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Keeping the Pitch in Mind:
A Case Study of Intonational Awareness in a Violin Student with Dyscalculia

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Abstract

Bowed-string intonation requires constant self-correction via an internal pitch reference (Keller, 2012; Zatorre et al., 2007), a magnitude-judgment process tied to the intraparietal sulcus (Schwenzer & Mathiak, 2011) – a region known to function atypically in dyscalculia (Kaufmann et al., 2008), possibly compromising pitch monitoring in individual practice. The study asks whether reinforcing this internal reference through multisensory training can improve intonation in a violin student with dyscalculia. Four strategies were combined: vocalization, guided-active listening, kinesthetic interval mapping, and sing-play transfer. Video recordings of lessons and practice were scored by two raters on consistency, self-regulation, and pitch anticipation, alongside self-reflection. Results showed steady gains on all parameters, supporting the role of internal pitch reference training for intonational autonomy in dyscalculia.

Keywords: intonation control, multisensory learning, perceptual–motor transfer, dyscalculia, bowed-string performance

Manter a altura em mente: um estudo de caso sobre a consciência entoacional em um estudante de violino com Discalculia

Resumo

A afinação em cordas friccionadas exige autocorreção constante por meio de uma referência interna de altura (Keller, 2012; Zatorre et al., 2007), um julgamento de magnitude ligado ao sulco intraparietal (Schwenzer & Mathiak, 2011) – região com funcionamento atípico na discalculia (Kaufmann et al., 2008), podendo comprometer o monitoramento da altura na prática individual. O estudo investiga se reforçar essa referência interna por treino multissensorial pode melhorar a afinação em um violinista com discalculia. Combinaram-se quatro estratégias: vocalização, escuta ativa guiada, mapeamento cinestésico de intervalos e transferência cantar-tocar. Gravações em vídeo de aulas e práticas foram avaliadas por dois avaliadores em consistência, autorregulação e antecipação da altura, com autorreflexão. Os resultados mostraram ganhos constantes em todos os parâmetros, apoiando o papel do treino da referência interna para a autonomia entoacional na discalculia.

Palavras-chave: controle de afinação, aprendizagem multissensorial, transferência perceptivo-motora, discalculia, performance em cordas friccionadas.

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Introduction

Achieving accurate intonation is a common objective in music performance, yet mastering it is among the most demanding challenges musicians face (Geringer et al., 2015; Tejada et al., 2022). This is because intonation is not a single ability but a complex cognitive-motor skill that simultaneously places multiple interrelated demands on the performer: it requires not only the ability to perceive and judge pitch differences accurately, but also the capacity to translate that perception into precise physical action (Morrison & Fyk, 2002; Watts et al., 2005). If any of these demands are not fully met, the consequences are instantly audible. Even slight pitch variations can affect the overall perceived quality of a performance.

Since good intonation is widely associated with high-quality performance (Morrison & Fyk, 2002), even small pitch inaccuracies can compromise the listener's overall assessment of a performer's musical ability (Geringer et al., 2015; Geringer & Madsen, 1981). Developing reliable intonational control is therefore an ongoing priority for singers and performers on variable intonation instruments such as winds and bowed-strings, for whom pitch must be actively produced and continuously regulated throughout performance (Seashore, 1938; Johnson, 2004).

For bowed-string players this challenge is compounded further by the nature of the instrument itself, which places additional motor demands on pitch production (Kanno, 2003; Bergonzi, 1997). Meeting these demands requires cognitive and motor resources that are not equally available to all learners. Individual cognitive characteristics can significantly affect how intonation develops (Morrison & Fyk, 2002). This is the case for learners with specific learning disorders, such as dyscalculia, whose neurological profiles may directly interfere with the perceptual, motor, and auditory mechanisms on which intonation control depends (Blanchet & Assaiante, 2022; Castaldi et al., 2024; Kaufmann et al., 2008). Yet the interplay between dyscalculia and intonation development has received remarkably little systematic attention in the research literature, and even less consideration has been given to whether targeted interventions can support its improvement in affected learners — a gap that the present study aims to address.

