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Review Article

Auditory Pitch Perception in Autism Spectrum Disorder: A Systematic Review and Meta-Analysis

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ABSTRACT

Purpose: Pitch plays an important role in auditory perception of music and language. This study provides a systematic review with meta-analysis to investigate whether individuals with autism spectrum disorder (ASD) have enhanced pitch processing ability and to identify the potential factors associated with processing differences between ASD and neurotypicals.
Method: We conducted a systematic search through six major electronic databases focusing on the studies that used nonspeech stimuli to provide a qualitative and quantitative assessment across existing studies on pitch perception in autism. We identified potential participant- and methodology-related moderators and conducted metaregression analyses using mixed-effects models.
Results: On the basis of 22 studies with a total of 464 participants with ASD, we obtained a small-to-medium positive effect size (g = 0.26) in support of enhanced pitch perception in ASD. Moreover, the mean age and nonverbal IQ of participants were found to significantly moderate the between-studies heterogeneity.
Conclusions: Our study provides the first meta-analysis on auditory pitch perception in ASD and demonstrates the existence of different developmental trajectories between autistic individuals and neurotypicals. In addition to age, nonverbal ability is found to be a significant contributor to the lower level/local processing bias in ASD. We highlight the need for further investigation of pitch perception in ASD under challenging listening conditions. Future neurophysiological and brain imaging studies with a longitudinal design are also needed to better understand the underlying neural mechanisms of atypical pitch processing in ASD and to help guide auditory-based interventions for improving language and social functioning.
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Atypical sensory perception is a remarkable feature in individuals with autism spectrum disorder (ASD; Leekam et al., 2007). As a result, sensory symptoms have been added among the core defining features of ASD in the *Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition* (*DSM-5*; American Psychiatric Association, 2013), including hyper- and hyposensitivity to visual (e.g., bright lights) and auditory (e.g., crowd noises) stimuli (Tomchek & Dunn, 2007). In the auditory domain, autistic individuals may demonstrate impaired, intact, or enhanced processing skills (Kellerman et al., 2005; O'Connor, 2012; Ouimet et al., 2012). To be specific, previous work characterized the heterogeneous profiles of language abilities that involve higher level information processing in ASD (Kjelgaard & Tager-Flusberg, 2001; Paul et al., 2008; Song et al., 2022). At one end on the spectrum, there are autistic individuals whose vocabulary, grammatical knowledge, and articulation skills are within the normal range of functioning, whereas at the other end, a significant proportion of the population remains

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minimally verbal (Lord & Paul, 1997). However, when discriminating simpler auditory stimuli without contextual information, autistic people are more likely to show intact or enhanced processing ability regardless of their significant phenotypical heterogeneity (Bonnel et al., 2003, 2010; Heaton, 2003; Jones et al., 2009).

Both the weak central coherence (WCC) theory and the enhanced perceptual functioning (EPF) model have been invoked to explain the atypical auditory performance in ASD. The WCC theory proposes that autism can be characterized by a cognitive style that biases processing toward local features at the expense of global, context-dependent meaning or gestalt. Frith's WCC interpretation of autism was first derived from the results of visuospatial tasks, which required segmenting a whole "gestalt" into its constituents. The central coherence refers to the tendency that typically developing (TD) people perceive and process input information under its general context, understand the information with a top-down approach in relation to the higher level structure and contextual knowledge, and even sacrifice the memory of some small details and parts (Frith, 1989; Frith & Happé, 1994; Happé, 1997, 1999; Happé & Frith, 2006). By contrast, autistic individuals are more likely to be absorbed in details and fractions and are unable to extract the whole ideas and information structures from segmental information. Happé (1997) demonstrated that this WCC might be a universal characteristic of all autistic individuals, regardless of the theory of mind status. Apart from the WCC theory, the EPF model (Mottron & Burack, 2001; Mottron et al., 2006) was proposed as an alternative account that emphasizes the role of enhanced feed-forward low-level perception in cognitive processing (Mottron et al., 2013). For instance, the enhanced pitch perception in autism is one of the manifestations of the overdevelopment of low-level perceptual operations (Mottron & Burack, 2001). Unlike WCC that highlights holistic processing deficits, EPF attributes the local bias to superiority in low-level perceptual operations without necessarily involving a global perception weakness (Mottron et al., 2006, 2013).

As a fundamental perceptual attribute of sound and an information carrier in both music and language, pitch plays a vital role in encoding musical melody and linguistic prosody (Jiang et al., 2015). Pitch height, range, and contour shapes are among the most salient and effective acoustic cues for emotional prosody identification, reflecting different levels of physiological arousal (Laukka et al., 2005; Levin & Lord, 1975). An extensive body of literature has established that pitch processing at the auditory brainstem and at the cortical level is experience dependent and malleable (Russo et al., 2008; Zatorre & Gandour, 2008), which provides the impetus for developing speech and language therapy based on pitch-related training. For instance, speakers with a tonal language background and musicians have been shown to demonstrate enhanced pitch processing skills (Bent et al., 2006; Bidelman et al., 2013; Giuliano et al., 2011). By contrast, altered speech prosody is considered a hallmark of pragmatic language impairment in autism, and pitch, being one crucial prosodic element of spoken language, has been extensively reported to be aberrant in ASD in both perception and production (Hubbard & Trauner, 2007; Russo et al., 2008).

Understanding the characteristics of atypical pitch processing in ASD is of great theoretical and practical significance. Unlike the reported pitch processing alteration associated with ASD concerning high-order linguistic functions and socio-affective signals in spoken language, empirical evidence in the auditory modality has mainly focused on superior pitch perception in ASD. The superior ability in perceiving absolute pitch (AP; DePape et al., 2012; Masataka, 2017; Mottron et al., 2013) and discriminating between pitch height or pitch direction (Bonnel et al., 2003, 2010; Heaton et al., 1998; Heaton, Hudry, et al., 2008; Jones et al., 2009; O'Riordan & Passetti, 2006) has been widely reported in individuals on the spectrum. Enhanced pitch memory ability in autism has also been documented (Heaton et al., 1998; Heaton, Williams, et al., 2008; Stanutz et al., 2014). A number of studies have shown that autistic individuals prefer to listen to nonspeech sounds over speech sounds (e.g., Kuhl et al., 2005). Event-related potential (ERP) studies further indicate that there are distinct patterns of neural sensitivity to discriminate pitch differences in linguistic and nonlinguistic sounds in participants with ASD (e.g., Yu et al., 2015). Such distinctions in pitch processing also extend to the production domain, as a recent study on high-functioning autism (HFA) demonstrates pitch imitation problems only in the speech context, but not the nonspeech stimuli (F. Chen et al., 2021). These findings suggest that researchers may need to treat pitch processing in speech and nonspeech differently. The nonspeech stimuli such as isolated pitch or pitch interval in the ASD literature tend to be relatively simple, and the experimental tasks generally test lower order cognitive processing that does not require contextual integration (Mottron et al., 2000), giving rise to findings compatible with predictions based on both WCC and EPF. Nonetheless, some studies also showed enhanced ability of individuals with ASD in pitch processing in the melodic context, including discriminating pitch change in a melody (Mottron et al., 2000; Stanutz et al., 2014), identifying the whole pitch contour (Jiang et al., 2015), and dissembling pre-exposed isolated pitch from musical chords (Heaton, 2003), which appears to be incompatible with the global processing deficit account.

Complications and controversies exist as the results cannot always be replicated. Some studies found that there were no significant differences between performances of participants with ASD and TD participants in pitch height discrimination (Cheng et al., 2017; Globerson et al., 2015; Mayer et al., 2016), pitch labeling and pitch chord disembedding (Altgassen et al., 2005), pitch direction detection (Germain et al., 2019; Globerson et al., 2015; Heaton, 2005; Heaton, Williams, et al., 2008), pitch contour discrimination (Foxton et al., 2003; Heaton, 2005; Jamey et al., 2019; Jiang et al., 2015; Schelinski & von Kriegstein, 2019), and melodic pitch perception (Foster et al., 2016). Although many studies indicate enhanced or at least preserved ability in nonspeech pitch processing in ASD, some studies have reported significantly worse performance of participants with ASD than TD participants (Weiss et al., 2021). The discrepancies may arise due to a number of factors including stimulus complexity, task demand, and participant characteristics such as cognitive ability, age, gender, language background, and autism severity.

