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Review

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 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 meta-regression 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 (0.26) in support of enhanced pitch perception in ASD. Moreover, the mean age and non-verbal IQ of participants were found to significantly moderate the between-studies heterogeneity. **Conclusion:** Our study provides the first meta-analysis on auditory pitch perception in ASD and demonstrates the existence of different developmental trajectories between individuals with ASD and neurotypicals. Non-verbal ability can 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 research studies with a longitudinal design are also needed to better understand the nature of the atypical processing in ASD to obtain new insights into the underlying neural mechanisms and to help guide auditory-based interventions for improving language and social functioning.

Keywords: pitch perception; autism spectrum disorder; meta-analysis

1. Introduction

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 DSM-V (American Psychiatric Association, 2013), including hyper- and hypo- sensitivity to visual (e.g., bright lights) and auditory stimuli (e.g., crowd noises; Tomchek & Dunn, 2007). In the auditory domain, individuals with autism may demonstrate impaired, intact, or enhanced processing skills (Kellerman et al., 2005; O'Connor, 2012; Ouimet et al., 2012). To be specific, individuals with ASD tend to show impairments in tasks that require higher-level information processing such as phoneme categorization, linguistic prosody recognition, speech-in-noise perception, and multisensory integration (Zhang et al., 2019; Alcantara et al., 2004; Groen et al., 2009; DePape et al., 2012). However, when discriminating simpler auditory stimuli without contextual information, they are more likely to show intact or enhanced processing ability (Heaton, 2003; Bonnel et al., 2003, 2010; 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 Weak Central Coherence (WCC) theory proposes that autism can be characterized by a cognitive style that biases processing towards 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 constituent elements. The Central Coherence (CC) refers to the tendency that typically developing people (TD) 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; Happé, 1999; Happé & Frith, 2006). By contrast, individuals with ASD are more likely to be absorbed in details and fractions and unable to extract the whole ideas and information structures from segmental information. Happé (1997) demonstrated that this weak central coherence might be a universal characteristic of all individuals with autism, 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 which 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 over-development 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 or deficit (Mottron et al., 2006; Mottron et al., 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 (Levin & Lord, 1975; Laukka et al., 2005). An extensive body of literature has established that pitch processing at the auditory brainstem as well as 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 (Giuliano et al. 2011; Bent et al., 2006; Bidelman et al., 2013). By contrast, deficient 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 (Russo et al., 2008; Hubbard & Trauner, 2007).

Understanding the characteristics of atypical pitch processing in ASD is of great significance in both theory and practice. Unlike the reported pitch processing deficits 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 (Bouvet et al., 2016; DePape et al., 2012; Mottron et al., 2013; Masataka, 2017), 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 with ASD. 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 individuals with ASD 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 discriminating pitch differences in linguistic and nonlinguistic sounds in individuals with ASD (e,g., Yu et al., 2015). Such distinctions in pitch processing also extend to the production domain, as a recent autism study demonstrates pitch imitation problems only in the speech context but not the nonspeech stimuli (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 in ASD individuals' pitch processing in the melodic context, including discriminating pitch change in a melody (Mottron et al., 2000; Stanutz et al., 2014), identification of 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 ASD and TD participants in pitch height discrimination (Globerson et al., 2015; Mayer et al., 2016; Cheng et al., 2017), pitch labelling and pitch chord disembedding (Altgassen et al., 2005), pitch direction detection (Heaton, 2005; Heaton, Williams, et al., 2008; Globerson et al., 2015; Germain et al., 2019), pitch contour discrimination (Foxton et al., 2003; Heaton, 2005; Jiang et al., 2015; Schelinski & von Kriegstein, 2019; Jamey et al., 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 ASD participants 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 towards complex speech stimuli in autism are consistently reported, it remains controversial whether individuals with autism 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 (ERFs) 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 children with autism, 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, the evidence for the superiority in these abilities in autism is rather weak. Individuals with autism 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 importance for evidence-based theory and practice to identify relevant studies systematically and conduct a meta-analysis of the different results with suitable theoretical frameworks to better describe auditory processing characteristics of ASD individuals and guide auditory-based interventions that aim to alleviate auditory processing and language problems in ASD. A systematic review with meta-analysis has the advantage of allowing a better synthesis of the available data by analyzing the overall average effect and investigate the size and consistency with respect to the differences between the ASD and TD populations on the selected research topic of interest. This is particularly valuable considering the fact that the auditory research studies are generally limited by small sample sizes and high heterogeneity of sample characteristics of the participants. The statistical tools in the meta-analysis can objectively elucidate the pooling effects as well as 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 Table 1) (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: (1) To investigate whether ASD individuals have enhanced pitch processing ability, compared with typically developing participants; (2) To identify the potential factors associated with the disparate findings in pitch processing of nonspeech stimuli in individuals with ASD; (3) To assess the explanatory power of the leading theoretical accounts in the domain of pitch processing in ASD.