The Cognitive Sub-skills of Intonation

Accurate intonation may be better understood as the outcome of multiple distinct yet interrelated cognitive, perceptual, and productive sub-skills (Morrison & Fyk, 2002). Among these, one of the first prerequisites is the ability to develop a stable internal representation of the target pitch — what Keller (2012) terms *auditory imagery*. The resulting mental construct, the *auditory image*, guides both the expectation and the execution of sound (Bergonzi, 1997; Keller, 2012). This internal representation is not innate but develops gradually through sustained exposure to accurate musical models, such as listening to professional performers, teachers, and recordings (Cox, 2016). The more detailed and precise this internal representation is, the more reliably it can guide pitch production — encompassing not only the target pitch itself, but its rhythmic, timbral, and expressive qualities, as well as its harmonic relationship with surrounding notes (Keller, 2012). Translating this mental intention into physical action is what Morrison and Fyk (2002) describe as *pitch matching*, understood as the ability to reproduce a target pitch accurately, whether vocally or instrumentally — a process that depends on the development of both aural and motor proficiency. Indeed, in pitch matching, performers must continuously compare the pitch they produce with the pitch they intend to hear. Whenever a discrepancy is detected, motor adjustments are required to bring the produced pitch closer to the intended one. In the early stages of learning, this process of comparison and correction requires continuous, conscious monitoring — a form of closed-loop control, whereby performers rely on ongoing auditory and kinesthetic feedback to modify their movements in real time whenever the pitch produced does not match the intended one (Schmidt & Wrisberg, 2000). With sustained practice, however, these corrective processes become increasingly automatic, allowing a gradual shift towards open-loop control, in which movements can be executed with less conscious supervision, resulting in faster and more fluent performance (Schmidt & Wrisberg, 2000). As conscious auditory monitoring becomes less necessary, performers increasingly rely instead on a kinesthetic memory of intonation: a bodily sense of how an in-tune pitch feels, formed through the association between specific finger positions and their auditory outcomes (Keller, 2012). Over time, this physical sensation becomes increasingly familiar and can contribute to the regulation of future performances.

Yet none of these processes would be possible without the performer's ability to maintain an internal auditory target that can guide performance.

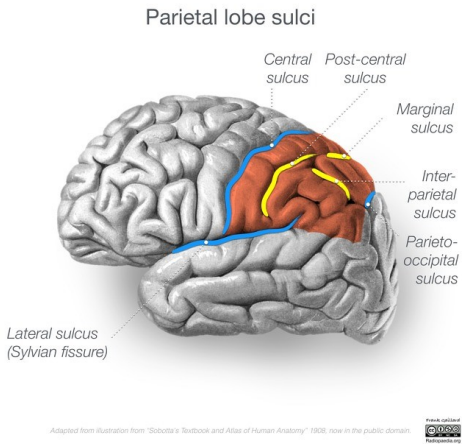
Anticipatory Auditory Imagery and Its Neural Basis

Auditory imagery relies on the interaction of several cognitive and motor mechanisms (Keller, 2012). Working memory is the cognitive resource that makes this possible: it keeps the internal representation of the target pitch alive throughout performance, ensuring it remains available as a guide for motor action. Drawing on this internal representation, the brain mentally rehearses the upcoming movement before any actual motion takes place — simulating the precise physical action needed to produce the intended pitch and preparing the motor system in advance, so that before the finger touches the string, the body is already ready to act (Keller, 2012). Internal models further support this process by generating predictions about the auditory consequences of upcoming movements: forward models anticipate what the movement will sound like before it occurs, while inverse models translate the intended sound into the precise motor commands needed to produce it (Keller, 2012). The interplay of these mechanisms reflects a deeper neural truth: in musicians, imagining a pitch and actually producing it activate the same brain regions — suggesting that, at the level of the brain, auditory imagery and motor execution are deeply interconnected (Zatorre et al., 2007).

