tones and colors. Finally, our results indicate that when investigating the impact of AP on cognitive performance, it is important to include an assessment of sound-color synesthesia to consider its potential influence.

Appendix A

Table A1
Full list of color triplets and the corresponding tone triplets used for the familiarization phase.

Color triplets			Tone triplets		
White	Magenta	Purple	c3	a#3	a3
White	Orange	Pink	c3	f#3	d#3
Brown	Cyan	Red	f3	c#3	d3
Brown	Yellow	Navy	f3	e3	b3
Green	Magenta	Navy	g3	a#3	b3
Green	Yellow	Purple	g3	e3	a3
Lime	Orange	Red	g#3	c#3	d#3
Lime	Cyan	Pink	g#3	f#3	d3

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.concog.2026.104086>.

Overall, the results of this study suggest that musicianship, AP and sound-color synesthesia create unique learning opportunities. Musical expertise provides an advantage in statistical learning, and this advantage is further boosted by the presence of both AP and synesthesia. On the other hand, AP provides for a unique memory advantage for incidental learning of tone-color associations.

As an avenue for future research, it might be interesting to use our tone-color statistical learning paradigm to increase the likelihood of developing AP during this sensitive period of development. As AP typically appears in early childhood, longitudinal training with this method would be feasible. Furthermore, both synesthetes and AP musicians have described a degradation of their condition in older age (Athos et al., 2007; Glasser, 2018; Glasser, 2021; Meier et al., 2014).

In consequence, employing the kind of statistical learning paradigm used in the present study may help to train and maintain tone-color associations in musicians that report a waning of their AP ability. The potential application of this research in this population is therefore an exciting avenue to explore. An interesting avenue for future research may be an intergenerational research project that addresses both the impact of incidental tone-color association training on the development of AP during childhood, and the impact on the age-related loss or deterioration of these conditions.

CRediT authorship contribution statement

Beat Meier: Writing – original draft, Visualization, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Solange Glasser:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