Compared with research on social cognition and sensory processing in other sensory domains such as vision, research on auditory processing in ASD is still limited. Although atypical behavioral responses toward complex speech stimuli in autism are consistently reported, it remains controversial whether autistic individuals have superior ability to process nonspeech stimuli. To address this issue, Jorgensen et al. (2021) conducted a meta-analysis focusing on nonspeech processing in terms of the auditory mechanisms and neurological underpinnings. Their review compared long-latency ERPs and event-related fields from autistic and neurotypical individuals in response to nonspeech auditory stimuli. There were significant differences in the way autistic individuals process lower level nonspeech stimuli when compared with neurotypical individuals. The highlight of the findings was a delayed cortical processing of nonspeech auditory stimuli in autistic children, which indicates atypical and immature development in the general auditory processing system. Similarly, Foss-Feig et al. (2012) reviewed studies to examine whether specific acoustic properties (pitch, loudness, timing, source location, and filtering demands) in nonspeech stimuli are associated with atypical processing in autism. Although behavioral studies are more likely to show intact pitch memory, labeling, discrimination, and contour change detection abilities, evidence for the superiority in these abilities in autism is rather weak. Individuals on the spectrum were often reported to be markedly enhanced in using local cues and not worse at using global cues.

To date, the inconsistent findings on pitch processing in autistic individuals have not been addressed in previous systematic review studies. It is of great theoretical and practical necessity to identify relevant studies systematically and conduct a meta-analysis integrating different results with appropriate theoretical frameworks to better describe auditory processing characteristics of individuals with ASD and guide auditory-based interventions that aim to alleviate auditory processing and language functioning in ASD. A systematic review with meta-analysis has the advantage to allow a better synthesis of the available data for a given research topic (X. Zhang et al., 2022). For instance, the differences in auditory perception between the ASD and TD groups could be aggregated by qualitatively interpreting the literature and quantitatively calculating the overall effect size. This is particularly valuable considering the fact that auditory research studies are generally limited by small sample sizes and high heterogeneity of sample characteristics. The statistical tools in the meta-analysis can objectively elucidate the pooling effects and the moderating factors that may influence the reported outcomes of pitch processing ability in individual autism studies.

Given the distinct preference and response patterns for speech and nonspeech stimuli in autism, the current systematic review with a meta-analysis chose to focus on the studies that used nonspeech stimuli to provide a qualitative and quantitative assessment across existing studies on pitch processing in autism. The study was conducted following PRISMA guidelines (see Supplemental Material S1; Moher et al., 2009). The focus on nonspeech stimuli allows a close examination of the basic pitch processing atypicality in ASD without the influence of confounding contexts related to the linguistic and social relevance. There are three specific aims: (a) to investigate whether individuals with ASD have enhanced pitch processing ability, compared with TD participants; (b) to identify the potential factors associated with the disparate findings in pitch processing of nonspeech stimuli in autistic individuals; and (c) to assess the explanatory power of the leading theoretical accounts in the domain of pitch processing in ASD.

Method

Inclusion and Exclusion Criteria

Types of Studies

The studies eligible for inclusion in this review must specifically examine the pitch perception ability of individuals with ASD compared with at least one matched control group. Studies exclusive on pitch processing in speech sounds were not within the scope of the current review. For studies that involved one or more tasks of auditory processing, only tasks focusing on pitch processing of nonspeech stimuli were included. The studies needed to use behavioral tasks with standard measures. Studies with eye-tracking, electrophysiological, and neuroimaging experiments could also be included if they contained behavior tasks that met the inclusion criteria. Studies should employ experimental or quasi-experimental methods and have a detailed report on the quantitative research design. Moreover, the included studies had to provide sufficient information for further effect size calculations (e.g., mean and standard deviation for both ASD and TD groups). Studies had to be published as research articles in English from peer-reviewed journals. Review articles, editorials, and meta-analyses were not considered in this review because of the lack of original data, nor were conference papers.

Types of Participants

Studies had to include individuals who had a confirmed diagnosis of ASDs by a clinical psychologist or psychiatrist as meeting the criteria of the *DSM*, the International and Statistical Classification of Diseases and Related Health Problems, the Autism Diagnostic Observation Schedule, or other valid diagnostic procedures. Studies involving participants with hearing or visual impairments were excluded. Given that co-occurring psychological disorders are common among autistic individuals (Goldstein & Schwebach, 2004), the inclusion of autistic participants with co-occurring presentations of attention-deficit/hyperactivity features, depression, or social phobia was not part of the exclusion criteria in the current review.

Outcome Measures

We defined the accuracy of pitch processing as any measure calculation from percent correct scores of each group for the relevant tasks. If the results were provided as percentages of errors, corresponding percent correct data were calculated.

Quality Assessment

We assessed study quality using the standard quality assessment criteria for evaluating primary research papers from various fields for quantitative studies (Kmet et al., 2004). The checklist contains 14 items, examining study objectives, study designs, subject selection, subject allocation, controlling, sample size, outcome measures, analysis methods, and so forth. Items relating to the use of interventions (i.e., Items 5, 6, and 7) were not applicable for the included studies, so these three items were not assessed. Two authors (Y.C. and E.T.) rated the studies independently.

Moderator Variables

Based on the information we collected from the included articles, the following variables were taken as moderators for further analyses: participants' age; gender; the value of Full Scale IQ (FSIQ), verbal IQ (i.e., the Wechsler's Abbreviated Scale of Intelligence [WASI; Wechsler, 1999] and the Peabody Picture Vocabulary Test [PPVT; Dunn & Dunn, 1997] or British Picture Vocabulary Scale [BPVS; Dunn et al., 1997]) and nonverbal IQ (i.e., WASI and the Raven's Standard Progressive Matrices [RSPM/RM; Raven et al., 1998]); the score of Social Communication Questionnaire (SCQ); Autism-Spectrum Quotient (AQ); participants' language background (tonal language or nontonal language); task paradigm (pitch contour discrimination task, pitch chord disembedding task, pitch contour identification task, pitch direction recognition task, pitch height discrimination task, pitch labeling task, pitch memory task, and pitch naming task); stimuli form (isolated tone, pitch interval, and melodic contour); stimuli modality (auditory stimuli only or auditory combined with visual stimuli); task difficulty (number of trials and number of answer options); the type of pitch (AP or relative pitch [RP]); year of publication; and region (Europe, North America, and Asia).

Search Strategy

To identify relevant articles, we conducted a systematic search through major electronic databases (Web of Science Core Collection, MEDLINE, ERIC, PsycINFO, PsycARTICLES, and Psychology and Behavioral Sciences Collection). The following combination of words was used as search terms: (a) "ASD OR autism OR Asperger OR HFA" AND (b) "pitch OR speech" AND (c) "perception OR processing OR detection OR discrimination." The search was then limited to studies published in peer-reviewed journals between January 1980 (the first inclusion of autism diagnosis in the *DSM-III*) and January 2022. In addition, manual searches of reference lists were conducted to identify additional potential studies.

