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ARTICLES

Music perception, sound production, and their relationships in bowed string instrumentalists: A systematic review

Percepción musical, producción sonora y su relación en instrumentistas de cuerda frotada: Una revisión sistemática

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Abstract

Music perception and sound production are very important skills in the formation of musicians who play bowed string instruments. The purpose of this literature review is to summarize the knowledge of these abilities and the relationship between them. A systematic literature review using the PRISMA protocol has been conducted. Studies were extracted from Sage, Scopus, WoS, and JSTOR using the terms: music, tuning, intonation, and perception. A total of 1819 studies were found, and 29 were selected. The studies analyzed covered the period from 1937 to 2019 and the levels from elementary school to professional players. The analysis applied six predetermined categories to data extracted from the selected studies showing at best a moderate relationship between both abilities. The data could confirm an increase in the relationship between the two skills due to factors such as learning and developmental stages. However, these stages are related to automation of psychomotor schemas and cognitive development, as well as the development of the musical expression of the students. Several apparent trends related to music perception and sound production are discussed.

Key words: Music Perception; Sound Production; Bowed String Players; Systematic Review.

Resumen

La percepción musical y la producción de sonido son habilidades muy importantes en la formación de músicos que tocan instrumentos de cuerda frotada. El propósito de esta revisión bibliográfica es resumir el conocimiento de estas habilidades y la relación entre ellas. Se ha realizado una revisión sistemática de la literatura utilizando el protocolo PRISMA. Los estudios se extrajeron de Sage, Scopus, WoS y JSTOR utilizando los términos: música, afinación, entonación y percepción. Se encontraron un total de 1819 estudios y se seleccionaron 29. Los estudios analizados abarcaron el período de 1937 a 2019 y los niveles desde la escuela primaria hasta los instrumentistas profesionales. El análisis aplicó seis categorías predeterminadas a los datos extraídos de los estudios seleccionados mostrando, en el mejor de los casos, una relación moderada entre ambas habilidades. Los datos podrían confirmar un aumento en la relación entre las dos habilidades debido a factores como el aprendizaje y las etapas de desarrollo. No obstante, estas etapas están relacionadas con la automatización de esquemas psicomotores y el desarrollo cognitivo, así como con el desarrollo de la expresión musical de los estudiantes. Se discuten varias tendencias aparentes relacionadas con la percepción musical y la producción de sonido.

Palabras clave: percepción musical, producción sonora; instrumentistas de cuerda frotada; revisión sistemática.

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1. Introduction

Music perception and sound production abilities are very important facets for instrumental music students, especially those studying bowed string instruments. Therefore, students spend a lot of time developing these abilities. Students who are well educated in music perception have the ability to make accurate judgements about the quality of their own and others' performance (Rakowski, 1985; Sorenson, 2021). This would suggest the importance of perceptual ability and would subordinate sound production to it (Morrison, & Fyk, 2002). Accordingly, string players should base their performance on their own perceptual achievement (Ha, 2015; Hallam, & Bautista, 2018). However, research with wind players and singers does not seem to corroborate a relationship between music perception and sound production (Ballard, 2011; Byo *et al.*, 2011; Ely, 1992; Geringer, 1978, 1983; Morrison, 2000; Silvey *et al.*, 2019; Yarbrough *et al.*, 1995, 1997; Worthy, 2000). The purpose of this systematic review was to learn more about the music perception and sound production abilities of bowed string players and to find out whether any relationships exist between them. An understanding of the relationships between the two abilities, and their limitations, may provide important information for educators to adjust their demands to facilitate learners' ability development.

1.1. Music perception

The concept of music perception encompasses various aural factors related to sound (Deutsch, 2007). For example, music perception includes pitch discrimination. Pitch discrimination is "the ability to distinguish between two successive pitches or two dissimilar examples of a single pitch" (Morrison, & Fyk, 2002, p.183). Pitch discrimination uses comparative judgements of pitch (sharp-low), direction (ascending-descending), and/or quantity (cents). The concept of music perception also includes higher-level features, such as the perception of intonation (Deutsch, 2007). The perception of intonation is the way in which people perceive the pitch of a set of sounds (Geringer *et al.*, 2012). This skill values more information and therefore can be considered more complex. The perception of intonation also uses comparative judgements, but "it concerns the performance of pitch within musical contexts" (Yarbrough, & Ballard, 1990, p.19). This is the reason for using sound patterns instead of pairs of sounds.

Several factors can affect the music perception ability of bowed string players. Musical training, for example, positively affects pitch discrimination (Micheyl *et al.*, 2006; Sorenson, 2021). However, sometimes people with musical training perform poorly in pitch discrimination tasks. Vurma and Ross (2006) suggest that experienced musicians are not able to appreciate differences of an eighth of a tone. Other studies suggest that trained individuals may perceive intervals differently (Hubbard, 2022; Russo, & Thompson, 2005b; Samplaski, 2005; Wong *et al.*, 2021) and that this may occur even when considering different high and low pitch registers (Gockel, & Carylon, 2021; Guest, & Oxenham, 2020; Russo, & Thompson, 2005b; Samplaski, 2005).

Interval identification is an important factor for detecting intonation mismatches. Recent studies related the ability to identify intervals to the ability to detect intonation mismatches in short melodies (Stambaugh, & Nichols, 2020). Moreover, the ability to identify intervals is an important predictor of achievement in melodic dictation (Nichols, & Springer, 2022). In addition, beginner students may benefit more from working on several intervals at once than one at a time (Wong *et al.*, 2021).

Another factor for achievement in pitch discrimination could be the kind of instrument played (Loh, 2007; Micheyl *et al.*, 2006, but see for absence of implications Wolf & Kopiez, 2018). The type of instrument is also usually related to a certain tuning system. The tuning system used to carry out the analysis can be another factor affecting results, because they are determined on the basis of the tuning system to which they are compared (Hubbard, 2022). Throughout history, many tuning systems with different divisions of the octave have been developed (Apel, 1974; Barbour, 1951; Grove, 2009). However, equal temperament, Pythagorean, and just tuning systems (Table 1) have received the most attention and scientific interest (e.g., Ballard, 2011; Geringer, 2018; Springer *et al.*, 2021).