Pitch Identification and Its Neural Implications

This auditory imagery can only take place once the target pitch has already been identified. Indeed, this cognitive process is built on *pitch identification*, the ability to mentally locate a specific pitch on a continuous scale of values (Schwenzer & Mathiak, 2011). This process shares key features with the way we process numerical magnitudes. Just as we identify a number by locating it on a mental number line, we identify a pitch by locating it on a continuous mental scale of pitch values — a form of auditory magnitude judgment (Schwenzer & Mathiak, 2011). Neuroimaging evidence supports this overlap: correct pitch identification correlates with activation in the left intraparietal sulcus (IPS) (Schwenzer & Mathiak, 2011), a brain region also recruited during numerical magnitude processing (Dormal & Pesenti, 2009; Butterworth, 1999), (Image 1).

Image 1
Lateral view of the parietal lobe showing the intraparietal sulcus.



Source: Image adapted from Sobotta's Textbook and Atlas of Human Anatomy (1908), reproduced by Radiopaedia.org. Available at: https://radiopaedia.org/articles/intraparietal-sulcus

This shared pattern of neural activation, however, is not equally stable across all learners — a vulnerability most evident in dyscalculia. Classified in the DSM-5-TR as a manifestation of a Specific Learning Disorder with impairment in mathematics (APA, 2022), dyscalculia is characterized by an atypical functioning of the left intraparietal sulcus (Kaufmann et al., 2008). Because pitch identification relies on this same region, this atypical functioning may prevent learners with dyscalculia from forming a stable internal representation of the target pitch (Schwenzer & Mathiak, 2011; Kaufmann et al., 2008), making accurate intonation control more challenging.

Developmental Dyscalculia and Intonation: A Convergent Vulnerability

Altered functioning of the left IPS, however, may not be the only mechanism through which dyscalculia affects intonation development. Recent research has identified impairments in auditory temporal processing in children with dyscalculia, specifically in the perception of time intervals at both sub-second and supra-second scales, suggesting that auditory monitoring processes may also be less reliable in this population (Castaldi et al., 2024).

In addition, research has documented significant motor difficulties in these individuals, including impairments in upper-limb coordination, fine-motor precision, and motor integration,

which may further compromise the execution of accurate instrumental movements (Blanchet & Assaiante, 2022).

Taken together, these findings suggest that dyscalculia may interfere with intonation development through multiple converging pathways. Atypical IPS functioning may compromise the development of stable pitch representations, auditory temporal-processing deficits may reduce the reliability of auditory monitoring, and motor difficulties may affect the physical execution of sound. For learners who play bowed-string instruments — where intonation is largely self-regulated and depends on the coordinated functioning of perceptual, auditory, and motor processes — the cumulative effects of these vulnerabilities may be particularly pronounced. The consequences of these difficulties may therefore be measured not only in missed pitches but also in their impact on the learners who repeatedly experience them.

The Human Cost of Playing Out of Tune: Motivation and Well-being in Learners with Dyscalculia

For bowed-string players with dyscalculia, persistent intonation difficulties may carry deeper implications. Given that intonation is a fundamental skill in bowed-string performance, repeated struggles to achieve and maintain accurate pitch can affect more than performance outcomes. When learners continue to struggle with pitch accuracy despite sustained practice, they may begin to perceive a growing gap between effort and progress — a pattern already linked to frustration, self-doubt, and a diminished sense of competence (Kucian et al., 2018; Rubinsten & Tannock, 2010).

What emerges, therefore, is more than a technical challenge. Over time, such experiences may influence not only musical development, but also learners' willingness to continue engaging with music (Evans & Liu, 2019). These considerations raise important questions regarding the experiences of learners with dyscalculia in bowed-string education. If the perceptual, auditory, motor, and emotional vulnerabilities discussed throughout this chapter do indeed influence intonation development, it becomes essential to understand how these challenges manifest themselves in real educational contexts and how teachers might respond to them effectively.

Research Aims and Objectives

This study aims to investigate the challenges that learners with dyscalculia face in mastering intonation control in bowed-string performance, and to use these insights to develop pedagogical responses that might support them. The following research question guides the study:

Can a multisensory pedagogical intervention targeting internal pitch representations and auditory–motor integration improve intonation control in a bowed-string player with dyscalculia?

This main question is explored through three specific sub-questions, each reflecting a different aspect of intonation control discussed in the theoretical framework.