2. Methods

2.1. Inclusion and Exclusion Criteria

2.1.1. Types of Studies

The studies eligible for inclusion in this review must specifically examine the pitch perception ability of individuals with ASD compared with a matched control group. Studies exclusively 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 to allow for further effect size calculations (e.g., M, SD 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.

2.1.2. Types of Participants

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

2.1.3. Outcome measures

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

2.1.4. Quality Assessment

We assessed study quality using the standard quality assessment (SQA) 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., Item 5, Item 6 and

Item 7) were not applicable for the included studies, so these three items were not assessed. Two authors rated the studies independently.

2.2. 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, verbal IQ (i.e., WASI and PPVT/BPVS) and non-verbal IQ (i.e., WASI and RSPM/RM), the score of SCQ (i.e., Social Communication Questionnaire), AQ (i.e., Autism spectrum Quotient), participants' language background (tonal language or non-tonal language), task paradigm (pitch contour discrimination task, pitch chord disembedding task, pitch contour identification task, pitch direction recognition task, pitch height discrimination task, pitch labelling task, pitch memory task, pitch naming task), stimuli form (isolated tone, pitch interval, 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 (absolute pitch or relative pitch), year of publication, region (Europe, North America, Asia).

2.3. 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: 1) "ASD OR autism OR Asperger OR HFA", AND; 2) "pitch OR speech", AND; 3) "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 so as to identify additional potential studies.

2.4. Study Selection and Data Extraction

In total, 2487 potentially eligible articles were identified in the process of database search. 1850 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 detected 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 Fig.1 for the description of selection process). Data were extracted from the 22 included studies concerning the following elements: (1) general task characteristics (e.g., task design, stimuli modality, response option, (2) demographic information of participants (e.g., age, gender, IQ, language background), (3) major statistic results (e.g., performance of experimental and control groups).