Table 1. Differences in cents between pairs of intonation systems using the C major Scale: equally tempered (T); just system (J); Pythagorean tuning system (P)

Note	T-J	T-P	P-J
C	0	0	0
D	-4	-4	0
E	+14	-8	-22
F	+2	+2	0
G	-2	-2	0
A	+16	-6	-22
B	+12	-10	-22
C	0	0	0

Font: Loosen (1994)

The timbre factor also seems to affect the achievement of pitch discrimination. Differences of +15 to +20 cents[2] have been observed in the perception of the same sound with instrumental or vocal timbre (Vurma *et al.*, 2010). There also seems to be a tendency to perceive high-pitched sounds with a brighter timbre than low-pitched sounds (Russo, & Thompson, 2005a).

Musical accompaniment also seems to affect the perceptual achievement of intonation. Musical stimuli with accompaniment backing seem to be perceived better, but achievement decreases when the pitch register becomes higher (Geringer, 1978). However, wind and percussion students perceived music stimuli better without any backing (Springer, & Silvey, 2018).

1.2. Sound production[3]

Studies investigating achievement in sound production often use concurrent strategies. The method of adjustment or pitch matching consists of adjusting the pitch of a sound using it or a different pitch as a reference. This method involves perceptual evaluation and practical action. Another strategy is the production of sound, which is used to measure achievement (intonation) in musical contexts. This method also requires perceptual evaluation and practical action (Morrison, & Fyk, 2002).

[2] Cent has been included here and elsewhere as a factor for measuring deviation because (1) it is shown to be so in the studies reviewed and (2) to facilitate the reader's understanding.

[3] Studies using the method of adjustment or pitch matching and intonation achievement have been included in sound production. Although these works involve a pitch discrimination stage, the final production phase includes the assessment of sound production.

There are several factors that can affect the sound production achievement of bowed string players. One such factor is the absence of automation. Beginner bowed string students are limited in their achievement in sound production. This is because it is essential to assimilate (automate) certain mental schemas before they can pay sufficient attention to intonation (Hallam, 2001; Morrison, & Fyk, 2002). These fundamental mental schemas are based on: (a) mechanical development (actions of timing, sequencing, and spatial organization of movement) (Zatorre *et al.*, 2007); and (b) the association of graphic representations (musical notes) and/or an aural (sound elements) stimulus to the mechanical factor. The development and assimilation of these primary and future schemes will allow for focus on intonation, the musical content to be transmitted, and for more effective processes to achieve the desired result.

Tuning a bowed string instrument is a complex task (Powell, 2010). This ability seems to require more experience than playing with the proper rhythm or keeping the beat (Hallam, 2001). It could be the reason why some good students in ear training make productive mismatches that tend to compress the size of small intervals and stretch the size of large ones (Rakowski, 1985). Perhaps these mismatches are related to the preference for a tuning system other than equal temperament, even though equal temperament has predominated in formal music education due to the use of the piano (Loh, 2007). Another cause for the mismatches could be the lack of systematization in the teaching of intonation, as seems to occur in the field of teaching brass instruments (Tejada *et al.*, 2022). However, considering the relevance a sound may have within the tonality, its pitch may be intentionally raised or lowered (Gardner, 2020). This is related to the Expressive Intonation, a concept coined by the cellist Pablo Casals (Yarbrough, & Ballard, 1990). The intervals that make up a melody are not static elements but are handled differently to convey the musical content. Several pedagogical and research studies support the expressive and adaptive function of intonation (e.g., Galamian, 2013; Ha, 2015; Kanno, 2003).

Musical accompaniment is another factor that can affect achievement in sound production. Some students perform better when using harmonic accompaniments (Bergonzi, 1997; Geringer, 1978), while others do not (Laux, 2015; Springer *et al.*, 2021). However, wind (Springer *et al.*, 2021) and string students (Zabanal, 2020) believe that accompaniment helps them in their intonation work. In addition, it is usually a widely implemented resource in the pedagogical literature (López-Calatayud *et al.*, 2022).

2. Method

2.1. Design and data collection

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses protocol (PRISMA) (Page *et al.*, 2021). The search was conducted in February 2022 in four databases: Sage, Scopus, WoS and JSTOR. The search criteria were: music* AND tuning* AND intonation* AND perception*. Likewise, the references section of the selected studies was also checked for new sources of interest. This practice is not new and allows the inclusion of relevant studies (Oliveira *et al.*, 2021).

The main focus in the first phase of analysis was on the title, keywords, and abstract to check the eligibility of the studies. The studies that passed this phase were read in full and assessed for inclusion. An Excel document was created to record the filtering process.

The author of this study carried out on two different occasions all the phases of the filtering process (period of time between them of six weeks). Studies where there was disagreement were reviewed to reach a consensus. Once the number of studies was decided, the information was extracted. This process was also carried out on two occasions (time period of six weeks between them). Finally, the categories in which the works would be classified were created.

2.2. Eligibility criteria

The following reasons for inclusion were considered:

- The perceptual ability of string players.
- Both tuning and intonation abilities were addressed.
- Studies without a time limit.
- Studies from any educational and professional level.
- Studies in which the authors, despite not isolating the results of each instrumental family, indicated that the results did not differ between them.

Some papers were excluded because:

- They consisted of theoretical papers or reviews
- They were not written in English
- Participants were not bowed string players
- The results were not shown separately for bowed string players

3. Results

A total of 1,819 studies were found (Sage, *n* = 727; Scopus, *n* = 28; Web of Science, *n* = 37; and JSTOR, *n* = 1027). Fifty-four duplicate studies were removed, remaining 1,765. Of these, 1,525 were eliminated as they were not related to the objective of this review. Theoretical studies or reviews (*n* = 57), studies written in non-English (*n* = 1), and studies that did not involve bowed string players or did not detail their results (*n* = 163) were also removed, leaving 19 studies.