RQ1. Can a multisensory pedagogical intervention strengthen spatial awareness on the instrument and support the development of automatized finger-placement responses in bowed-string players with dyscalculia?

RQ2. Can a multisensory pedagogical intervention foster the development of intonation self-regulation in bowed-string players with dyscalculia?

RQ3. Can a multisensory pedagogical intervention contribute to improve intonation consistency in bowed-string players with dyscalculia?

Research Design

This study employs a qualitative, exploratory, single-case design with embedded units of analysis (Yin, 2018; Trinchero, 2002), grounded in an interpretive epistemological framework (Denzin & Lincoln, 2011). Case study methodology was adopted for its capacity to generate detailed, contextually meaningful accounts of complex educational phenomena, and for its suitability for exploratory research in underexplored areas (Yin, 2018). A qualitative approach was chosen to gain an in-depth understanding of the student's learning process and the teacher's interpretive responses, rather than to produce generalizable causal claims. The small sample size is consistent with the single-case design and is not intended to support statistical generalization. To ensure the rigor and depth of the findings, a data triangulation strategy was adopted.

This case study is part of an international doctoral research project developed under a joint supervision agreement between xxxxx University (Italy) and xxxx University (Germany). The broader project, conducted across four countries (Italy, Germany,

Austria, and Switzerland), investigates dyslexia and dyscalculia in instrumental music education, focusing on learning processes, educational outcomes, and teachers' pedagogical awareness, with the aim of contributing to the design of inclusive pedagogical approaches that support effective and equitable instrumental learning. Three interconnected pedagogical interventions were designed within this framework: a multisensory intervention designed to reduce cognitive overload during practice through the integration of multiple sensory channels; an embodied practices intervention incorporating *Qigong*-based strategies to support body awareness and manage performance anxiety; an AI-assisted individual practice intervention designed to support students' individual learning and enhance teachers' pedagogical awareness of their students' difficulties.

This study focuses exclusively on multisensory intervention; the comparative findings of the wider project will be reported separately. It is important to acknowledge that this intervention did not take place in isolation; the sample was involved in two other pedagogical interventions concurrently as part of the broader doctoral research project. The presence of these concurrent interventions means that the specific contribution of the multisensory intervention alone cannot be determined. Consequently, this study does not seek to attribute causality to the intervention alone. Instead, the study provides a descriptive, exploratory account of how the intervention was integrated into a complex educational context, and the changes observed in students' intonation development.

Participant

Participants in the broader doctoral research project were recruited through purposive sampling (Patton, 2002), resulting in twelve participants across four European countries: Italy, Germany, Austria, and Switzerland. The present study, however, focuses on a single case selected from this larger group, chosen because it offered a particularly rich and well-documented example of how dyscalculia may intersect with intonation difficulties on a bowed-string instrument. Several factors made this participant especially suitable: her advanced level of instrumental proficiency allowed intonation difficulties to be examined independently of more basic technical limitations; her diagnosis of dyscalculia, formally established in childhood by a qualified specialist, ensured diagnostic clarity; and the fact that the intervention was requested by her own teacher — who

recognized the limits of her conventional pedagogical tools in addressing these difficulties — provided a naturally occurring, ecologically valid context for the study, rather than one constructed for research purposes.

The participant is a 15-year-old female violin student enrolled at the xxxxx conservatory in Switzerland, with eight years of violin study and a well-developed level of instrumental proficiency. She is a native speaker. The student's teacher is an experienced string instrument professional with extensive experience in individual instrumental instruction. Although familiar with the term dyscalculia, she reported limited practical knowledge of its specific features and implications for instrumental learning.

The Intervention

The intervention comprised four interconnected multisensory strategies designed to support the processes underlying intonation control in learners with dyscalculia, designed to target the learner's neurocognitive profile (Bergonzi, 1997; Pardue & McPherson, 2019; López-Calatayud & Tejada, 2023): *vocalization*, targeting the development of stable pitch representations; *guided active listening*, addressing the monitoring of auditory feedback; *kinesthetic mapping*, aimed at strengthening the association between finger placement and pitch; and *sing-play*, designed to integrate the gains of the previous three strategies within the context of real performance. The strategies were implemented progressively across the intervention period, with each building on the gains of the previous one, and were applied both during lessons and during the student's individual practice sessions.