References

- Athos, E. A., Levinson, B., Kistler, A., Zemansky, J., Bostrom, A., Freimer, N., & Gitschier, J. (2007). Dichotomy and perceptual distortions in absolute pitch ability. *Proceedings of the National Academy of Sciences of the United States of America*, 104 (37), 14795–14800. <https://doi.org/10.1073/pnas.0703868104>
- Bachem, A. (1954). Time factors in relative and absolute pitch determination. *The Journal of the Acoustical Society of America*, 26, 751–753.
- Baharloo, S., Johnston, P. A., Service, S. K., Gitschier, J., & Freimer, N. B. (1998). Absolute pitch: An approach for identification of genetic and nongenetic components. *American Journal of Human Genetics*, 62(2), 224–231. <https://doi.org/10.1086/301704>
- Baharloo, S., Service, S. K., Risch, N., Gitschier, J., & Freimer, N. B. (2000). Familial aggregation of absolute pitch. *American Journal of Human Genetics*, 67, 755–758.
- Bairnsfather, J. E., Mosing, M. A., Osborne, M. S., & Wilson, S. J. (2025). Conceptual coherence but methodological mayhem: A systematic review of absolute pitch phenotyping. *Behavior Research Methods*, 57(2), 61. <https://doi.org/10.3758/s13428-024-02577-z>
- Brauchli, C., Leipold, S., & Jancke, L. (2019). Univariate and multivariate analyses of functional networks in absolute pitch. *Neuroimage*, 189, 241–247.
- Burkhard, A., Hanggi, J., Elmer, S., & Jancke, L. (2020). The importance of the fibre tracts connecting the planum temporale in absolute pitch possessors. *Neuroimage*, 211, Article 116590. <https://doi.org/10.1016/j.neuroimage.2020.116590>
- Carmichael, D. A., Smees, R., Shillcock, R. C., & Simner, J. (2019). Is there a burden attached to synaesthesia? Health screening of synaesthetes in the general population. *British Journal of Psychology*, 110(3), 530–548. <https://doi.org/10.1111/bjop.12354>
- Chiou, R., & Rich, A. N. (2014). The role of conceptual knowledge in understanding synaesthesia: Evaluating contemporary findings from a “hub-and-spokes” perspective. *Frontiers in Psychology*, 5, 105. <https://doi.org/10.3389/fpsyg.2014.00105>
- Deutsch, D., & Dooley, K. (2013). Absolute pitch is associated with a large auditory digit span: A clue to its genesis. *The Journal of the Acoustical Society of America*, 133, 1859–1861.
- Deutsch, D., Dooley, K., Henthorn, T., & Head, B. (2009). Absolute pitch among students in an American music conservatory: Association with tone language fluency. *Journal of the Acoustical Society of America*, 125(4), 2398–2403. <https://doi.org/10.1121/1.3081389>
- Di Stefano, N., & Spence, C. (2024). Should absolute pitch be considered as a unique kind of absolute sensory judgment in humans? A systematic and theoretical review of the literature. *Cognition*, 249, Article 105805. <https://doi.org/10.1016/j.cognition.2024.105805>
- Dohn, A., Garza-Villarreal, E. A., Chakravarty, M. M., Hansen, M., Lerch, J. P., & Vuust, P. (2015). Gray- and white-matter anatomy of absolute pitch possessors. *Cerebral Cortex*, 25(5), 1379–1388. <https://doi.org/10.1093/cercor/bht334>
- Dooley, K., & Deutsch, D. (2010). Absolute pitch correlates with high performance on musical dictation. *The Journal of the Acoustical Society of America*, 128(2), 890–893. <https://doi.org/10.1121/1.3458848>
- Dooley, K., & Deutsch, D. (2011). Absolute pitch correlates with high performance on interval naming tasks. *The Journal of the Acoustical Society of America*, 130(6), 4097–4104. <https://doi.org/10.1121/1.3652861>
- Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods*, 159(1), 139–145. <https://doi.org/10.1016/j.jneumeth.2006.07.012>
- Frost, R., Armstrong, B. C., & Christiansen, M. H. (2019). Statistical learning research: A critical review and possible new directions. *Psychological Bulletin*, 145(12), 1128–1153. <https://doi.org/10.1037/bul0000210>
- Gervain, J., Vines, B. W., Chen, L. M., Seo, R. J., Hensch, T. K., Werker, J. F., & Young, A. H. (2013). Valproate reopens critical-period learning of absolute pitch. *Frontiers in Systems Neuroscience*, 7, 102. <https://doi.org/10.3389/fnsys.2013.00102>
- Glasser, S. (2018). *The impact of synesthesia and absolute pitch on musical development*. Melbourne: Melbourne University. <https://hdl.handle.net/11343/214580>
- Glasser, S. (2021). Perceiving music through the lens of synaesthesia and absolute pitch [Peer Reviewed]. *Perception*, 50(8). <https://doi.org/10.1177/03010066211034439>
- Gregersen, P. K. (1998). Instant recognition: The genetics of pitch perception. *American Journal of Human Genetics*, 62, 221–223.
- Gregersen, P. K., Kowalsky, E., Lee, A., Baron-Cohen, S., Fisher, S. E., Asher, J. E., ... Li, W. (2013). Absolute pitch exhibits phenotypic and genetic overlap with synesthesia. *Human Molecular Genetics*, 22(10), 2097–2104. <https://doi.org/10.1093/hmg/ddt059>
- Kim, S. G., & Knosche, T. R. (2017). Resting state functional connectivity of the ventral auditory pathway in musicians with absolute pitch. *Human Brain Mapping*, 38(8), 3899–3916. <https://doi.org/10.1002/hbm.23637>
- Leipold, S., Klein, C., & Jancke, L. (2021). Musical expertise shapes functional and structural brain networks independent of absolute pitch ability. *The Journal of Neuroscience*, 41(11), 2496–2511. <https://doi.org/10.1523/JNEUROSCI.1985-20.2020>
- Levitin, D. J., & Rogers, S. E. (2005). Absolute pitch: Perception, coding, and controversies. *Trends in Cognitive Sciences*, 9(1), 26–33. <https://doi.org/10.1016/j.tics.2004.11.007>