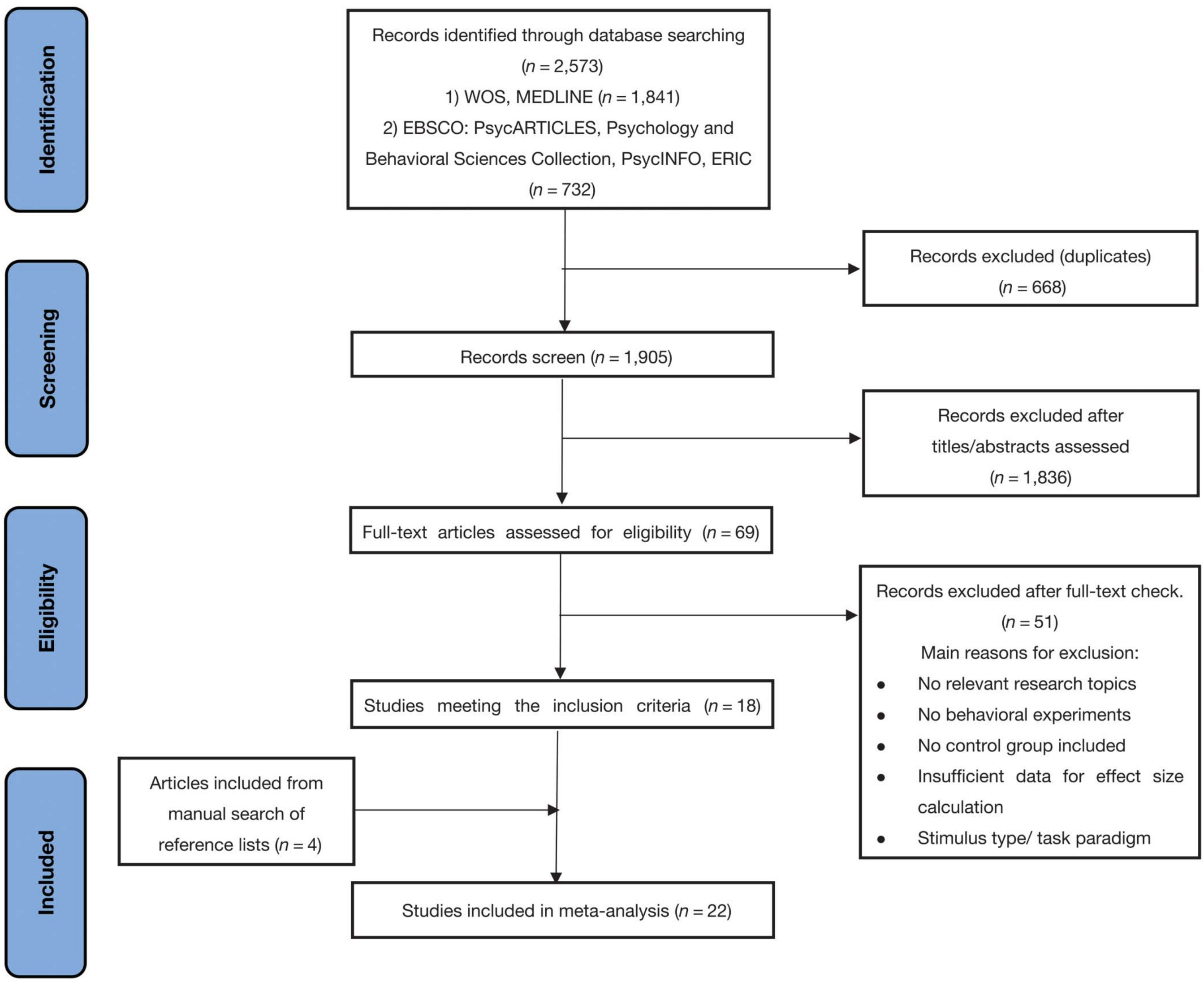
Study Selection and Data Extraction

In total, 2,487 potentially eligible articles were identified in the process of database search. One thousand eight hundred fifty articles remained after excluding duplicates. The title and abstract of each article were then checked in accordance with the mentioned inclusion and exclusion criteria, yielding 69 articles for full-text reviews. We read through the whole 69 articles and screened 18 eligible articles. Another four articles were identified from the reference of relevant articles and were finally included. Thus, the resulting 22 studies were selected for further meta-analysis (see Figure 1 for the description of selection process). Data were extracted from the 22 included studies concerning the following elements: (a) general task characteristics (e.g., task design, stimuli modality, and response option), (b) demographic information of participants (e.g., age, gender, IQ, and language background), and (c) major statistic results (e.g., performance of experimental and control groups).

Statistical Analysis

A quantitative meta-analytic approach was conducted using the open-source R software (Version 4.0.3). The effect sizes from methodologically similar studies

Figure 1. Flow diagram for the different phases of the systematic review and meta-analysis.



were calculated as standardized mean differences with Hedges' *g*, which offers the same interpretation as Cohen's *d*. Considering that the included studies varied in group sizes and the majority recruited smaller sample sizes in the ASD group, Hedges' *g* was used to calculate the effect size given that it is appropriate for studies with uneven group sizes and smaller samples (Hedges, 1981). Effect sizes of 0.20, 0.50, and 0.80 were considered to imply small, medium, and large effects, respectively (Field, 2013).

We used a random-effects model to estimate the mean of a distribution of effect sizes due to variability between studies such as specific tasks used (Field & Gillett, 2010). The between-studies variance estimator used in the current analysis was the DerSimonian–Laird estimator (DerSimonian & Laird, 2015), which was widely used in medical and psychological research. For studies that recruited more than one control group or more than one subtype of autism group, the performance results were averaged and recalculated as new single values. The mean effect size of all the 22 included studies (33 tasks) was calculated and reported in the form of a forest plot.

We assessed between-studies heterogeneity using both Cochran's Q statistic and the I^2 statistic. A significant result on the Q test indicates that the observed effect sizes are widely dispersed (Higgins & Thompson, 2002). I^2 reflects what proportion of the observed dispersion is real and whether it would make sense to speculate about reasons for the variance (Borenstein et al., 2011). The I^2 values of 25%, 50%, and 75% are interpreted as low, moderate, and substantial degrees of heterogeneity, respectively (Higgins et al., 2003). Given that between-studies heterogeneity can be resulted from one or more studies with extreme effect sizes, and such outlier(s) might have even distorted the overall effect, outlier(s) with extreme effect size will be detected and excluded to obtain a new pooled effect estimate. A study will be regarded as an outlier if its confidence interval (CI) does not overlap with the CI of the pooled effect (Harrer et al., 2021). Influential analyses were also conducted based on the leave-one-out method to detect studies that influence the overall estimate the most and have the potential to distort the pooled effect (Viechtbauer & Cheung, 2010).

Meta-analyses are usually at risk of being affected by publication bias. The estimated pooled effect might be higher than the true value because the studies with lower effects may not be published. We assessed publication bias by first inspecting contour-enhanced funnel plots (Peters et al., 2008). An asymmetrical pattern in the funnel plot might be indicative of publication bias. Then, we quantified the asymmetry by Egger's test (Egger et al., 1997). If Egger's regression test indicates publication bias ($p < .1$), the trim-and-fill method was applied to adjust funnel plot asymmetry by adding the potential missing effects until the funnel plot is symmetric (Duval & Tweedie, 2000). The adjusted pooling effect size and 95% CI were reported after the addition of the potential unpublished studies.

Metaregression analyses were conducted using a mixed-effects model, which can detect the sources of heterogeneity and the degree of their contribution to effect size differences among studies. All moderators were included in the metaregression analyses provided that information was available for a sufficient number of studies (≥ 4; Velikonja et al., 2019). The regression coefficients (β values), Q_{model} (Q_M) statistics, and p values were reported. The proportion of variability explained by the moderator (R^2) was also calculated to quantify the magnitude of the estimated effects associated with the significant moderators (Borenstein et al., 2011).

Results

Description of Included Studies

Twenty-two articles published from 1998 to 2021 were eligible for inclusion in the quantitative meta-analysis. Supplemental Material S2 presents the general characteristics of the studies included in our quantitative analysis, including task paradigms, stimulus modalities and forms, response options, and the demographic information of the ASD and TD groups. Nine of the included articles contained more than one task and were listed in different rows in the table; thus, a total of 33 tasks were included in the review.

The included studies provided a combined sample of 464 participants with ASD (mean [standard deviation] age of samples across studies, 16.64 [9.02] years) and 481 TD participants (16.63 [8.73] years). Most of the 22 studies were conducted in Europe (13 studies, 59.09%), followed by North America (six studies, 27.27%), and the rest of the three studies were conducted in China (two studies) and Israel (one study). English (18 studies) was the language used by the majority of the included studies, and the rest were Hebrew (one study), Germany (one study), Mandarin (one study), and Cantonese (one study). As pitch processing is known to be influenced by language background and music training (Zatorre & Gandour, 2008), we call attention to the fact that the studies (20) in nontonal languages (languages that do not use syllable-level pitch variations or lexical tones) to distinguish words (e.g., English, Hebrew, and Germany) significantly outnumbered those (two studies) in tonal languages (languages where pitch functions to encode word meaning; e.g., Mandarin Chinese and Cantonese; Yip, 2002). Although the majority of studies clearly reported that their participants in both TD and ASD groups were either musically untrained (six studies) or strictly matched in musical experiences (eight studies), six studies did not provide the participants' information regarding their musical training experiences. In regard to the selection of the control group, only two among the 22 studies (Heaton, 2003, 2005) used more than one matching system, and the remaining studies contained only one control group. The majority of the studies (20) considered chronological age as a matching condition for the control group. Chronological age, nonverbal IQ, verbal IQ, FSIQ, and gender are among the most frequently used matching conditions for the control groups among the included studies.