Vocalization

The first strategy drew on the Kodály principle that singing constitutes the basis of musical development in instrumental learning — a principle that has been specifically extended to string pedagogy, where vocalizing pitches and intervals before playing them is used to support the development of stable pitch representations and promote accurate intonation (Richards, 2025). This approach is further supported by Gordon's concept of *audiation* (1989) — the ability to hear and comprehend music internally in the absence of external sound — which identifies the internalization of pitch through singing as a prerequisite for accurate pitch production. Building on these principles, the present intervention translated them into a structured set of vocalization exercises.

Vocalization exercises comprised four activities targeting pitch and interval internalization. First, the teacher played a single pitch; after silent listening, the student sang it back on "ta" — the Kodály syllable for a quarter note — sustaining it until stable, then compared it with the pitch produced by the teacher. Second and third, the teacher played ascending or descending two-note intervals, which the student sang in turn on the same syllable, attending to the felt distance between pitches, with complexity progressing from thirds to fifths and octaves. Fourth, in call-and-response, the student echoed a pitch or interval sung by the teacher, linking listening to vocal reproduction.

Throughout, pitches stayed within the student's natural range, avoiding *falsetto* or strain, keeping the focus on the stability of the internal auditory image rather than on vocal technique.

Guided-Active Listening

The second strategy was grounded in the principle that playing against a stable external pitch reference allows the performer to engage in active, real-time comparison between the produced pitch and the intended target. This process directly supports auditory monitoring, allowing the performer to detect and correct pitch deviations as they occur, rather than only after the fact (Zatorre et al., 2007; Keller, 2012).

Research on bowed-string instruments specifically supports this principle, having explored a range of pedagogical strategies for supporting intonation development through external pitch reference (Tejada & Fernández-Villar, 2023; Pardue & McPherson, 2019; Zabanal, 2019).

This intervention implemented this principle using a chromatic tuner as the external reference tool. The device employed was the Korg CA-50 chromatic tuner, used in its "Sound Out" mode, which generates a sustained reference tone through the device's internal speaker across a range of one octave (C4 to C5). This provided the student with a stable external pitch reference against which to compare the pitch produced on the violin, while simultaneously offering real-time visual feedback on intonation accuracy through the needle-type display.

Exercises followed a fixed sequence. The teacher selected a target pitch on the device, producing a sustained reference tone; as in the vocalization exercises, the student first sang the pitch — forming and stabilizing the internal auditory image — before placing the finger and playing it on the violin. She then

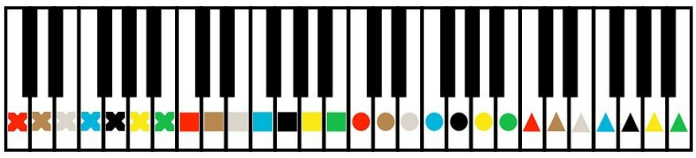
compared the produced pitch against the reference tone, using both active listening and the needle display, adjusting finger placement accordingly until the two sounds aligned and the needle centered. The teacher guided this process verbally — e.g., asking whether the pitch was higher or lower — to build discriminative listening. As single-pitch accuracy improved, the same listen-sing-play sequence was extended to intervals: the teacher set the lower pitch first, the student listened, sang, and played it, then the reference shifted to the upper pitch for the same sequence — building interval awareness step by step through both internal imagery and external reference.

Kinesthetic Mapping

The third strategy drew on the Dalcroze approach, which treats the body as the primary instrument of musical learning and spatial awareness as central to musicianship (Jaques-Dalcroze, 1921). It aimed to develop the student's internal spatial map of the fingerboard through a progressive sequence of embodied exercises targeting the proprioceptive sense of where the finger must land to produce the intended pitch (Pardue & McPherson, 2019; Keller, 2012), consistent with research showing that accurate finger placement depends on this kind of internalized physical knowledge (Pardue & McPherson, 2019).