After this selection, 10 studies from other sources (papers known by the author and papers found in the review of the reference sections) were added to the list. The number of studies included was 29. Figure 1 shows the filtering process. Appendix A presents a structured summary of the 29 studies included in this review.

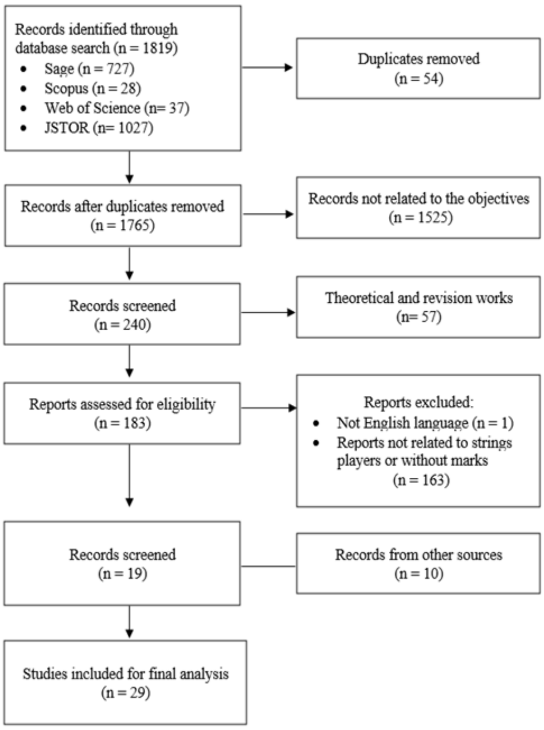

Figure 1. Results of the PRISMA-based filtering process

The 29 studies reviewed in this work span from 1937 to the present. However, the number of studies is greater in the decade from 1990 to 1999 and from 2010 to 2019, with nine investigations in each case, than in the other decades (Figure 2).

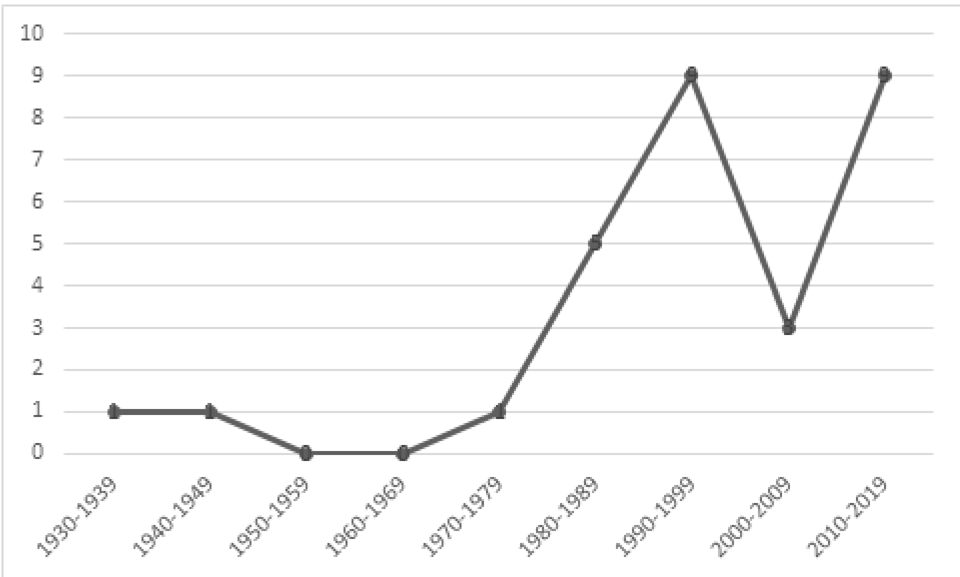

Figure 2. Temporal distribution of the studies reviewed

The works reviewed dealt with music perception (n = 5), sound production (n = 20), or both (n = 4), and all of them focused on bowed string players.

Researchers in general have been more interested in university level (*n* = 7) and professional level (*n* = 6) than in lower levels (initial, *n* = 1; middle school, *n* = 2; and high school, *n* = 2). In other studies, participants were reported to have the sufficient experience (*n* = 3), but the experience they had was not specified. Participants in 8 studies had varying levels of proficiency. Researchers have also been more interested in cross sectional studies on the whole.

The 29 studies investigated music perception and sound production of bowed string players. They were classified into six categories based on the topics extracted:

a. Specific training.
b. Tuning systems.
c. Achievement.
d. Timbre as a factor.
e. *Vibrato*.
f. The relationship between music perception and sound production.

The studies belonging to each of the analytical categories are detailed below.

3.1. Specific training

Fogarty *et al.* (1996) studied the effect of auditory training music lessons after 4-8 months on the perception of intonation of university students. The results showed no significant differences in the ability of students (*n* = 71) to detect intonation mismatches. The authors suggested the students had good perceptual ability and it was sufficiently developed not to show significant improvement after one academic year of training.

Other included work has investigated the effect of specific training on sound production. Smith (1995) investigated the effect on achievement with the instrument derived from training with supporting software. Middle school students (*n* = 80) were randomized into groups. The instrumental practice was assessed by three experts using a 5-point rating scale. The results showed that the group that worked with the software significantly improved their sound production with the instrument.

3.2. Tuning system

Loosen (1995) investigated the perception of intonation in professional violinists (*n* = 7) judging pairs of scales (C4-C5) tuned in different musical systems (Pythagorean, equal temperament, and just system). The results suggested that the string players did not conform to any particular system, although some tendency towards the Pythagorean system was found (55% > equal temperament; 93% > just system).

Six included studies investigated the sound production of bowed string players looking for trends toward particular tuning systems. However, the results of these studies differ. In some studies, string players did not conform to any specific tuning system. Professional violinists (*n* = 7) who tuned the pitch of C Major scalar patterns deviated similarly from Pythagorean and equal temperament systems (Loosen, 1994). In another study, professional violinists (*n* = 8) also deviated similarly from Pythagorean and equal temperament (Loosen, 1993).