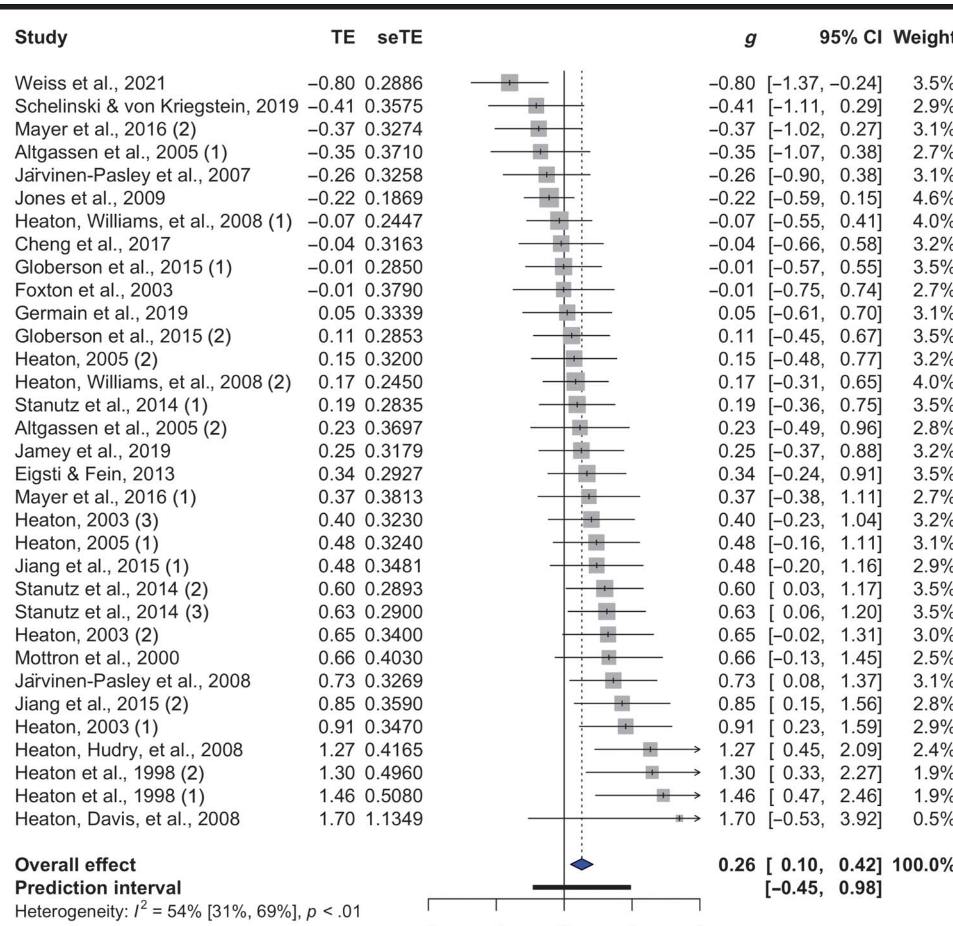
The sample sizes (both TD and ASD groups) varied greatly among studies, ranging from 10 participants (Heaton, Davis, & Happé, 2008) to 120 participants (Jones et al., 2009), and the mean is 41. The sample size for most studies (73.9%) was between 20 and 50. Autistic participants in the majority of included studies were diagnosed with classical autism or Asperger's syndrome (AS), especially those without intellectual disabilities. The task paradigms used in the 33 tasks can be grouped into eight broad categories, including the investigation of pitch contour discrimination ability (eight studies), pitch height discrimination ability (eight studies), pitch memory ability (five studies), pitch direction recognition ability (four studies), pitch chord disembedding ability (three studies), pitch labeling ability (two studies), pitch contour identification (two studies), and pitch naming ability (one study). The majority of included studies presented participants with only one stimulus modality (i.e., auditory), whereas four studies also mobilized participants' visual channels by presenting them with animal pictures or pictures of pitch contour. The stimuli were mainly presented in three manners: isolated tone/pure tone (six studies), pitch interval/tone pair (nine studies), and melodic contour (18 studies). All the participants in the included studies were required to make responses during these pitch perception tasks, verbally (seven studies) or behaviorally (26 studies).

The included studies had a mean quality index score of 0.87 (SD = 0.06, range: 0.68–0.95). The quality assessment of the included studies is reported in Supplemental Material S3. The interrater correlation coefficient (using Spearman correlation; Gwet, 2014) between the two raters was .72. Disagreements were resolved by follow-up discussions to reach a consensus.

Overall Performance of Individuals With ASD on Pitch Processing

Supplemental Material S3 summarizes the overall accuracy of participants with ASD on pitch processing of nonspeech stimuli compared with that of TD participants in each task. Figure 2 presents the forest plot with effect size for included studies. The standardized pooling effect size was small to medium and significant (Hedges' g = 0.26, 95% CI [0.10, 0.42], $p < .005$; see Figure 2). The between-studies heterogeneity was significant, $Q(32)$ = 69.05, $p < .005$, indicating the existence of large differences in the effect size of the included studies. This was corroborated by the moderate-to-substantial heterogeneity between the included studies (I^2 = 53.7%). The CI of pooled effect size, stretching from g = 0.10 to g = 0.42, filtered out three potential outliers (Heaton et al., 1998; Heaton, Hudry, et al., 2008; Weiss et al., 2021). It is noticeable that the lowest I^2 heterogeneity was reached when the mentioned three outliers were removed in the leave-one-out analyses (see Supplemental Material S4). The results of outlier analysis and influence analysis pointed to the same direction. Thus, the three studies were identified as potential outliers that may distort the effect size estimate and decrease the precision. After removing outliers, the standardized mean effect size remained nearly small to medium (Hedges' g = 0.24, 95% CI [0.10, 0.38], $p < .001$; see Supplemental Material S5), and I^2 shrunk considerably to the low-to-moderate heterogeneity, from 53.7% to 34.4%.

Figure 2. Forest plot with effect size (Hedges' g) and confidence interval (CI) for the included studies. Gray squares depict individual effect sizes of pitch processing in the autism spectrum disorder group compared with the typically developing group, with sizes indicating the relative weight of each study's effect size estimate to the analysis. Blue diamond reflects the overall pooling effect across studies.



For publication bias, visual inspection of the contour-enhanced funnel plot detected an asymmetrical pattern (see Supplemental Material S6). The result of Egger's test was significant ($p < .005$), confirming significant publication bias. The trim-and-fill analysis estimated and added eight studies (see Supplemental Material S7), indicating that our initial results might be overestimated due to publication bias. The adjusted effect became much smaller (Hedges' $g = 0.09$, 95% CI [−0.09, 0.28], $p = .32$).

Moderators

Metaregressions revealed that, among the included moderators, year of publication, $Q_M(1) = 8.27$, $R^2 = 28.74\%$, $p = .004$; mean age, $Q_M(1) = 6.04$, $R^2 = 28.53\%$, $p = .002$; and nonverbal ability (RSPM/RM), $Q_M(1) = 4.99$, $R^2 = 99.98\%$, $p = .026$, significantly explained the between-studies heterogeneity. Moreover, compared with pitch interval, isolated tone as the stimulus form can significantly explain the heterogeneity between studies ($p = .046$). To further investigate the difference among the three stimulus forms, we calculated the pooled effect size separately according to the stimulus form. The pooled effect size of studies using isolated tone is the highest (Hedges' $g = 0.70$, 95% CI [0.07, 1.33], $p < .05$), followed by melodic contour (Hedges' $g = 0.28$, 95% CI [0.04, 0.52], $p < .05$), and pitch interval is the lowest (Hedges' $g = 0.04$, 95% CI [−0.14, 0.21], $p = .68$). The other variables did not account for the between-studies heterogeneity (see Supplemental Material S8). Effect size difference was not significantly correlated with the percentage of men, $Q_M(1) = 0.94$, $p = .33$; FSIQ, $Q_M(1) = 1.77$, $p = .18$; verbal IQ (WASI: $Q_M(1) = 0.18$, $p = .67$; PPVT/BPVS: $Q_M(1) = 0.01$, $p = .91$); nonverbal IQ (WASI), $Q_M(1) = 0.49$, $p = .48$; AQ, $Q_M(1) = 1.87$, $p = .17$; SCQ, $Q_M(1) = 3.11$, $p = .08$; task type, $Q_M(7) = 5.34$, $p = .62$; stimulus form, $Q_M(2) = 4.07$, $p = .13$; number of options, $Q_M(1) = 0.55$, $p = .46$; stimulus modality, $Q_M(1) = 2.60$, $p = .11$; number of trials, $Q_M(1) = 0.05$, $p = .82$; pitch type (AP or RP), $Q_M(1) = 2.06$, $p = .15$; and region, $Q_M(2) = 0.08$, $p = .96$.

Discussion

Evidence for Enhanced Pitch Perception Ability in ASD

The present systematic review and meta-analysis provides the first analysis on whether autistic individuals show enhanced ability in processing pitch in nonspeech sounds compared with TD individuals and investigates the potential factors that may account for the differences in the findings among the eligible studies in extent findings. Although the results indicate that autistic individuals show slightly enhanced ability when processing nonspeech pitch, there is likely the presence of publication bias. Moreover, age and nonverbal ability can affect autistic individuals' pitch perception ability. Stimulus design (e.g., isolated pitch vs. pitch interval used in the task) can also have an impact on performance.