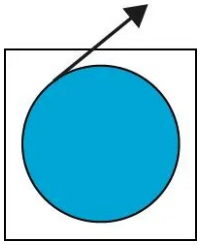
The pedagogical tool was a visual-markers strategy, an approach long used in string pedagogy to support spatial orientation and finger-placement accuracy (Bergonzi, 1997; Pardue & McPherson, 2019). The intervention drew on Figurenotes, an inclusive Finnish notation system developed in the 1990s at Helsinki's Resonaari Music Centre for students with special educational needs (Kivijärvi, 2019). Each pitch is coded by colour (C red, D brown, E grey, F blue, G black, A yellow, B/H green) and shape, which marks the octave (Image 2); an arrow over the note marks sharps (pointing right) and flats (pointing left) (Image 3–4).

Image 2
The Figurenotes colour-and-shape system: colour identifies pitch, shape identifies octave.



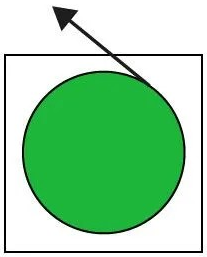
Source for Figures 2–4: Figurenotes. Available at: https://figurenotes.org/

Image 3
Figurenotes notation for a sharp: arrow pointing forward indicates a higher pitch.



Source for Figures 2–4: Figurenotes. Available at: https://figurenotes.org/

Image 4
Figurenotes notation for a flat: arrow pointing backward indicates a lower pitch.



Source for Figures 2–4: Figurenotes. Available at: https://figurenotes.org/

Though designed originally for keyboard and guitar (Kivijärvi, 2019), the system has since extended to strings, percussion, brass, woodwind, and voice. On the violin, it is typically introduced using only natural notes: stickers mark the open-string positions — commonly at the bridge or at the end of the fingerboard nearest the bridge — (Image 5) and each natural-note finger position, leaving sharps and flats unmarked (Image 6).

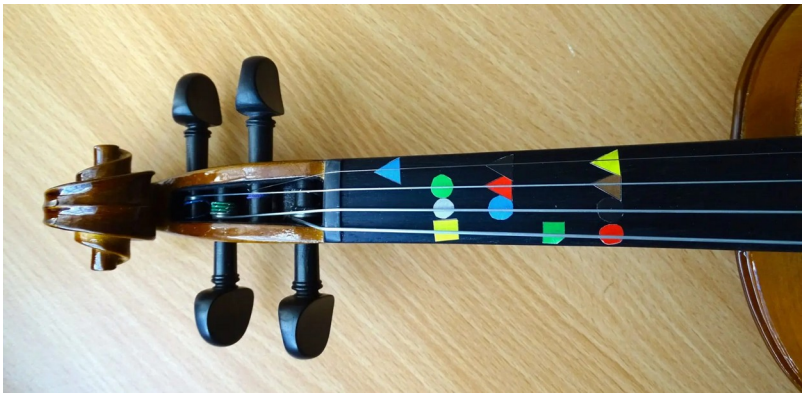
This lets the student internalize the relationship between natural and altered pitches by ear, rather than memorizing each as a separate position; a plain white strip can be added beneath the stickers to mark position generally without disturbing the colour-to-pitch coding.

Image 5
Open-string stickers placed at the bridge end of the violin fingerboard.



Source for Figures 5–6: Figurenotes. Available at: https://figurenotes.org/setting-up-strings/dsc01409/

Image 6
Figurenotes stickers placed on the natural-note finger positions along the fingerboard.



Source for Figures 2–4: Figurenotes. Available at: https://figurenotes.org/

The intervention personalized this system, with the student herself choosing her own colour for each pitch — C red, D green, E yellow, F orange, G blue, A fuchsia, B/H brown — reproduced on fingerboard stickers, fostering a sense of ownership over her own learning tool. Written notation retained standard Western notation with noteheads coloured to this same personalized scheme, following the logic of Colournotes, a Figurenotes-derived application (Kivijärvi, 2019). Over time, however, tracking colour, shape, and arrow simultaneously proved cognitively demanding enough to interfere with, rather than support, intonation accuracy; at the student's request, the system was simplified and replaced with the *Don't Fret* decal.