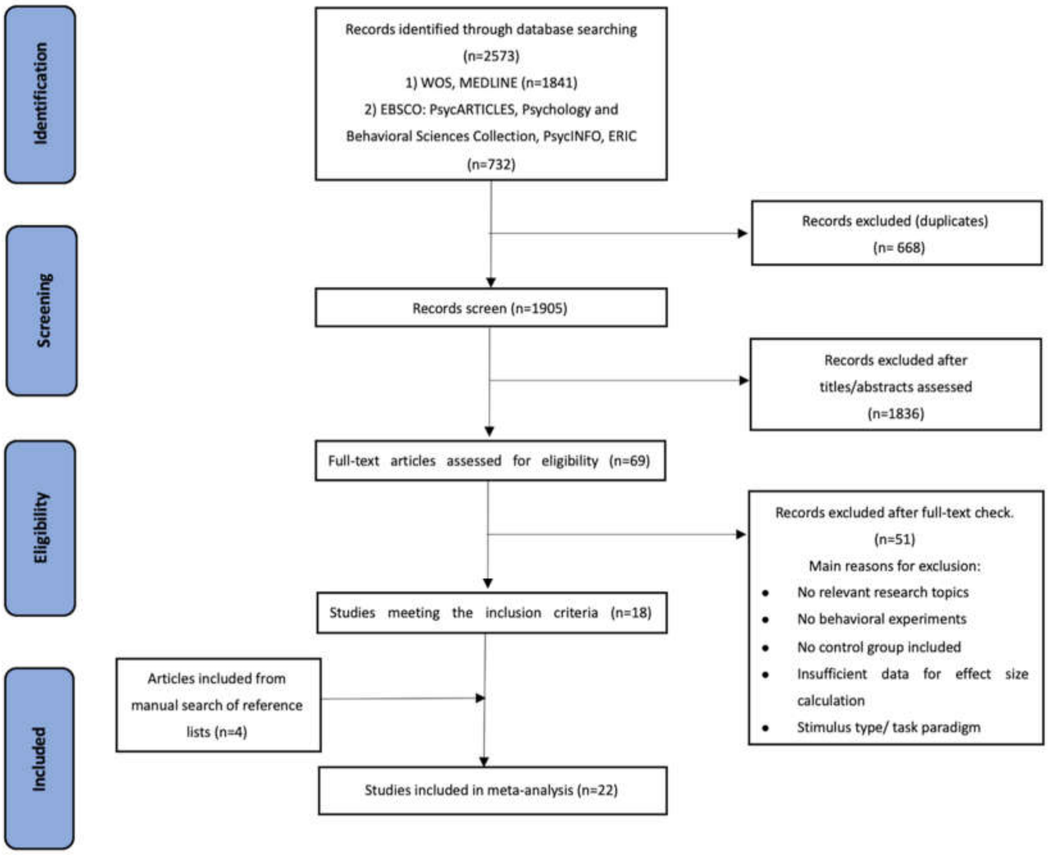

Figure 1. Flow diagram for the different phases of the systematic review and meta-analysis.

2.5. 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 were calculated as standardized mean differences with Hedges *g*, which offers the same interpretation as Cohen's *d*. Considering that included studies varied in group sizes, and the majority recruited smaller sample sizes in ASD group, so Hedge's *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-study 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-study 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 value of 25%, 50% and 75% are interpreted as low, moderate and substantial degrees of heterogeneity (Higgins et al., 2003). Given that between-study 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 does not overlap with the confidence interval 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 detected publication bias by drawing contour-enhanced funnel plots (Peter et al., 2008) and quantifying the funnel plot asymmetry by Egger's test. A significant result of Egger's test means a substantial asymmetry, thereby the publication bias (Egger et al., 1997). If publication bias was found, the trim-and-fill method (Duval & Tweedie, 2000) was applied, providing effect sizes adjusted for publication bias.

Meta-regression 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 meta-regression analyses provided that information was available for a sufficient number of studies (≥4) (Velikonja et al., 2019). The regression coefficients (β-values), the Q_{model} (Q_M) statistics, and the p values were reported. The proportion of variability explained by the moderator (R^2) was also calculated to quantify the magnitude of the relationship of the significant moderator to the estimated effect (Borenstein et al., 2011).

3. Results

3.1. Description of Included Studies

Twenty-two articles published from 1998 to 2021 were eligible for inclusion in the quantitative meta-analysis. Supplemental Table 2 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 [SD] 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 (6 studies, [27.27%]), and the rest three studies were conducted in China (2), Israel (1) respectively. English (18 studies) was the language used by the majority of the included studies, and the rest were Hebrew (1), Germany (1), Mandarin (1) and Cantonese (1). 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 non-tonal languages (languages use pitch to convey word meaning, e.g., English, Hebrew, Germany) significantly outnumbered those (2) in tonal languages (languages where the meaning of words is affected by the lexical tone, e.g., Mandarin Chinese, Cantonese (Yip, 2002)).

The sample sizes (both TD group and ASD group) varied greatly among studies, ranging from 10 participants (Heaton, Davis and 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. The task paradigms used in the 33 tasks can be grouped into eight broad categories, investigating pitch contour discrimination ability (8 studies), pitch height discrimination ability (8), pitch memory ability (5), pitch direction recognition ability (4), pitch chord disembedding ability (3), pitch labelling ability (2), pitch contour identification (2) as well as pitch naming ability (1). The majority of included studies presented participants with only one stimulus modality (i.e., auditory), while 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 (6), pitch interval/ tone pair (9), and melodic contour (18).