Some string players did not conform completely to any particular system but were closer to the Pythagorean system. Greene (1937) analyzed the performance of experienced violinists (*n* = 6) at various intervals. The results showed a tendency towards the Pythagorean system. This tendency coincides with the performance of other experienced string players (*n* = 24) of solo and ensemble melodies (Nickerson, 1949). Likewise, the analysis of several recordings of professional violinists (*n* = 8) without accompaniment also suggested that string players did not adopt any particular system continuously. However, performances were better suited to the Pythagorean system (Geringer, 2018).

The lack of consensus[4] from string players toward some tuning system is more evident in a different study. Geringer *et al.* (2013) analyzed fragments of recordings of professional violinists (*n* = 4) with piano accompaniment. The results suggested that: (a) two violinists were closer to the Pythagorean system in most of the major intervals, but not in the minor ones; (b) another violinist was between Pythagorean and equal temperament, and (c) another violinist was closer to equal temperament.

3.3. Achievement

Four studies included in this review were dedicated to music perception. All of them suggest that experienced players make mismatches in their perceptual performance. In Parker's (1983) study, university violin students (*n* = 15) and piano students (*n* = 15) indicated whether they heard one or two pure tones sounding at the same time. The pitch of one of the sounds was raised, while the other sound remained at its original pitch. The pupils perceived the two sounds differently when the difference between them was about +20 cents. In another study (Rosner, 1999), experienced players (*n* = 6) perceived intervals differently. For example, large intervals (8th) were perceived more stretching; medium intervals (4th) were perceived more stretching in low pitch register and more compressing in high pitch register; and small intervals (2nd) were perceived more compressing in extreme pitch registers. Nevertheless, violin students in their last year of middle school (*n* = 46) were able to detect mismatches with margins between +5 and +8 cents (Hopkins[5], 2015). However, high school students (*n* = 60) and college students and professionals (*n* = 60) tend to lower the pitch when producing intonation mismatches (Geringer, & Witt, 1985).

Researchers of seventeen studies that discussed sound production suggest that string players make mismatches in their performances. An analysis of recordings of professional violinists (*n* = 4) with piano accompaniment showed a mismatch between -17 and +26 cents relative to the accompaniment (Geringer *et al.*, 2013). Other recordings of professional violinists (*n* = 8) without accompaniment were more accurate, with a mismatch of ±10 cents (Geringer, 2018). The mismatch of professional players (*n* = 60) tends to raise the pitch (Geringer, & Witt, 1985). That raising of the pitch may be greater at the end than at the beginning of each sound (Sogin, 1989) or greater in the descending direction than in the ascending direction (Loosen, 1993; Sogin, 1989). The mismatch of professional players (*n* = 8) is also greater in the high pitch register than in the middle pitch register, but with minimal differences between both registers (Loosen, 1993).

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[4] The lack of consensus in instrumental practice is addressed. However, the same lack of consensus exists among researchers analyzing interpretations.

[5] Although this work has used the pitch matching or method of adjustment strategy, it has been included here to maintain the logic of this research that seeks to compare pitch perception and production.

College students also tend to raise the pitch (Geringer, & Allen, 2004; Geringer *et al.*, 2005; Geringer, & Witt, 1985; Kantorski, 1986; Papich, & Rainbow, 1974; Salzberg, 1980; Sogin, 1989; Yarbrough, & Ballard, 1990). However, there are some college students who tend to decrease the sound frequency of sounds (Hopkins, 2014), while for other students, accuracy is almost complete (Geringer *et al.*, 2014). The tendency to raise the pitch is greater in high than in low pitch registers with values around three eighths of a tone (Kantorski, 1986). However, Geringer *et al.* (2014) suggest that in high pitch register there is a tendency to lower the pitch. Likewise, the type of instruction also seems to affect the mismatch of college students, although the achievement is similar across a variety of musical tasks (Salzberg, 1980). The mismatch of the students seems to be greater in descending direction (Kantorski, 1986), but another study shows no significant differences related to direction (Yarbrough, & Ballard, 1990). Musical unison accompaniment is significantly more effective (less mismatch) than two-octave, two-octave plus third or at a third interval accompaniment (Kantorski, 1986). Furthermore, some fingerings seem to have significant implications for the achievement of slur sounds (Geringer *et al.*, 2005).

Middle and high school students also tend to raise the pitch (Geringer & Allen, 2004; Geringer, & Witt, 1985; Zabanal, 2019). However, some students tend to lower the pitch in high pitch register (Geringer *et al.*, 2014). The size of the mismatch also maybe greater for sounds in low pitch register (Hamann *et al.*, 2006; Hopkins, 2014, 2015). The use or non-use of musical accompaniment does not seem to affect the intonation of students at this level (Zabanal, 2019).

Beginning string students (*n* = 8, college level of another instrument) also tend to raise the pitch (Sogin, 1997). Students in their last year of elementary school (*n* = 48) also produce mismatches, especially in low-pitch register (Hopkins, 2014).

3.4. Timbre as a factor

The effect of timbre on the musical perception of bowed string players has been investigated in two studies. Geringer *et al.* (2012) recorded the performance of Bach's Ave Maria by a violinist, a trumpeter, and a singer with piano accompaniment. The pitch for first two bars of the accompaniment were in tune while the remaining bars were raised or lowered (10, 20 and 30 cents) with respect to the accompaniment. Middle school and high school students (*n* = 71) rated the stable pitches consistently. However, students were more sensitive to progressive mismatches when the violinist raise the pitch. The students consistently rated all performances where the pitch was progressively reduced, but at -30 cents the violin pitch was rated as the most out-of-tune.

Geringer et al. (2014) investigated how students perceive pitches from a violin or a cello timbre. High school students (*n* = 180) and university students (*n* = 60) consistently perceived stable pitches with violin and cello timbre. However, sounds raising (+15 cents) and lowering the pitch (-15 cents) were perceived more raised and lowered, respectively.