Don't Fret is a commercial decal marking finger placement directly on the fingerboard. Unlike Figurenotes, it colour-codes

fingers rather than pitches — first finger yellow, second red, third blue, fourth orange-red — with thin lines marking the semitone positions within each colour zone (Image 7).

Image 7
Don't Fret finger position chart for a 4/4 violin.



Source: Thomann. Available at: https://www.thomann.it/dont_fret_finger_position_violin_4_4.htm

Both tools were applied across three progressive phases. In the first, away from the instrument, the student used her own forearm as a simulated fingerboard, singing each pitch or interval named by the teacher while pointing to the corresponding spot — exploring the physical distance between pitches through bodily gesture before transferring it to the violin. In the second, the exercises moved onto the instrument with coloured markers (first the personalized Figurenotes system, later the Don't Fret decal): the teacher named a pitch, and the student found the matching colour or finger position, sang the note, and placed her finger on the marker. In the third, the markers were gradually withdrawn: the student closed her eyes, sang the target pitch, and located it on the fingerboard by feel alone, drawing on the proprioceptive memory built in the previous phases — a progression from visual to purely kinesthetic guidance that echoes the shift from closed-loop to open-loop motor control described in the theoretical framework (Schmidt & Wrisberg, 2000).

Sing-Play Transfer

The fourth strategy integrated the gains of the three previous exercises (vocalization, guided active listening, and kinesthetic mapping) into a unified performance act — bringing together

internal auditory imagery, real-time monitoring, and motor execution within the context of the student's actual repertoire. Drawing on research demonstrating that a combined approach involving auditory imagery, overt singing, and physical playing produces measurable improvements in music performance (Steenstrup et al., 2021), the strategy aimed to consolidate the auditory-motor loop developed through the preceding exercises and transfer it to real musical contexts. This approach is grounded in the theoretical principle — articulated by Keller (2012) and supported by Zatorre et al. (2007) — that hearing and playing are, at the neural level, inseparable: singing the intended pitch before and during playing reinforces the internal auditory image that guides motor action and enables real-time self-correction.

Exercises were structured in three progressive phases. In the first phase, the teacher selected a short excerpt from the student's repertoire — typically a phrase of two to four bars — and asked the student to sing it before playing it. Drawing on the vocalization skills developed in the first strategy, the student sang the excerpt on a neutral syllable, forming a stable internal auditory image of the entire phrase before any motor action took place. This ensured that the intended pitches were clearly represented internally before being translated into finger placement on the violin. In the second phase, the student was asked to sing and play simultaneously — vocalizing the melodic line on a neutral syllable while bowing the strings. This simultaneous engagement of voice and instrument aimed to reinforce the connection between the internal auditory image and the motor action in real time: any discrepancy between the sung pitch and the produced pitch became immediately audible, providing the student with a direct, continuous channel of self-monitoring that did not depend on external feedback. This phase directly engaged the auditory-motor loop described in the theoretical framework — the student was simultaneously producing the internal reference and monitoring the produced sound against it (Keller, 2012; Zatorre et al., 2007). In the third phase, the vocal support was gradually withdrawn. The student was asked to play the excerpt without singing — but to continue hearing the melody internally, maintaining the auditory image in working memory as a guide for motor action. This phase represented the culmination of the entire intervention: the student was no longer relying on external references, visual cues, or overt vocalization, but on an internalized auditory-motor representation of the target pitches, formed and consolidated through all four strategies. The aim was to achieve the kind of integrated, self-regulating performance in which the internal

auditory image guides motor action, the produced sound is continuously monitored against that image, and any deviation is detected and corrected automatically — the hallmark of fluent, consistent intonation (Keller, 2012; Zatorre et al., 2007; Schmidt & Wrisberg, 2000).

Data Collection

Data were collected through three sources: video recordings of lessons, audio-video recordings of individual practice sessions, and field notes from unstructured self-reflection interviews with the student. The intervention lasted six months, spanning the second semester of the academic year. Lessons took place once a week at the conservatory, lasting 45 to 60 minutes each, for a total of 24 lessons, and were systematically video-recorded by the teacher using a fixed camera.