The included studies had a mean quality index score of 0.87 (*SD* = 0.06, range: 0.68 - 0.95). The results of the quality assessment of the included studies are provided in Supplemental Table 3. The interrater correlation coefficient (using Spearman correlation; Gwet, 2014) between the two raters was 0.72. Disagreements were resolved by follow-up discussion to reach a consensus.

3.2. Overall Performance of Individuals with ASD on Pitch Processing

Supplemental Table 3 presents the summary results concerning the overall accuracy of ASD participants on pitch processing of nonspeech stimuli compared with that of TD participants in each task. Fig.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 to 0.43, $p < 0.005$; Fig.2). The between-study heterogeneity was significant (Q (32) = 68.96, $p < 0.005$), 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 ($I^2 = 53.6\%$). The pooled effect confidence interval, stretching from $g = 0.10$ to $g = 0.43$, 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 (Supplemental Fig.1). The results of outlier analysis and influence analysis pointed to the same direction. Thus, the three studies were potential outliers that may distort the effect size estimate, as well as precision. After removing outliers, the standardized mean effect size remained nearly small to medium (Hedges g = 0.24, 95% CI 0.10 to 0.39, $p < 0.005$; Supplemental Fig.2) and I^2 shrunk considerably to the low to moderate heterogeneity, from 53.6% to 34.2%.

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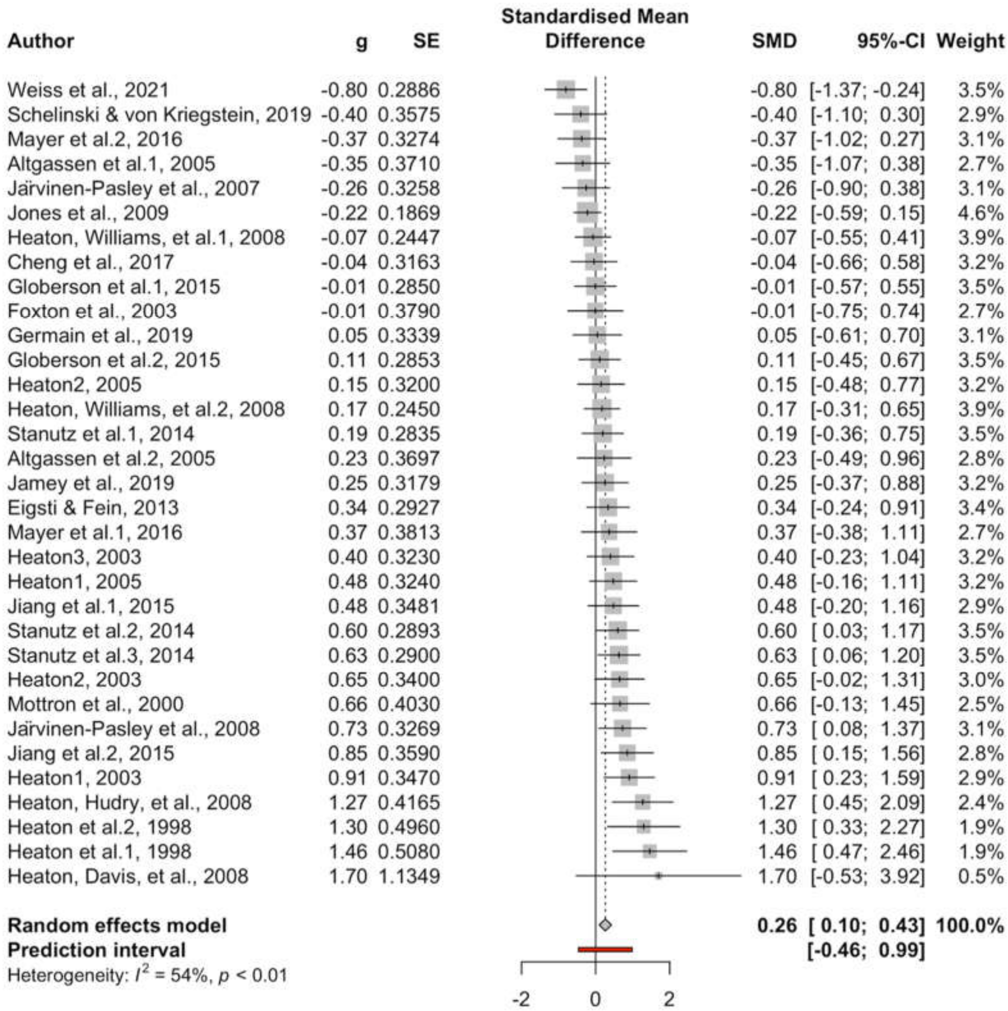