Two studies investigated the effect of timbre on the sound production of bowed string players. However, both works suggest that the use of different timbres for tuning the instrument has no effect on the results. For example, tuning to A=440 Hz with the timbre of a violin or by an electronic tuner had no effect on the accuracy of high school students (*n* = 139) (Alexander, 2011). This is consistent with the tuning results of middle school students (*n* = 60) (Hamann *et al.*, 2006).

3.5. *Vibrato*

Two studies investigated the effect of the *vibrato* variable on music perception. The study by Brown and Vaughn (1996) reports several experiments. In one experiment, graduated students (*n* = 5) and a professional (*n* = 1) judged the similarity between sounds with and without *vibrato*. The results suggested that sounds with and without *vibrato* were perceived similarly. In another experiment, a professional violist also perceived the same sounds in a similar way. However, in the study by Geringer *et al.* (2014), high school students (*n* = 126) and university students (*n* = 126) perceived sounds with *vibrato* significantly lower in pitch than those without vib *vibrato* rato. Likewise, sounds that had been intentionally raised and lowered in pitch were perceived as more raised and lowered respectively. This was for sounds with and without *vibrato*.

Six included studies investigated the effect of the *vibrato* variable on the sound production of the instrument. Several of them suggest no differences in the production of sounds with and without *vibrato* (Brown, & Vaughn, 1996; Geringer *et al.*, 2005; Sogin, 1989). However, Geringer and Allen (2004) found that high school students (*n* = 20) and music majors (*n* = 20) raise the pitch of sounds without *vibrato* more than sounds with *vibrato*. Students also performed worse with intonation adjustment when the vibrato condition was applied. Finally, music majors tended to raise the pitch of sounds with and without vibrato more than high school students. Geringer *et al.* (2014) also found significant differences in the production of sounds with and without *vibrato*. High school students (*n* = 180) and university students (*n* = 60) tended to lower the pitch of sounds with vibrato more than sounds without *vibrato*. Another study interested in the achievement of sounds with different vibrato and different timbre suggests that music majors (*n* = 72) consistently adjust the pitch of sounds with different *vibrato* and timbre (cello and violin) conditions (Geringer *et al.*, 2010).

3.6. Relationship between music perception and sound production

Three of the studies included explicitly investigated the relationship between music perception and sound production. Another study did not intentionally look for a relationship, but an apparent relationship can be seen in their data.

In Geringer and Witt's (1985) study, high school students (*n* = 60) and college students and professionals (*n* = 60) made a perceptual judgement and matched the A = 440 Hz sound of their instrument with that of an oboe. The results showed a degree of relationship between pitch discrimination and sound production. For college students and professionals, the relationship was higher (62%) than for high school students (43%).

In the study of Brown and Vaughn (1996) a professional violist (*n* = 1) played a musical pattern which was analyzed for achievement with and without *vibrato*. The same pattern was resampled and judged perceptually by the violist. The results of both tests suggested that the violist had a mismatch of about 10 cents.

In Hopkins' (2015) study, middle school students (*n* = 46) adjusted the pitch of different pairs of sounds and tuned the open string sounds of two violins. The violins sounds could be raising or lowering the pitch. The results suggested a moderate relationship between these abilities. In addition, pitch discrimination tasks were more accurate than tuning tasks. The latter is consistent with the results of the study by Geringer *et al.* (2014). The study by Geringer *et al.* (2014) also suggests that sounds where the pitch has been intentionally raised or lowered are perceived and tuned even more raised and lowered, respectively. Sounds without mismatch are perceived and adjusted consistently.

4. Discussion and conclusions

The purpose of this literature review was to summarize the knowledge on the music perception and sound production abilities of bowed string players to detect relationships between the two abilities. The studies reviewed cover from 1937 to the present, but it is from 1990 to 1999 and from 2010 to 2019 when researchers have been more interested in these issues. Therefore, this work supports the current interest and can also provide relevant data and conclusions to researchers. The most frequently used design in the research was cross sectional, and researchers have been generally more interested in sound production than in music perception or both together.

The findings emerging from the music perception studies reviewed suggest that perception achievement of violin students in their last year of middle school (Hopkins, 2015) is more accurate than that of university students (Parker, 1983). This is unexpected considering that increased experience would intuitively lead to greater achievement (Micheyl *et al.*, 2006; Sorenson, 2021). This is possibly due to the fact that these university students had reached their own maximum level of ability (Fogarty *et al.*, 1996). However, the mismatch rates of music perception of string players are lower than those of experienced vocalists (Vurma, & Ross, 2006). This may support that the practice of specific instruments has implications for perceptual achievement (Loh, 2007; Micheyl *et al.*, 2006). Perhaps the mismatches rates of bowed string players are related to the fact that they do not fully conform to any particular tuning system, although it tends towards the Pythagorean system (Loosen, 1995).

The variable timbre does not seem to affect how different sounds are perceived as long as their pitch is not manipulated. When the pitch is intentionally manipulated, students are more sensitive to the timbre of their own instrumental family (Geringer *et al.*, 2012). This contrasts with results from players other than bowed string players, who showed perceptual achievement with differences between +15 and +20 cents (Vurma *et al.*, 2010). On the other hand, bowed string players tend to perceive sounds with and without *vibrato* consistently (Brown & Vaughn, 1996; Geringer *et al.*, 2014).

The findings emerging from the studies reviewed regarding instrumental sound production show that string players make mismatches in their performances and these mismatches indicate a tendency to raise the pitch. This tendency to raise the pitch is found among professionals (Geringer, 2018; Geringer *et al.*, 2013; Geringer, & Witt, 1985; Loosen, 1993; Sogin, 1989), university students (Geringer, & Allen, 2004; Geringer *et al.*, 2005; Geringer, & Witt, 1985; Hopkins, 2014; Kantorski, 1986; Papich, & Rainbow, 1974; Salzberg, 1980; Sogin, 1989; Yarbrough, & Ballard, 1990), and high school and middle school students (Geringer, & Allen, 2004; Geringer, & Witt, 1985; Zabanal, 2019) and beginning students (Sogin, 1997), although there are also exceptions (Hamann *et al.*, 2006; Hopkins, 2014, 2015).