We examined 22 studies including 464 autistic participants and detected a small-to-medium positive effect size ($g = 0.26$), suggesting that there were indeed certain differences between autistic individuals and TD people when processing pitch in nonspeech sounds. However, the effect estimate of the meta-analysis was reduced (to 0.09) after the correction for publication bias, and the p value exceeded .05. This indicates that there was a potential substantial influence of publication bias. Therefore, one cannot rule out the possibility that studies with nonsignificant results or small effect sizes have been deprived of the opportunity of publication and cannot be integrated into our meta-analysis. Before the correction of the potential publication bias, the results suggest that autistic people possess better pitch processing ability, which is in line with the statements of the EPF model and the WCC theory. Autistic individuals allocate more attention to lower level prosodic features and have better performance in local processing. However, it should be noted that the enhanced performance found in autism is relatively conservative, and their processing advantage might disappear if the potential publication bias is taken into account. The small pooled effect size ($g = 0.09$) after correction calls for further extensive research to obtain a more comprehensive and objective outcome to determine the existence of superior pitch ability in autistic individuals and the variables that may contribute to the individual differences. Results of the current review are consistent with the previous narrative review by Foss-Feig et al. (2012), highlighting the main observation that although behavioral studies in ASD tended to show intact or enhanced ability in pitch memory, labeling, discrimination, and contour change detection, evidence for an enhancement or superiority in these abilities was rather weak.

The Enhanced Pitch Perception in ASD: Domain-General or Domain-Specific?

Our meta-analysis findings prompt the suggestion that autism may be characterized by a nonspeech pitch perception advantage. In regard to pitch perception ability of ASD in speech context, previous studies elucidated different findings. Heaton, Hudry, et al. (2008) investigated pitch contour discrimination in autistic children and matched controls and found enhanced performance in ASD across different types of auditory stimuli (words, nonsense words, and nonspeech pitch contour). Their findings replicated previous studies showing superior processing of speech pitch in ASD (Järvinen-Pasley & Heaton, 2007; Järvinen-Pasley et al., 2008), thus providing support to the opinion that the enhanced pitch perception is more domain-general in autism. A recent study (Wang et al., 2022) also found that autistic participants showed similar mental representations of speech and musical pitch contours, indicating that pitch processing mechanisms are shared across domains in ASD. However, a strand of studies showed that the enhanced pitch sensitivity in autism was only found in the nonspeech conditions but not for speech stimuli (e.g., F. Chen et al., 2021; Yu et al., 2015), suggesting that pitch enhancement in ASD in nonspeech did not extend to the speech domain. It merits further investigation whether there is a definitive linguistic processing influence on the perception of pitch changes in speech. A recent meta-analysis investigating mismatch negativity to different deviant changes in ASD showed that sensitivity to tone–frequency deviants in autistic people is generally not impaired (T. C. Chen et al., 2020); however, the performance may vary with age and the symptom level of clinically diagnosed autism (T. C. Chen et al., 2020; Järvinen-Pasley et al., 2008; Schwartz et al., 2018). The divergence in speech pitch perception research again points to the need to study age- and severity-related individual differences in ASD and different subgroups within the heterogeneous spectrum.

Pitch plays a vital role in encoding linguistic prosody (Jiang et al., 2015), whereas enhanced pitch processing ability in ASD was often reported to coexist with highly variable speech functioning. This concurrent enhanced and decreased performance in autism is of particular interest when considering any links between auditory processing and social abilities (Kuhl et al., 2005). According to the EPF model, the bias toward lower level processing in ASD results in the enhanced extraction of elementary perceptual information in the context of higher level tasks (Germain et al., 2019; Mottron & Burack, 2001; Mottron et al., 2006). Such a bias may come at the cost of reduced resources or ability to process higher order information such as linguistic meanings and social functioning in higher level processing tasks. One direct consequence could be impaired language acquisition in a social communication environment that integrates verbal and nonverbal messages and demands contextual and cultural understanding. This notion is also in line with the statement that hyperacuity for pitch might contribute to overly detailed representations of phonological information, thereby delaying the acquisition of phonological categories and word learning (Eigsti & Fein, 2013), and superior lower level perceptual skills might contribute to the undercutting of higher level language processing in ASD (Järvinen-Pasley & Heaton, 2007; Järvinen-Pasley et al., 2008; Yu et al., 2015).

Some researchers have emphasized the role of attention deficit rather than perceptual deficit in the divergent processing ability of autistic individuals. Simple auditory stimuli require little load on the attention system, whereas complex stimuli and demanding listening conditions can cause more disruption and place greater strains on cognitive load. It is worth noting that individuals on the spectrum often exhibit difficulty in executive attention that handles the suppression of competing sensory input streams (Dunlop et al., 2016). Therefore, the uneven attentional resources distributed to speech sounds and nonspeech sounds may be associated with the enhanced lower level processing (e.g., pitch perception ability) and relatively impaired speech-in-noise perception and language processing in ASD.

Another related explanation for the concurrent enhanced and decreased performance for different types of sounds or sound attributes may lie in the impaired temporal representation in ASD. Compared with accumulating evidence that individuals on the spectrum show enhanced or intact spectral perception, temporal perception ability in ASD is reported to be impaired (Huang et al., 2018; Wallace & Happé, 2008). Gap detection testing has constantly found that individuals on the spectrum need longer gaps to identify stimuli (Bhatara, Babikian, et al., 2013), whereas gap detection ability was associated with lessened phonological awareness and impaired speech-in-noise perception (Foss-Feig et al., 2017), which thereby relates to the altered language functioning in autism. More studies are needed to address how the spectral and temporal processing abilities in autistic individuals vary from each other and how they may jointly or separately be linked to early language delay or various forms of later language problems (Boets et al., 2015; Eigsti & Fein, 2013).

In a nutshell, pitch is an important sound attribute, and the nonspeech pitch perception superiority in ASD may not always successfully extend to the speech domain and tend to exhibit high variability in language ability, which may be rooted in disorder in sensory, cognitive, or social processes. However, it may be the case that the enhanced attention toward perceptual components in sounds may aid, rather than hinder, language acquisition in ASD, especially in those without intellectual disabilities (Järvinen-Pasley & Heaton, 2007). It is well established that there is a strong transfer of learning in pitch processing across auditory and linguistic domains involving sensory–motor integration (Rimmele et al., 2022; Zatorre & Gandour, 2008). Together with the discovery of musical skills and musical preferences/enjoyment in ASD (Bhatara, Quintin, et al., 2013; Molnar-Szakacs & Heaton, 2012), the evidence for superior pitch perception ability in our meta-analysis could provide some justifications or motivations to include musical training as a candidate for nonverbal intervention to help develop linguistic, communicative, and social skills among autistic individuals (Janzen & Thaut, 2018; Yan et al., 2021).

Influential Factors of Pitch Perception in Autism

The pitch perception findings may be subject to several factors. The relatively high between-studies heterogeneity found in the current meta-analysis indicated that there were some other sources affecting the pooled effect size. This is also confirmed by the metaregression analyses, suggesting that several other factors contribute to the differences of pitch perception ability in autism.

Participant-Related Factors

To further investigate whether there is an association between autistic participants' heterogeneity with the effect size variation, we examined the relationship between the effect estimate and the participants' mean age, gender, FSIQ, verbal IQ, nonverbal IQ, AQ, and SCQ. The studies in this systematic review covered a wide age range from children to adolescents and adults in participants with ASD, and moderator analyses showed that the mean age of participants was a significant contributor to the between-studies heterogeneity. Specifically, an increase in age led to a decrease in effect size, which indicates that ASD's processing advantage of pitch reaches its peak during childhood. This result is consistent with the observation that abnormal sensitivity to sensory stimuli is inclined to decrease with age in autistic children (Kern et al., 2006). Moreover, research on age-related changes in executive function indicated that executive dysfunction in ASD abate with age (Happé et al., 2006). These age-related improvements may result from individual compensatory strategies acquired during development. Heaton et al. (2007) conducted a musical priming task to test local and global processing abilities in a group of autistic individuals with high heterogeneity (IQ = 55–131; ages 7–19 years). The study revealed the typical global processing in autistic individuals and an increase in global advantage with age in ASD. Similar results have been replicated and extended by Foster et al. (2016). They tested the performance of 32 HFA children ranging in age from 7 to 17 years old and 40 matched neurotypical controls with a task requiring participants to judge local and global pitch structure. Although their findings indicated that both TD and ASD showed a global precedence effect with similar global advantage as well as global and local interference effects, a group difference in the age trajectory of global interference was also found. Autistic children showed a diminished effect of global interference at younger ages, and this increase in the global advantage effect with age in ASD is in line with previous findings in the auditory domain (DePape et al., 2012; Heaton, 2005; Heaton et al., 2007). The relative insensitivity to interference from global information in ASD at their younger ages may contribute to their increased attention to piecemeal information and superior lower level auditory perceptual ability. One important caveat here is that the developmental trajectory is different between individuals on the spectrum and their neurotypical counterparts. Although pitch discrimination ability is enhanced in childhood in ASD and remains stable over development, there is a reversal of the developmental pattern in TD individuals who show a significant improvement in pitch discrimination from childhood and adolescence into adulthood (Mayer et al., 2016). The differences in a developmental perspective provide a potential explanation for our results here, that is, an increase in age, leading to a decrease in pitch processing advantage in autistic individuals relative to the neurotypical controls and the consequent smaller effect sizes. However, there are also exceptions. For instance, Jamey et al. (2019) reported that melodic discrimination ability increased with age in participants with ASD. Stimulus characteristics could be a factor contributing to the difference here as melodic perception involves auditory stimuli with larger pitch units than isolated pitch and pitch interval, which are widely investigated in the studies included in our meta-analysis. Task differences could be another source for this divergence since melodic pitch perception requires more global information processing than simple pitch discrimination. Future autism research needs to recruit larger samples and gain a more precise understanding of the impacts of age on pitch perception in nonspeech sounds for the different types of tasks and stimuli.