Figure 2. Forest plot with effect size (Hedge' *g*) and confidence intervals for included studies. Grey squares depict individual effect sizes of pitch processing in ASD compared with TD, with sizes indicating the relative weight of each study's effect size estimate to the analysis. Black diamond reflects the overall pooling effect across studies.

For publication bias, visual inspection of the contour-enhanced funnel plot distinguished asymmetry (Supplemental Fig.3). The result of Egger's test was significant (p < 0.005). In the trim and fill analysis, the procedure identified and trimmed eight studies (Supplemental Fig.4), assuming that our initial results might be overestimated due to publication bias. The adjusted effect became much smaller (Hedges g = 0.09, 95% CI -0.08 to 0.27, p = 0.30).

3.3. Moderators

Meta-regressions revealed that among the included moderators, year of publication (Q_M (1) = 8.12 R^2 = 27.14%, p = 0.004), mean age (Q_M (1) = 5.72, R^2 = 22.60%, p = 0.017), nonverbal ability (RSPM/RM) (Q_M (1) = 4.77, R^2 = 91.45%, p = 0.027) significantly explained the between-study heterogeneity. Moreover, compared with pitch interval, isolated tone as the stimulus form can significantly explain the heterogeneity between studies (p = 0.046). To further investigate the difference among three stimulus forms, we calculated the pooled effect size separately according to stimulus form. The pooled effect size of studies using isolated tone is the highest (Hedges g = 0.69, 95% CI 0.08 to 1.29, p < 0.05), followed by melodic contour (Hedge g = 0.28, 95% CI 0.043 to 0.53, p < 0.05), and pitch interval is the lowest (Hedge g = 0.04, 95% CI -0.14 to 0.21, p = 0.68). The other variables did not account for the between-study heterogeneity (Supplemental Table 4). Effect size difference was not significantly correlated with the percentage of men (Q_M (1) = 0.94, p = 0.33), full-scale IQ (Q_M (1) =1.78, p = 0.18), verbal IQ (WASI: Q_M (1) = 0.21, p = 0.65; PPVT/BPVS: Q_M (1) = 0.01, p = 0.91), nonverbal IQ (WASI: Q_M (1) = 0.44, p = 0.51), AQ (Q_M (1) = 1.82, p = 0.18), SCQ (Q_M (1) = 2.99, p = 0.08), task type (Q_M (7) = 5.36, p = 0.62), stimulus form (Q_M (2) = 4.09, p = 0.13), number of options (Q_M (1) = 0.55, p = 0.46), stimulus modality (Q_M (1) = 2.57, p = 0.11), number of trials (Q_M (1) = 0.05, p = 0.83), whether it was absolute pitch or relative pitch (Q_M (1) = 0.94, p = 0.33), region (Q_M (2) = 0.08, p = 0.96).