The data from the studies reviewed regarding instrumental sound production suggest that achievement in sound production seems to be composed of four developmental phases related to automatization and musical expression. The first developmental phase includes beginning learners, who produce mismatches between one eighth and three eighths of a tone (Hopkins, 2014; Sogin, 1997). This may be because they have not automated certain psychomotor and cognitive schemas (Hallam, 2001; Morrison, & Fyk, 2002; Zatorre *et al.*, 2007). The second phase of development includes middle and high school students, who considerably improve the previous mismatch rates (Zabanal, 2019). This is possibly due to the automation of psychomotor schemas and cognitive development. This allows the students to focus on intonation (Hallam, 2001; Morrison, & Fyk, 2002). The third phase of development includes university students, who increase their previous achievements (Geringer *et al.*, 2005; Kantorski, 1986). The data also suggest that university students may seek expressive intonation (Galamian, 2013; Ha, 2015; Kanno, 2003; Yarbrough, & Ballard, 1990). This is so considering that the mismatch is around one eighth of a tone (Salzberg, 1980), but can be as high as three eighths of a tone (Kantorski, 1986). Finally, the fourth phase includes professional players, who increase achievement in sound production (Geringer, 2018; Loosen, 1993; Sogin, 1989). They do so by possibly incorporating their own stylistic considerations and tendency (Geringer, 2018; Geringer *et al.*, 2013; Greene, 1937; Nickerson, 1949) or not (Geringer *et al.*, 2013; Loosen, 1993, 1994) towards some particular tuning system. In any case, learning support increases sound production achievement (Smith, 1995), which progresses with experience (Geringer *et al.*, 2014; Hopkins, 2014; Zabanal, 2019). However, this developmental approach to bowed string players' learning needs to be supported by studies investigating how students' progress through the proposed levels to a possible intentional use of expressive intonation.

Musical accompaniment does not seem to benefit achievement in sound production of middle and high school students (Zabanal, 2019), university students (Kantorski, 1986), or professionals (Geringer *et al.*, 2013). This is consistent with the results of other studies in which accompaniment had no effect in sound production (Laux, 2015; Springer *et al.*, 2021). However, there are students for whom accompaniment is beneficial (Bergonzi, 1997; Geringer, 1978). Perhaps that is the reason why accompaniment is so present in didactic literature (López Calatayud *et al.*, 2022). Other bowed string students believe that the use of accompaniment improves their achievement in scales and arpeggios (Zabanal, 2020).

Two trends seem to emerge from the data of the included studies examining the achievement in sound production of bowed string players. One tendency is related to timbre. The use of different timbres to adjust the pitch of sounds does not affect achievement in sound production (Alexander, 2011; Hamann *et al.*, 2006). This holds even when the *vibrato* variable is involved (Geringer *et al.*, 2010). Another tendency is related with the *vibrato* variable. Bowed string players produce sounds with and without *vibrato* consistently (Brown & Vaughn, 1996; Geringer *et al.*, 2005; Sogin, 1989). Other studies do not support the *vibrato* tendency (Geringer, & Allen, 2004; Geringer *et al.*, 2014). However, the results of these studies suggest a mismatch rate of sounds with and without *vibrato* of about 10 cents. This amount has been considered appropriate for categorizing an optimal sound production (Geringer, & Witt, 1985) and perception (Geringer *et al.*, 2012), and could therefore support this sound production trend.

Several studies that have explicitly investigated the relationship between music perception and sound production in bowed string players suggest that it is moderate at best (Geringer, & Witt, 1985; Hopkins, 2015). This coincides with other players for whom there was no significant relationship between the two factors (Ballard, 2011; Byo *et al.*, 2011; Ely, 1992; Geringer, 1978, 1983; Morrison, 2000; Silvey *et al.*, 2019; Yarbrough *et al.*, 1995, 1997; Worthy, 2000). However, it is worth considering that the achievement of a professional violist is similar in perceptual and productive tasks (Brown, & Vaughn, 1996).

The intra-category analysis provides more information on patterns of relationship between music perception and sound production. For example, string players do not fully conform to any particular tuning system either perceptually or productively, but if they favour any, it is predominantly the Pythagorean system (Geringer, 2018; Geringer *et al.*, 2013; Greene 1937; Loosen, 1995; Nickerson, 1949). A comparison of the achievements of students of last year of middle school, high school students, university students and professionals suggest that perceptual (Hopkins, 2015; Parker, 1983, Rosner, 1999) and productive (Geringer, & Allen, 2004; Geringer *et al.*, 2013; Geringer *et al.*, 2014; Hopkins, 2015; Kantorski, 1986; Salzberg, 1980; Zabanal, 2019) achievements of students of last year of middle school and high school students are better. Perhaps the expressive intonation discussed above has some implication. Likewise, timbre seems to have no effect on the perceptual and productive ability of bowed string players when sounds are not manipulated (Alexander, 2011; Geringer *et al.*, 2012; Geringer *et al.*, 2014; Hamann *et al.*, 2006).