Studies on the association between auditory perception and verbal/nonverbal cognition in ASD are crucial for better understanding the individual differences in ASD. The current analysis also examined whether cognitive abilities were related to the variability of results. Our moderator analyses indicated that nonverbal IQ (RSPM/RM) was a significant contributor for the between-studies heterogeneity. However, no significance was found for FSIQ, verbal IQ, or nonverbal IQ (WASI). Here, the positive correlation between nonverbal IQ and pitch processing ability is a novel but consistent finding in autism research. For example, Jamey et al. (2019) discovered that melodic pitch perception in the ASD group was positively associated with nonverbal cognitive intelligence. Mayer et al. (2016) further indicated that nonverbal intelligence had a direct effect on the efficiency with which autistic individuals allocate their attentional resources. Together, the positive correlation between pitch processing and nonverbal ability in autism may reflect the more effective allocation of attentional resources in individuals with higher nonverbal abilities.

Similar correlation results have been widely reported between nonverbal cognitive ability and auditory processing skills including pitch discrimination ability (Jamey et al., 2019), isolated pitch memory (Stanutz et al., 2014), and melodic memory ability (Heaton et al., 1998; Stanutz et al., 2014). In some studies, such significant correlations between ASD's auditory perception and nonverbal ability were not observed (Heaton, Hudry, et al., 2008; Heaton, Williams, et al., 2008). Of particular importance is the finding that auditory pitch perception is related to nonverbal ability instead of verbal skills in both children with ASD and TD children (Chowdhury et al., 2017). Note that our moderator analysis revealed significant effects for nonverbal (RSPM/RM) and variability of effect sizes but no significant effect of nonverbal IQ (WASI) across the studies. Caution is needed for the discrepancy and null finding as our moderator analysis included a small number of eligible studies. The fact that a moderator is not significantly associated with effect size variation does not necessarily mean that there is no relationship between the moderator and effect size variation (Hedges & Pigott, 2004). More large-scale studies with a broader representative sample of autistic individuals, including participants with a wide range of FSIQ, nonverbal IQ, and verbal IQ, can help determine the role of nonverbal intelligence in explaining individual differences in sensory processing in autism and deepen our understanding of perceptual–cognitive phenotypes in ASD.

In our analysis, we further considered the levels of symptom severity as a moderator with the value of SCQ as an indicator. The SCQ (Rutter et al., 2003) is a 40-item parent questionnaire developed for screening symptoms and behaviors typically associated with ASD. The SCQ is known for its clinical utility with a high correlation with more extensive and stringent diagnostic tools such as the Autism Diagnostic Interview. In addition, the AQ, as a useful brief assessment instrument for examining autistic traits in research studies, has been widely used among neurotypical individuals and HFA/AS adults of normal intelligence (Baron-Cohen et al., 2001; Wakabayashi et al., 2006); therefore, where applicable in our meta-analysis, the value of AQ was also collected as a supplementary indicator. Although the majority of the studies reported enhanced pitch discrimination at the group level in ASD, some studies argued that this advantage was limited to certain subgroups within the spectrum. This was also supported by the observation that the incidence of exceptional pitch discrimination was more common among individuals on the spectrum who had a history of delayed speech onset (Heaton, Davis, & Happé, 2008; Jones et al., 2009). Brandwein et al. (2015) also demonstrated that clinical severity could affect nonspeech perception in ASD. There was additional evidence that the enhanced ability in pitch discrimination was only detected in individuals meeting full diagnostic criteria for autism, but not in those with Asperger's syndrome (Bonnel et al., 2010). Even in the TD group, positive correlations between pitch discrimination and AQ scores were detected, suggesting that individuals with higher levels of ASD traits were more likely to have superior pitch processing ability (Mayer et al., 2016). The participants with ASD for the studies in our systematic review ranged from higher functioning to lower functioning with varying levels of clinical severity. However, neither SCQ nor AQ scores of the ASD group showed a significant result in the moderator analyses. Only SCQ scores showed a trending association (p = .08) with effect size variation. Again, caution is needed for the interpretation of these null findings as the number of eligible studies that provided information on scores of SCQ and AQ was rather small.

Compared with nontonal language speakers, neurotypical individuals with tonal language backgrounds tend to have superior pitch processing abilities. This processing advantage in the neurotypical population has been confirmed in experiments involving lexical tone identification and discrimination (Bent et al., 2006; Xu et al., 2006). Pfordresher and Brown (2009) suggested that tonal language acquisition refined the processing of auditory dimensions in speech, and such attunement can be transferred to nonlinguistic contexts. This was later confirmed in a study where the tonal language group showed better performance in discriminating pitch contour in both spoken words and musical sounds (Stevens et al., 2013). Additionally, tonal language speakers also outperformed nontonal language speakers in the detection of pure pitch and interval changes (Giuliano et al., 2011). However, the results in our meta-analysis did not reveal a significant effect of language experience on pitch perception performance. Note that only two ASD studies with tonal language speaker participants were included in the current meta-analysis. Many more autism studies involving tonal language users to test their pitch processing skills are needed to allow a proper evaluation of whether tonal language background would significantly influence the effect sizes across the studies.

Methodology-Related Factors

In addition to factors associated with participants, methodological differences were considered as potential contributors to the heterogeneity. In the current analysis, six methodology-related factors were taken into consideration: task type, stimulus type (AP or RP), stimulus form, number of options, stimulus modality, and number of trials. Moderator analyses showed that none of these factors had a significant impact on the variability across studies.

Studies included in the current meta-analysis varied in eight different task types, that is, pitch contour discrimination (to detect differences between melodies with certain note alterations that preserved or violated the melodies), pitch chord disembedding (to parse and identify individual component tone from within a musical chord), pitch contour identification (to match melodic contours to the visual display of the pitch contours), pitch direction recognition (to determine whether pitch interval between two tones moves up or down), pitch height discrimination (to detect the presence of pitch distance between the tone pairs or between two melodic contours), pitch labeling (to associate certain isolated tones to certain pictures), pitch memory (to memorize and identify certain isolated tones or melodic contours after a time interval), and pitch naming (to name isolated decontextualized musical tones). These task paradigms were among the most common and classic methods in testing pitch processing ability. Studies using different paradigms can sometimes obtain mixed results, and internal discrepancies can even appear within the same paradigm. For example, enhanced pitch processing in autism was found in pitch contour discrimination (Stanutz et al., 2014), pitch contour identification (Jiang et al., 2015), pitch labeling, and pitch chord disembedding (Altgassen et al., 2005), whereas no processing advantage was found in autism in pitch chord disembedding (Heaton, 2003), pitch contour discrimination (Jiang et al., 2015), and pitch contour perception (Foster et al., 2016). However, no significance was detected in our analyses, suggesting that differences in task paradigm did not contribute to between-studies heterogeneity.

Our meta-analysis divided the studies included in the systematic review into two groups based on whether they tested RP or AP. AP refers to the ability to identify the pitch of an isolated tone out of context, whereas RP refers to the ability that people classify pitch of notes within context (Stanutz et al., 2014). Previous research showed that there is a greater incidence of AP privilege in ASD (DePape et al., 2012). Reports of such prevalence of AP in ASD suggest that AP is associated with some of the distinctive cognitive and social characteristics of autism (Brown et al., 2003). Additionally, AP has been regarded as an indicator of WCC in that enhanced memory for isolated pitch information results from taking individual notes out of Gestal apart from the scales and melodies they form (Stanutz et al., 2014). However, metaregression results suggested that the stimulus type (AP vs. RP) was not associated with between-studies heterogeneity. Though the overall effect size of studies using AP was slightly higher than that of studies using RP, there was still no significant difference between AP perception and RP perception. The speculation by Brenton et al. (2008) that the talent of AP could be linked to a genetically distinct subset of autistic children can be a potential explanation for our null finding here as different studies recruited autistic participants with various symptom severity.