4. Discussion

4.1. Evidence for Enhanced Pitch Perception Ability in ASD

The present systematic review and meta-analysis provides the first analysis on whether individuals with ASD show enhanced ability in processing pitch in nonspeech sounds compared with typically developing individuals and investigates the potential factors that may account for the differences in the findings among the eligible studies in the literature. While the results indicate that individuals with ASD 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 participants with ASD and detected a small-to-medium positive effect size (0.26), suggesting that there were indeed certain differences between individuals with ASD and typically developing 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 increased to above 0.05. This indicates that there was a potential substantial influence of publication bias. Therefore, one cannot rule out the possibility that studies with non-significant results or small effect sizes have been deprived of the opportunity of publication and cannot be integrated into our meta-analysis. Before correction of the potential publication bias, the results suggest that individuals with ASD possess better pitch processing ability, which is in line with the statements of the EPF model and the WCC theory. Individuals with ASD 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 (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 individuals with autism 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 while behavioral studies in ASD tended to show intact or enhanced ability in pitch memory, labeling, discrimination, and contour change detection, the evidence for an enhancement or superiority in these abilities was rather weak.

Enhanced pitch processing ability coexists with deficient speech functioning in ASD. This concurrent enhanced and decreased performance in autism is of particular interest when considering any links between auditory processing and social abilities. 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 (Mottron & Burack, 2001; Mottron et al., 2006; Germain et al., 2019). 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 hyper-acuity 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 hamper the processing of speech sounds at a higher level (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, while complex stimuli and demanding listening conditions can cause more disruption and place greater strains on cognitive load. It is worth noting that individuals with ASD often exhibit deficits in executive attention that handles the suppression of competing sensory input streams (Dunlop et al., 2016). Therefore, the uneven attentional divide attributed 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 the accumulating evidence that individuals with ASD show enhanced or intact spectral perception, temporal perception ability in ASD is reported to be impaired (Huang et al., 2018; Wallace & Happe, 2008). Gap detection testing has constantly found that individuals with autism need longer gaps to identify stimuli (Bhatara et al., 2013), while gap detection ability was associated with lessened phonological awareness and deficient speech-in-noise perception (Foss-Feig et al., 2017), which thereby relates to the impaired 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 detected pitch perception superiority in ASD is widely reported to be domain-specific, which may be rooted in disorder in sensory, cognitive or social processes. However, 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 et al., 2013; Molnar-Szakacs & Heaton, 2012), the evidence for superior pitch perception ability in our meta-analysis could provide some justification or motivation to include musical training as a candidate for non-verbal interventions to help develop linguistic, communicative and social skills (Janzen & Thaut, 2018; Yan et al., 2021).

4.2. Influential Factors of Pitch Perception in Autism

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

4.2.1. 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, and non-verbal IQ, AQ, 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 children with ASD (Kern et al., 2006). Foster et al. (2016) tested the performance of ASD children and neurotypical controls when judging local and global pitch structure. They found a group difference in the age trajectory of the global interference effect and a less sensitivity to global interference in ASD at younger ages compared with neurotypical controls. The reduction in sensitivity to interference from global information in ASD may contribute to the increased attention to piecemeal information and the superior lower-level auditory perceptual ability in ASD, especially at their younger ages. One important caveat here is that the developmental trajectory is different between individuals with ASD and their neurotypical counterparts. While pitch discrimination ability is enhanced in childhood in ASD and remains stable over development, there is a reversal of the developmental pattern in typically developing 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 with 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 individuals 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 non-verbal IQ (RSPM/RM) was a significant contributor for the between-study heterogeneity. However, no significance was found for FIQ, verbal IQ or non-verbal IQ (WASI). Here, the positive correlation between non-verbal 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 autism group was positively associated with non-verbal cognitive intelligence. Mayer et al. (2016) further indicated that non-verbal intelligence had a direct effect on the efficiency with which individuals with autism allocate their attentional resources. Together, the positive correlation between pitch processing and non-verbal ability in autism may reflect the more effective allocation of attentional resources in individuals with higher non-verbal abilities.