This systematic review provides relevant data for educators and researchers interested in the music perception and sound production abilities of bowed string players. Musical instrument educators at different levels may find in the results of this work relevant information to support or guide their teaching practice. For example, specific training programs can be of significant benefit to the educational development of some students, apparently up to the intermediate level. The preference of bowed string players for equal temperament may favor joint practice with instruments based on that musical system. Preference for a different musical system may result in intonation needing greater attention when practicing with those instruments based on equal temperament. This requires educators to make students aware of the differences between these musical systems. In this way, students will be able to improve their practice with these instruments (Galamian, 2013). The studies reviewed suggest that the achievement of bowed string players is mainly conditioned by automation. The higher the degree of automation, the higher the level of cognitive load release. This automation gradually allows students to focus their attention on the sound quality task and on more advanced aspects (Hallam, 2001; Morrison, & Fyk, 2002), as expressive intonation. Educators should accurately assess the level of automatization achieved by their students and consequently provide feedback on the productive quality of their practice. Comments about productive goals that are far beyond the student's current capabilities can have a negative influence on their interest in learning the instrument (McPherson, 2005). Timbre and *vibrato* are powerful tools that can have an effect on sound. Knowing how these tools affect string players perceptually and productively is important for their formative development. Finally, assessing an incremental relationship between musical perception and sound production implies that more attention should be paid to the coordinated work of these two skills in the field of training (Tejada *et al.*, 2022). Furthermore, researchers may value the conclusions of this work and feel motivated to support or refute them. In any case, this will help to broaden our knowledge of the relationship between music perception and sound production in bowed string players.

The number of studies and the differences in their conditions and results make it difficult to recognize further apparent relationships. The effect of instructional programs and the use or non-use of *vibrato* on perceptual and productive ability are areas that require more attention. The development of studies that investigate together music perception and sound production is necessary to support the trends and conclusions of this work, which sometimes are based on a minimal number of studies. Furthermore, investigating both abilities together is beneficial to understanding how they are related. This work is also limited by the eligibility criteria. The inclusion of studies involving bowed string players, even if their results were not isolated, could have had different implications for the results. These limitations must be considered, as they may condition the results of this systematic review.

Music perception and sound production are very important aspects for bowed string players. The studies reviewed that directly investigated the relationship between these two skills do not show a significant relationship between them. Nevertheless, it could be appropriate to consider this relationship incrementally more important. This is so when considering the data from the different studies analyzed in this work. The students gradually improve their productive achievement, to the extent that they automate certain psychomotor and cognitive schemes, and to do this they require perceptual abilities that highlight the productive improvements to be made. Moreover, the relationship between music perception and sound production is more present when most of the work is done at home without help, where one relies on one's abilities supported by teaching. The expressive intonation itself can also be seen as supporting this relationship. A high level of perception is required to recognize the small margins that sometimes occur in music performance and their productive application to the instrument. However, it is necessary to develop more studies that provide information on the relationship between music perception and sound production in bowed string players.

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Supplementary material

Appendix A. Studies examined in this review

Reference	Participants	Design	Procedures	Aims	Key findings	Achievement in cents
Alexander (2011)	HS (*N* = 139)	CS	MOA	Difference between tuning (A = 440Hz) with violin timbre and an electronic turner	There are no significant differences	NA
Brown and Vaughn (1996)	P (*N* = 1); GS (*N* = 5)	CS; CR	PR; PJ	Achievement in sound production and in music perception of sounds with and without *vibrato*	There are no significant differences in the production and perception achievement of sounds with and without *vibrato*	PR: ±10 cents, PJ: 0-3 cents; with-without *vibrato*: -0.5-4 cents
Fogarty, Buttsworth and Gearing (1996)	US (*N* = 71)	LG	PJ	Effect of classes on achievement in perception of intonation	There are no significant differences	NA
Geringer (2018)	P (*N* = 8)	CS	PR	Tendency towards some tuning system; Achievement in sound production	No clear trend, but tending slightly towards the Pythagorean system. Intra- and interpersonal mismatches are realised	±10 cents
Geringer and Allen (2004)	HS (*N* = 20); MM (*N* = 20)	CS	PR	Achievement in sound production of sounds with and without *vibrato*	Significant differences between age groups and *vibrato* condition and between instrument and finger used. Students were significantly more stable with than without *vibrato*	MM and HS without *vibrato* x̄ +3 and x̄ +0.7; 4th violinists' finger +6.5 cents than others, 2nd and 3rd finger -3-6 cents

Geringer, Allen and MacLeod (2005)	HS (*N* = 20); MM (*N* = 20)	CS	PR	Achievement in sound production of sounds with and without *vibrato*; Achievement in sound production of slur sounds	There are no significant differences between with-without *vibrato*. There are significant differences for slur sounds	From -2 to +10 cents
Geringer, MacLeod and Allen (2010)	MM (*N* = 72)	CS	MOA	Achievement in sound production of sounds with and without *vibrato* and different timbres	There are no significant differences	cello: +4.36 cents, violin: +5.33 cents
Geringer, MacLeod and Ellis (2013)	P (*N* = 4)	CS	PR	Tendency towards some tuning system; Achievement in sound production	Two violinists tended towards the Pythagorean System, one between Pythagorean and equal temperament and one toward equal temperament. Differences in achievement in sound production	From -17 to +26 cents
Geringer, MacLeod and Ellis (2014)	HS (*N* = 126); US (*N* = 126)	CS	PJ; MOA	Achievement in sound production of sounds with and without *vibrato*	Minimal mismatches in sound production in high register. Sound production are more positive and negative when the mismatch is positive or negative. Sounds without mismatch are perceived consistently	High register: -3 and +5 cents. Mismatch: With-without *vibrato* in +15: +7.03 and +10.2. Mismatch -15: -13.4 and 10.5. Without mismatch: -3.01 and +0.1
Geringer, MacLeod and Sasanfar (2012)	MS, HS (*N* = 71)	CS	PJ	Achievement in perception of intonation of sounds with different timbres and progressive mismatches	Timbre does not seem to affect perception of intonation when they are stable sounds, but it does	-10, -20, -30

					when there are mismatches	
Geringer and Witt (1985)	HS (*N* = 60); US (*N* = 60)	CS; CR	PJ; MOA	Relationship between music perception and sound production	Higher relationship in university students and professionals than in high school students. Tendency to raise the pitch than to lower the pitch	NA
Greene (1937)	P (*N* = 6)	CS	PR	Tendency towards some tuning system	Tendency towards the Pythagorean system	NA
Hamann, Lauver and Asher (2006)	MS (*N* = 60)	CS	MOA	Effect produced by different timbres on the achievement in sound production	Trend to lower the pitch of sounds (66%) and minor achievement in the lower pitch frequencies	Lower frequencies: Doble bass: x̄ +25; viola and cello: x̄ +24; and violin: x̄ +21; other strings: x̄ +17 cents
Hopkins (2014)	ES (*N* = 48); MS (*N* = 32); HS (*N* = 36); MM (*N* = 14)	CS	MOA	Achievement in sound production	Trend to lower the pitch. Achievement improves with level pass. Minor achievement in the lower pitch frequencies	58% flat pitch matching responses and 42% sharp pitch matching responses Students' mismatches in last year of elementary school: x̄ 25.9 and x̄ 36.6 cents; middle school students: x̄ 14.4 and x̄ 12.8 cents; high school students: x̄ 18.7 and x̄ 15.5 cents; university students: x̄ 3.5 and x̄