In our meta-analysis, stimulus form was classified into three levels (isolated pitch, pitch interval, and melodic contour) based on the embedded hierarchical pitch structure (Altgassen et al., 2005). The isolated pitch has an absolute height value, pairs of isolated pitches form pitch intervals, and the direction that intervals take further comprises the melodic contour (Mottron et al., 2000). Generally speaking, stimulus discrimination at the higher levels involves more complex pitch structures with higher task difficulty. In our meta-analysis, stimulus form showed no significant impact on the heterogeneity. However, the isolated tone had significantly stronger explanatory strength than pitch interval in the between-studies heterogeneity. Isolated pitch relies more on AP perception, being a rather local way of processing, whereas interval recognition relies on RP perception with a relatively global way of processing (Altgassen et al., 2005; Germain et al., 2019; Mottron et al., 2000). Studies using isolated pitch had larger effect sizes than those using pitch interval in our meta-analyses, suggesting a locally oriented information-processing style and a propensity to rely on AP in autism (Mottron et al., 2000). This finding is compatible with expectations of both EPF and WCC. In our analysis, no significant difference between isolated pitch and melodic contour was found in terms of their impact on between-studies heterogeneity. Altgassen et al. (2005) also failed to find a local processing bias in all autistic children as comparable performance was found when they were presented with isolated tones and chords in research.

Previous studies suggest that autistic people have problems integrating information across auditory and visual modalities. This multisensory integration plays an important role in atypical social behaviors in autism (Magnée et al., 2011). In our analyses, nine studies used audiovisual (AV) stimuli, and the others used auditory stimuli only. Results detected no significant difference between the two. This is not unexpected. Some research suggested that although multisensory processing may be impaired in more complex phonological processes, the integration of low-level information is intact in autism (van der Smagt et al., 2007), and early nonlinguistic AV interactions are not impaired (Magnée et al., 2008).

In regard to the number of answer options and trials, no significance was found, though increases in the number of trials and answer options are more likely to result in greater task difficulty (Tang et al., 2022; M. Zhang et al., 2022). However, this result should be interpreted with caution since the failure in detecting significance may result from the limited number of eligible studies.

Nonverbal Ability Is Related to Local Processing Bias in ASD

Our meta-analysis results demonstrate that nonverbal ability plays a significant role in pitch perception for individuals on the spectrum. ASD is widely recognized as a complex, heterogeneous neurodevelopmental condition (Song et al., 2022). Over the past 40 years, there have been significant narrowing and broadening in the diagnostic criteria for ASD across the different revisions in *DSM-III*, *DSM-IV*, and *DSM-5*. The diagnostic changes and the increased social awareness have led to the rising trend in ASD cases diagnosed among adults, females, and individuals without intellectual difficulties during the past two decades (Arvidsson et al., 2018; Russell et al., 2022). Large-scale behavioral genetic studies showed that IQ may index etiological heterogeneity and provide a basis for identifying neurocognitive phenotypes in ASD (Fein et al., 1999; Szatmari et al., 2000). There is a high degree of phenotypic variance in autism, and nonverbal ability is highly heterogeneous across the spectrum. Different behavioral performances across individuals with varying nonverbal abilities may be ascribed to genetically meaningful variation in autism. Whether different cognitive profiles such as nonverbal ability can be associated with the variation in core symptomatology is one of the real concerns in analyzing the behavioral expression of autism.

Joseph et al. (2002) reported the high rate of discrepancy between nonverbal and verbal ability in autism and the significantly increased impairment in social functioning among children with discrepantly higher nonverbal abilities. In line with Joseph' findings, our pooling data also show discrepancies between the verbal and nonverbal abilities in participants with ASD, suggesting a high rate of uneven cognitive development in autistic children. Furthermore, our findings further support and explain the association of greater social impairment with discrepantly higher nonverbal abilities. Higher nonverbal ability is much more likely to be associated with a lower level perceptual ability or a local processing bias (i.e., the enhanced pitch perception ability in the current study). Chowdhury et al. (2017) suggested that nonverbal abilities predicted performance on the lower level pitch perception task and local pitch processing on the higher level melodic pitch task. Therefore, the cumulative evidence indicates that nonverbal ability is a significant contributor to the lower level processing advantage and local processing bias in ASD. Nonverbal ability may serve as a potential neurobehavioral marker for subtyping autism. In addition, using a quantitative measure of phenotype instead of roughly diagnostic division will be of great clinical significance in understanding the core symptomatology of autism and its underlying mechanisms.

Paucity of Research on Pitch Perception in Autistic People With Hearing Impairments and in Complex Listening Conditions

Prior to *DSM-5*, comorbidities in autism were largely disregarded, which limited our understanding of cognitive phenotypes in ASD and its implications for cognitive theory. With the adoption of *DSM-5*, there is a consensus in recognizing the cumulative evidence for ASD comorbidity with other developmental/psychiatric conditions, which characterizes the nature of heterogeneity in autism and prompts a caution against overgeneralization when integrating findings from studies prior to *DSM-5*. Our systematic review found that few existing studies have investigated the individuals with hearing loss despite the fact that hearing loss is much more common in autistic individuals than in neurotypicals. During our first screening of eligible studies, we found that participants with ASD with hearing impairments were noticeably absent from relevant literature, and few studies examined pitch processing ability in individuals with a dual diagnosis of autism and hearing loss. Evidence is accumulating that individuals with a dual diagnosis constitute a reasonably sizable clinical population (Do et al., 2017; Szarkowski et al., 2014). Rosenhall et al. (1999) studied 199 children and adolescents with autism with varied intellectual functioning and reported pronounced to profound bilateral hearing loss among autistic participants, which is 10 times higher than the prevalence of hearing loss in neurotypicals. In cases where autism and hearing loss co-occur, diagnosis of one condition often results in the delayed diagnosis of the other (Jure et al., 1991; Roper et al., 2003), impeding efficient and timely assessment and remediation. However, there is a paucity of research on describing this population and a lack of ASD screening tools specifically validated for children with hearing loss or interventions tailored to individuals with the dual diagnosis. As one of the authoritative assessments, the Autism Diagnostic Observation Schedule–Second Edition explicitly states that it is not valid on children with significant sensory disorders, including children with hearing impairments (Lord et al., 2012). In this regard, we call for more research investigating lower level auditory processing in individuals with dual diagnoses of ASD and hearing impairment to deepen our understanding toward this population and shed light on the early diagnosis of ASD among children with hearing impairments, which is of great importance in facilitating access to interventions to mediate the influence of autism disorder on developing language, cognitive, social, and motor skills.

Furthermore, despite the fact that noise is ubiquitous in our environment, there is a lack of pitch perception studies on autism in adverse listening conditions involving signal degradation, mixture, and noise interference. Therefore, whether the detected superior pitch perception ability in autism can be preserved in challenging listening conditions remains unknown. Previous studies have reported that autistic individuals tended to experience a distressing hyperreactivity to noise (Rosenhall et al., 1999), show impaired ability in segregating the dichotic pitch stimuli into distinct auditory objects that arises at an early pre-attentive level of processing (Lodhia et al., 2014), and perform worse in speech-in-noise recognition, which may result from the inability in ASD to benefit from temporal gaps in the competing speech or noise signal (Alcantara et al., 2004; Schelinski & von Kriegstein, 2020). Of particular importance is the finding that nonvocal pitch discrimination ability correlated positively with speech-in-noise perception abilities (Glasberg & Moore, 1989). In a similar vein, Schelinski & von Kriegstein (2020) also emphasized the role of fundamental frequency processing ability in understanding speech with competing speakers. These divergent findings raise the important question on whether the pitch perception advantage can extend to speech-in-noise recognition and speech processing. Answers to this question can provide insightful information regarding the altered cognitive functioning in autism and help to depict a more comprehensive picture of auditory perception ability in ASD.