Similar correlation results have been widely reported between non-verbal 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 non-verbal ability instead of verbal skills in both ASD and TD children (Chowdhury et al., 2017). Note that our moderator analysis revealed significant effects for non-verbal (RAPM/RM) and variability of effect sizes but no significant effect of non-verbal 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 individuals with autism, including participants with a wide range of FIQ, NVIQ, and VIQ can be helpful to determine the role of nonverbal intelligence in explaining individual differences in sensory processing in autism and deepening 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 AQ and SCQ as indicators. Similar to AQ, SCQ (Rutter et al., 2003) is a 40-item parent questionnaire for the screening of ASD symptoms in children. While the majority of the studies reported the 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 with autism who had a history of delayed speech onset (Heaton, Davis and 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 syndrome (Bonnel et al., 2010). Even in the typically developing group, positive correlations between pitch discrimination and scores on the AQ 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 ASD participants for the studies in our systematic review ranged from higher-functioning to lower-functioning with varying levels of clinical severity. But neither SCQ nor AQ scores of the ASD groups showed a significant result in the moderator analyses. Only SCQ scores showed a trending association (p = 0.08) with effect size variation. Again, caution is needed for the interpretation of these null findings as the number of eligible studies which provided information on scores of SCQ and AQ was rather small. Given the trend statistics, it is reasonable to conjecture that if there are more studies with reported SCQ and AQ scores, a significant correlation may be found between clinical severity in ASD and pitch perception ability.

Compared with non-tonal language speakers, neurotypical individuals with tonal language backgrounds tend to have superior pitch processing abilities. This processing advantage in the normal 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 non-tonal 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 there were only two ASD studies with tonal language speaker participants 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.

4.2.2. 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 (absolute/relative pitch), 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 (pitch contour discrimination, pitch chord disembedding, pitch contour identification, pitch direction recognition, pitch height discrimination, pitch labelling, pitch memory, pitch naming). 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 labelling and pitch chord disembedding (Altgassen et al., 2005), while no processing advantage was found in autism in pitch chord disembedding (Heaton, 2003), pitch contour discrimination (Jiang et al., 2015), as well as pitch contour perception (Foster et al., 2016). However, no significance was detected in our analyses, suggesting differences in task paradigm did not contribute to between-study heterogeneity.

Our meta-analysis divided the studies included in the systematic review into two groups based on whether they tested relative pitch (RP) or absolute pitch (AP). AP refers to the ability to identify the pitch of an isolated tone out of context, while 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 absolute pitch in ASD (DePape et al., 2012; Bouvet et al., 2016). 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, 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, meta-regression results suggested that the stimulus type (AP vs. RP) was not associated with between-study 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 (2008) that the talent of AP could be linked to a genetically distinct subset of children with autism 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, 2005). The isolated pitch has an absolute height value, pairs of isolated pitches form pitch intervals, and the direction that intervals take 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-study heterogeneity. Isolated pitch relies more on AP perception being a rather local way of processing while interval recognition relies on RP perception with a relatively global way of processing (Mottron et al., 2000; Altgassen et al., 2005; Germain et al., 2019). 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-study heterogeneity. Altgassen et al. (2005) had also failed to find a local processing bias in all children with autism as comparable performance was found when presented with isolated tones and chords in their research.

Previous studies suggest that autistic people have problems integrating information across auditory and visual modalities. This multisensory integration (MSI) 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 significance between the two. This is not unexpected. Some research suggested that while multisensory processing may be impaired for more complex phonological processes, the integration of low-level information is intact in autism (van der Smagt et al., 2007) and early non-linguistic 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 (Zhang et al., 2021). However, this result should be interpreted with caution since the failure in detecting significance may result from the limited number of eligible studies.

4.3. Non-verbal Ability is Related to Local Processing Bias in ASD

Our meta-analysis results demonstrate that non-verbal ability play a significant role in pitch perception for individuals with ASD. 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 non-verbal ability is highly heterogeneous across the spectrum. Different behavioral performances across individuals with ranging non-verbal abilities may be ascribed to genetically meaningful variation in autism. Whether different cognitive profiles such as non-verbal 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 non-verbal 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 non-verbal abilities in participants with ASD, suggesting a high rate of uneven cognitive development in children with ASD. Furthermore, our findings further support and explain the association of greater social impairment with discrepantly higher nonverbal abilities. Higher non-verbal 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 as well as local pitch processing on the higher-level melodic pitch task. Therefore, the cumulative evidence indicates that non-verbal ability is a significant contributor to the lower-level processing advantage and local processing bias in ASD. Non-verbal ability may serve as a potential neuro-behavioral 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.