						3.2 cents
Hopkins (2015)	MS (*N* = 46)	CS; CR	MOA; PJ	Relationship between music perception and sound production	Moderate relationship, better perception than production. Tendency to lower the pitch, especially at low pitch frequencies	Mismatches up to 5-8 cents
Kantorski (1986)	UG, GS, and other (*N* = 48)	CS	PR	Achievement in sound production of musical patterns with accompaniment and different pitch registers	Trend to lower the pitch. Higher mismatch in downward direction. Minor mismatch with unison accompaniment	Up to 70 cents mismatch. 18.2 cents descending and 8.8 cents ascending. With unison accompaniment +47.7; two octaves: 55.8; two octaves plus third: 63.2; from third: accompaniment 68.5 cents
Loosen (1993)	P (*N* = 8)	CS	PR	Tendency towards some tuning system	No clear trend between the Pythagorean and the equal temperament. Lower achievement in high pitch registers and in the descending direction	Pythagorean: 8.5; 9.8, equal temperament: 9; 10.4, just: 14.7; 14.2, High pitch register: +10;16, Middle: +8; 15, Descending: +9; 16, Ascending: +8; 14 cents
Loosen (1994)	P (*N* = 7)	CS	PR	Tendency towards some tuning system	No clear trend between the Pythagorean and equal temperament	Pythagorean: -3.5 Equal temperament: +4.8 cents
Loosen (1995)	P (*N* = 7)	CS	PJ	Tendency towards some tuning	There is no clear tendency,	NA

				system	but the subjects seem to prefer the Pythagorean to the equal temperament or just system	
Nickerson (1949)	EP (*N* = 24)	CS	PR	Tendency towards some tuning system	Tendency to the Pythagorean system	NA
Papich and Rainbow (1974)	US (*N* = 13)	CS	PR	Achievement in sound production	Tendency to raise the pitch as one moves from one to a higher pitched one. Individually more positive than in ensemble	NA
Parker (1983)	US (*N* = 15)	CS	PJ	Achievement in pitch discrimination	Two sounds are distinguished from a certain mismatch	20 cents
Rosner (1999)	EP (*N* = 6)	CS	PJ	Achievement in music perception	Large intervals stretching, medium intervals stretch in low registers and compress in high registers, small intervals compress at extreme frequencies	NA
Salzberg (1980)	MM (*N* = 50)	CS	PR	Achievement in sound production with and without feedback	Verbal feedback is more Effective. Achievement in sound production of a melody better than a scale, arpeggio or double strings	Verbal feedback: 23.60; instruction with recording: 29.28; with a model: 38.49; free practice: 25.58 cents: Melodies: 26.32; scale: 27.68; arpeggio: 31.45;

						double strings 30.02 cents
Smith (1995)	MS (*N* = 80)	CS	PR	Effect of software training on achievement in sound production	Significant improvements for those who practised with the software	NA
Sogin (1989)	UG, GS, P (*N* = 48)	CS	PR	Achievement in sound production of sounds with and without *vibrato*	Tendency to raise the pitch, specially at the end of sounds. There is no difference between sounds with and without *vibrato*	4-6 cents. End of each sound: Eb: x̄ +7.1; F: x̄ +9.9; G#: x̄ +1.6; A#: x̄ +3.1 cents, Beginning of each sound: Eb: x̄ +2.4; F: x̄ +4.3 cents; G#: x̄ -0.8; A#: x̄ -1.9 cents, With *vibrato*: x̄ +5.5; Without *vibrato* x̄ +4.1
Sogin (1997)	BS (*N* = 8)	CS	PR	Effect of feedback on achievement in sound production	Better achievement by knowing the finger instead of the sound name	Mismatching: 1st finger (x̄ +.31, SD=27.8), 2nd (x̄ +18.6, SD=46.0), 3rd (x̄ +10.3, SD=32.1) and 4th finger (x̄ +3.1, SD =40.2)
Yarbrough & Ballard (1990)	GS (*N* = 17); UG (*N* = 22)	CS	PR	Achievement in sound production	Tendency to raise the pitch. No difference between ascending and descending direction	NA
Zabanal (2019)	MS, HS (*N* = 28)	CS	PR	Effect of accompaniment on achievement in sound production	Tendency to raise the pitch. No difference	13-14 years: x̄ +15.23; 15 years: x̄ +9.15; 16-

		between with or without accompaniment	17 years: $\bar{x}$ +11.76, Accompanied: usage 13-14 years: $\bar{x}$: +15.94; 15 years: $\bar{x}$ + 8.83; 16-17 years $\bar{x}$ +11.23; unaccompanied: 13-14 years: $\bar{x}$ +16.01; 15 years: $\bar{x}$ +8.08; 16-17 years: $\bar{x}$ +11.35 cents

BS: Beginning students. **ES**: Elementary students. **MS**: Middle School. **HS**: High School. **US**: University students. **GS**: Graduated Students. **MM**: Music Majors. **UG**: Undergraduated. **EP**: Experienced players. **CS**: Cross sectional. **CR**: Correlational. **LG**: Longitudinal. **MOA**: Method of adjustment. **PR**: Production. **PJ**: Perceptual judgement