Theoretical Explanation for Enhanced Pitch Perception in ASD

The current meta-analysis detected a small-to-medium positive pooled effect size, indicating that autistic individuals have enhanced pitch perception ability for nonspeech sounds in comparison with TD individuals. Pitch processing in nonspeech sounds belongs to the lower level auditory processing, and the enhanced ability in pitch perception would count as evidence for local processing bias in ASD, which is compatible with expectations of the EPF model and the WCC theory. Moreover, the pooled effect size of studies using isolated tone was medium to large (Hedges' $g = 0.70$), whereas those using pitch interval and melodic pitch were only 0.28 and 0.04. Isolated tone relies more on a rather local processing style (Altgassen et al., 2005; Germain et al., 2019; Mottron et al., 2000), implying an overdevelopment of lower level perceptual operations in autism. According to EPF, although individuals on the spectrum prefer local details and segments, it does not lead to an imbalance or deficit in understanding details based on context (Mottron et al., 2006), which may explain the coexistence of slightly enhanced pitch processing ability at the level of contour perception and preserved processing ability at the level of pitch interval.

It is questionable whether pitch contour perception represents the global level of auditory perception. Foxton et al. (2003) posited that pitch contour consists of a succession of ascending and descending pitch directions, which can be considered as local features and the large-scale contour representations simply add these local features together, whereas this process does not consist of the involvement of a higher level of perceptual organization where the whole is greater than the sum of the parts. Mottron et al. (2000) suggested that "local" and "global" are reciprocally relative concepts and cannot be used in isolation. A global level must be included in the experimental design as a basis for comparison. Justus and List (2005) also argued that interval–contour stimuli failed to test the extent of independence between global and local levels. Thus, it is noteworthy that while completely independent manipulation of global and local levels in auditory processing is challenging in experimental design, providing more data to improve our current knowledge of global versus local processing styles in ASD remains a remunerative endeavor.

Although WCC and EPF have their theoretical values in explaining the positive symptoms in the lower level cognitive processing of autism, we need to keep in mind that the disorder is much more extended, manifesting in general sensory, motor, social, and language learning processes with the altered sensory processing being just one aspect or consequence of the more general disorder. Although supporters of these theories are convinced that cognitive differences between autistics and nonautistics have a "mandatory" basis, in the form of a profound and distributed difference in brain organization, there is a lack of explanation on the basis of the functional neuroanatomy of perception. In this regard, the neural complexity hypothesis can serve as an alternative reference. In particular, Bertone et al. (2005) hypothesized that superior sensitivity for first-order information and inferior sensitivity for second-order information detection in autism are related to atypical neutral connectivity, resulting in excessive lateral inhibition. Here, the first-order information perception can be considered as simple processing and the second-order information as complex, since the latter recruits more extensive neural circuitry and additional processing prior to orientation identification (Samson et al., 2006). In the domain of pitch perception, the simple versus complex hierarchy of analysis can be differentiated in the auditory cortex (Griffiths, 2001). Spectrally complex sounds require a larger neural complexity than pure tones (Scott & Johnsrude, 2003). At a macro level, the main finding of enhanced nonspeech pitch perception ability in ASD provides support for the neural complexity hypothesis since auditory perception can be divided into first-order information processing in the broader context of language processing. At a micro level, our meta-analysis found that the processing advantage in ASD tends to be more prominent in tasks using isolated pitch than in tasks using pitch interval, which is also in line with the statements of neural complexity hypothesis. Compared with isolated pitch, pitch interval contains more frequency components, and its detection requires more conscious access to information stored in memory.

In summary, although local processing bias for pitch processing shows evidence in support of EPF and neural complexity hypothesis, it may or may not stem from deficits in global processing as predicted by WCC, which emphasizes the top-down processing deficit at the global level of integration. Refined experimental designs are needed to further investigate the interactive/independent mechanisms in the process of “true global–local processing” in autistic individuals.

Limitations and Implications

Our systematic review and meta-analysis has several limitations. First, though the number of studies included in our review is adequate, it is quite limited for the moderator analysis as not all the studies reported the data for the key factors of interest. Therefore, caution is needed to interpret the results of moderator analysis. Second, autistic participants in the majority of the included studies in our meta-analysis were diagnosed with classical autism or Asperger’s syndrome, whereas behavioral studies about sensory sensitivity were not available for disorders on the other side on the spectrum, such as Rett syndrome, fragile X syndrome, or Angelman syndrome, which is poorly representative of the majority of the autism spectrum as currently defined (Mottron et al., 2021; Neklyudova et al., 2022). However, previous studies suggested that auditory hypersensitivity also exists in these syndromic forms of ASD (Neklyudova et al., 2022). There is a need to depict a more integrated picture of sensory processing in ASD with more syndromic forms being taken into consideration, which may also deepen our understanding toward the underlying genetic mechanisms associated with hyper- or hyposensory sensitivity in ASD and the high heterogeneity across the spectrum. Third, the majority of previous studies focused on pitch perception in autistic individuals from nontonal language backgrounds. Cross-linguistic studies have indicated that people with tonal language backgrounds tend to have superior pitch perception abilities. This processing advantage can be ascribed to experience-dependent neuroplasticity, suggesting that early sensory encoding of pitch is modulated by prior auditory experience and language learning (Chandrasekaran et al., 2014; Lau et al., 2021). If that is the case, it will be of great interest to include tonal language learning or musical training as the candidate for interventions to compensate for the impaired linguistic pitch processing related to ASD. As there were only two studies (out of 22) that enrolled tonal language speakers, our meta-analysis failed to discover a significant effect of tonal language background on pitch processing. Moreover, future research should take full consideration of participants’ musical training experiences, since musical experience may be a strong confounder associated with pitch processing ability. Fourth, there is a paucity of pitch perception studies on autism under adverse listening conditions, and autistic individuals with hearing impairments are noticeably absent in this research field. Whether pitch perception advantage could be preserved in complex listening conditions or be extended to autistic individuals with hearing loss in comparison with counterparts without ASD remains unclear. Answers to these questions will help gain a more precise understanding of auditory perception ability in ASD. Finally, the scope of the current review was limited to behavioral studies. Some neuropsychological studies also provide evidence for superior lower level processing ability such as enhanced reactivity during nonspeech pitch processing in autism (Gomot et al., 2002). In a similar vein, Yu et al. (2015) also demonstrated domain specificity of enhanced neural sensitivity to nonspeech pitch information in ASD from tonal language background. However, counter examples have also been reported as the advantage of autistic individuals in processing nonspeech pitch over TD people failed to be observed among Cantonese-speaking children (J. Zhang et al., 2019). Recent studies further suggest that hyper- and hyposensitive responses in ASD could occur in the processing of the same auditory stimuli, depending on the time window and attentional orientation/disengagement with the early responses showing enhanced sensitivity and the late responses showing reduced and delayed activity (Haigh et al., 2022; Hudac et al., 2018; Yu et al., 2018). Given the age-dependent changes and influences of speech-onset delay that affects a significant portion of autistic children, future studies need to implement a longitudinal design and combine both behavioral and neurophysiological measures in examining the developmental changes in lower level pitch processing in relation to both nonspeech and speech stimuli to further our knowledge of the underlying mechanisms in regard to hypersensitivity of auditory stimuli in ASD and deepen our understanding toward ASD phenotypes and early diagnosis of ASD (Ding & Zhang, 2023).

Conclusions

This study provides the first systematic review and meta-analysis in the area of pitch processing in individuals with ASD, covering articles on pitch perception of nonspeech sounds in individuals with ASD compared with TD controls. The results indicate slightly enhanced ability in autistic individuals’ overall performance in auditory pitch perception. Moderator analysis indicates that the developmental trajectory is different between autistic individuals and their neurotypical counterparts in pitch processing, and nonverbal ability can be a significant contributor to the lower level processing advantage and local processing bias in ASD. The results provide a tentative suggestion that nonverbal ability may serve as a potential neurobehavioral marker for subtyping of autism.

Theoretically, our results corroborate the EPF model and neural complexity hypothesis. Further evidence is needed to confirm WCC claims on global processing disadvantages. Future research using auditory and audiovisual stimuli that allow selective attention and independent manipulation of global and local levels can potentially provide more insightful information regarding the altered auditory processing of pitch information in ASD. Moreover, since pitch is the common psychoacoustical attribute in both music and language, there is scientific justification to develop intervention methods to make use of the superior/intact nonspeech pitch processing skills in autism, such as musical training, to compensate for the relatively weaker ability in processing speech sound, such as lexical tone acquisition. We highlight the importance and need to investigate pitch perception in challenging listening conditions while taking individuals with dual diagnoses of ASD and hearing impairments into consideration. Further research employing neurophysiological and brain imaging techniques with a longitudinal design is needed to better understand the nature of the atypical auditory processing in ASD to obtain new insights into the neural mechanisms underlying different developmental trajectories and to help guide auditory-based interventions to improve language, speech communication, and social functioning in ASD.

Data Availability Statement

The data for meta-analysis are accessible at https://osf.io/z4e5g/.

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