4.4. Paucity of Research on Pitch Perception in Autistic People with Hearing Impairments and in Complex Listening Conditions

Our systematic review found that few existing studies investigate the individuals with hearing loss despite the fact that hearing loss is much more common in individuals with ASD 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 ten 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 (ADOS-2) 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 further 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 hyper-reactivity to noise (Rosenhall et al., 1999), show impaired ability in segregating the dichotic pitch stimuli into distinct auditory objects which 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 non-vocal pitch discrimination ability correlated positively with speech-in-noise perception abilities (Glasberg & Moore, 1989). In a similar vein, Schelinski et al. (2020) also emphasized the role of F0 processing ability in understanding speech with competing speakers. These divergent findings raise the important question 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 proception ability in ASD.

4.5. Theoretical Explanation for Enhanced Pitch Perception in ASD

The current meta-analysis detected a small-to-medium positive pooled effect size, indicating that individuals with ASD have enhanced pitch perception ability for non-speech sounds in comparison with typically developing 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 can provide support for the EPF model and the WCC theory. Moreover, the pooled effect size of studies using isolated tone was medium to large (Hedges g = 0.69), while those using pitch interval and melodic pitch were only 0.28 and 0.04. Isolated tone relies more on a rather local processing style (Mottron et al., 2000; Altgassen et al., 2005; Germain et al., 2019), implying an over-development of lower-level perceptual operations in autism. According to EPF, although individuals with ASD 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 as 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, they developed a new set of auditory stimuli that allowed independent manipulation of two levels. This independence between levels permits the examination of both the global advantage and global interference effects (unlike interval-contour stimuli) (Foster et al., 2016). More studies allowing independent manipulation of global and local levels are needed to improve our knowledge of global vs. local processing styles in ASD.

Although WCC and EPF have their theoretical value 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 non-autistics 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 second-order information as complex since the latter recruits more extensive neutral circuitry as well as 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, 2003). 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 insolated pitch, pitch interval contains more frequency components than isolated pitch and the detection requires more conscious access to information stored in memory.

In sum, while 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 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 individuals with ASD.

4.6. Limitations and Implications

Our meta-analysis in this systematic review 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 report the data for the key factors of interest. Therefore, caution is necessary to interpret the results of moderator analysis. Second, the majority of previous studies focused on pitch perception in individuals with ASD from non-tonal language backgrounds. Crosslinguistic 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 tone 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) on tone language speakers, our meta-analysis failed to discover a significant effect of tonal language background on pitch processing. Moreover, there is a paucity of pitch perception studies on autism under adverse listening conditions, and autistic individuals with hearing impairments are noticeably absent from this area. 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 depict a more comprehensive picture of auditory proception 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 individuals with ASD in processing nonspeech pitch over typically developing people failed to be observed among Cantonese-speaking children (Zhang et al., 2019). Given the age-dependent changes and influences of speech-onset-delay which affects a significant portion of children with ASD, future studies need to implement a longitudinal design and combine both behavioral and neurophysiological measures in examining the developmental changes in domain-specific lower-level pitch processing in relation to both nonspeech and speech stimuli to further our knowledge of the nature in regard to hyper-sensitivity of auditory stimuli in ASD and deepen our understanding towards ASD phenotypes and early diagnosis of ASD.

5. Conclusion

The present study provides the first systematic review and meta-analysis in the area of pitch processing in individuals with ASD, covering articles on pitch perception in nonspeech sounds in individuals with ASD compared with TD individuals. 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 individuals with ASD and their neurotypical counterparts in pitch processing and non-verbal 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 neuro-behavioral marker for subtyping of autism. Our results are consistent with the EPF model and neural complexity hypothesis. Further evidence is needed to confirm WCC claims about 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, which may facilitate their social and communicative skills. 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 the different developmental trajectories, and to help guide auditory-based interventions to improve language, speech communication and social functioning.

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