- Loui, P., Li, H. C., Hohmann, A., & Schlaug, G. (2011). Enhanced cortical connectivity in absolute pitch musicians: A model for local hyperconnectivity. *Journal of Cognitive Neuroscience*, 23, 1015–1026.
- Loui, P., Zamm, A., & Schlaug, G. (2012). Enhanced functional networks in absolute pitch. *Neuroimage*, 63, 632–640.
- Mandikal Vasuki, P. R., Sharma, M., Demuth, K., & Arciuli, J. (2016). Musicians’ edge: A comparison of auditory processing, cognitive abilities and statistical learning. *Hearing Research*, 342, 112–123.
- Mandikal Vasuki, P. R., Sharma, M., Ibrahim, R. K., & Arciuli, J. M. (2017). Online performance during auditory and visual statistical learning tasks. *Frontiers in Human Neuroscience*, 11, 114.
- Meier, B. (2013). Semantic representation of synaesthesia. *Theoria et Historia Scientiarum*, 10, 125–134.
- Meier, B. (2021). Synesthesia. In S. D. Sala (Ed.), *Encyclopedia of behavioral neuroscience* (pp. 561–569). Elsevier.
- Meier, B., Rothen, N., & Walter, S. (2014). Developmental aspects of synaesthesia across the adult lifespan. *Frontiers in Human Neuroscience*, 8, 129.
- Mullensiefen, D., Gingras, B., Musil, J., & Stewart, L. (2014). The musicality of non-musicians: An index for assessing musical sophistication in the general population. *PLoS One*, 9(2), Article e89642. <https://doi.org/10.1371/journal.pone.0089642>
- Paraskevopoulos, E., Chalas, N., & Bamidis, P. (2017). Functional connectivity of the cortical network supporting statistical learning in musicians and non-musicians: An MEG study. *Scientific Reports*, 7, 16268.
- Paraskevopoulos, E., Chalas, N., Kartsidis, P., Wollbrink, A., & Bamidis, P. (2018). Statistical learning of multisensory regularities is enhanced in musicians: An MEG study. *Neuroimage*, 175, 150–160.
- Pesnot Lerousseau, J., & Schon, D. (2021). Musical expertise is associated with improved neural statistical learning in the auditory domain. *Cerebral Cortex*, 31, 4877–4890.
- Profita, J., & Bidder, T. G. (1988). Perfect pitch. *American Journal of Medical Genetics*, 29, 763–771.
- Rothen, N., & Meier, B. (2010). Higher prevalence of synaesthesia in art students. *Perception*, 39(5), 718–720. <https://doi.org/10.1068/P6680>
- Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience*, 10, 792–797.
- Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). *Statistical learning by 8-month-old infants* (p. 274). Science.
- Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone sequences by human infants and adults. *Cognition*, 70, 27–52.
- Shook, A., Marian, V., Bartolotti, J., & Schroeder, S. R. (2013). Musical experience influences statistical learning of a novel language. *The American Journal of Psychology*, 126(1), 95–104. <https://doi.org/10.5406/amerjpsyc.126.1.0095>
- Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., ... Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception*, 35(8), 1024–1033. <https://doi.org/10.1068/p5469>
- Takeuchi, A. H., & Hulse, S. H. (1993). Absolute pitch. *Psychological Bulletin*, 113, 345–361.
- Theusch, E., Basu, A., & Gitschier, J. (2009). Genome-wide study of families with absolute pitch reveals linkage to 8q24.21 and locus heterogeneity. *American Journal of Human Genetics*, 85, 112–119.
- Theusch, E., & Gitschier, J. (2011). Absolute pitch twin study and segregation analysis. *Twin Research and Human Genetics*, 14, 173–178.
- Tillmann, B., Bharucha, J. J., & Bigand, E. (2000). Implicit learning of regularities in western tonal music by self-organization. In *Connectionist models of learning, development and evolution: Proceedings of the sixth neural computation and psychology workshop*, Liège, Belgium, 16–18 September 2000 (pp. 175–184).
- Tillmann, B., & McAdams, S. (2004). Implicit learning of musical timbre sequences: Statistical regularities confronted with acoustical (dis)similarities. *The Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30, 1131–1142.
- Van Hedger, S. C., Heald, S. L., & Nusbaum, H. C. (2013). Absolute pitch may not be so absolute. *Psychological Science*, 24, 1496–1502.
- Van Hedger, S. C., Heald, S. L. M., & Nusbaum, H. C. (2019). Absolute pitch can be learned by some adults. *PLoS One*, 14(9), Article e0223047. <https://doi.org/10.1371/journal.pone.0223047>
- Ward, J. (2013). Synesthesia. *Annual Review of Psychology*, 64, 49–75. <https://doi.org/10.1146/annurev-psych-113011-143840>
- Ward, J., Simner, J., Simpson, I., Rae, C., Del Rio, M., Eccles, J. A., & Racey, C. (2024). Synesthesia is linked to large and extensive differences in brain structure and function as determined by whole-brain biomarkers derived from the HCP (Human Connectome Project) cortical parcellation approach. *Cerebral Cortex*, 34(11). <https://doi.org/10.1093/cercor/bhae446>
- Wilson, S. J., Lusher, D., Martin, C. L., Rayner, G., & McLachlan, N. (2012). Intersecting factors lead to absolute pitch acquisition that is maintained in a “fixed do” environment. *Music Perception*, 29(3), 285–296. <https://doi.org/10.1525/MP.2012.29.3.285>
- Zatorre, R. J. (2003). Absolute pitch: A model for understanding the influence of genes and development on neural and cognitive function. *Nature Neuroscience*, 6, 692–695.
- Zatorre, R. J., & Beckett, C. (1989). Multiple coding strategies in the retention of musical tones by possessors of absolute pitch. *Memory & Cognition*, 17(5), 582–589. <https://doi.org/10.3758/bf03197081>