Individual practice sessions were also documented by the student at home through audio and video recordings. The format varied across sessions, as video recording at times made the student feel overly exposed in this setting, leading her to prefer audio recordings; this preference became more pronounced as the intervention progressed, and video recordings became correspondingly less frequent. As a result, the home-recorded material varied considerably in format, recording equipment, and overall audio-video quality, occasionally limiting the level of detail that could be observed and analyzed, particularly in the later stages of the intervention. In addition, the recordings followed no fixed schedule, being gathered informally depending on when the student was available, how much time she had, and whether she remembered to record — a further source of variation, though one consistent with the study's exploratory and descriptive design, which aimed to document the learning process within its authentic educational context rather than under experimentally controlled conditions (Yin, 2018; Denzin & Lincoln, 2011).

In addition, data were collected through unstructured interviews with the student, conducted periodically throughout the intervention — typically following lessons in which a new strategy had been introduced, or in which a noticeable shift in performance had occurred. The teacher recorded the student's responses in field notes immediately after each conversation, noting the date, the lesson number, and a brief summary of the student's reflections.

Data Analysis

Data analysis was based on a rating scale comprising three parameters corresponding to the three research sub-questions: *consistency*, referring to how fluently the student played and how frequently intonational interruptions occurred during performance; *speed and self-regulation*, referring to how quickly and autonomously the student detected and corrected pitch errors; *pitch anticipation*, referring to how consistently the student anticipated correct finger placement before producing the sound.

Each parameter was assessed using a four-level descriptive scale: *Absent* (the behavior is not observable), *Emerging* (the behavior is present but inconsistent), *Developing* (the behavior is present consistently but not yet automatized), and *Established* (the behavior is automatic and fluent). This descriptive, graded format was chosen over a simple present/absent judgment because intonation control develops along a continuum, moving gradually from inconsistent, effortful attempts towards automatic, fluent execution. A binary scale would have obscured this gradual process, collapsing meaningful intermediate stages of development into a single undifferentiated category. A graded descriptive scale, by contrast, allowed raters to register these intermediate states, in line with the qualitative and longitudinal aims of the present case study (Yin, 2018).

The scale was applied qualitatively by two independent external raters — both experienced violin teachers — who reviewed the available audio and video recordings of lessons and audio recordings of individual practice sessions. To capture the student's pattern of progress over time, ratings were grouped into three two-month periods spanning the six-month intervention: a first period (lessons 1-8), an intermediate period (lessons 9-16), and a final period (lessons 17-24). Rather than treating any single recording as representative on its own, raters formed their judgment by considering the full body of recordings available within each period.

Given that the format of the home-recorded material varied between audio and video, as noted in the previous chapter, not all three parameters could be assessed with the same degree of detail across all recordings. *Pitch anticipation*, in particular, required visual access to finger placement prior to sound production, and could therefore only be assessed using video recordings. *Consistency* and *speed and self-regulation*, by contrast, could be reliably assessed from audio alone, as both relate primarily to audible features of performance (fluency, the frequency of interruptions, and the timing of error correction). Ratings for pitch anticipation were therefore based exclusively

on the subset of recordings that included video, while ratings for the other two parameters drew on the full body of available material, audio and video alike.

Inter-rater reliability was assessed using Cohen's Kappa coefficient (Cohen, 1960) on the 24 lesson recordings. Values of .80 or higher were considered acceptable.

The field notes from the self-reflection interviews were analyzed thematically (Braun & Clarke, 2006) following the same period-by-period structure: at the end of each two-month period, the available field notes were read and coded to identify recurring patterns in the student's self-perceptions. These themes were then cross-referenced with the findings from the rating scale for the corresponding period, to explore convergences and divergences between the raters' external observations and the student's own perspective on her intonation development (Yin, 2018; Patton, 2002).

Findings

Pattern of Change

Video recordings of lessons

Over the first four lessons of the first period, both intonation consistency and the student's ability to anticipate correct finger placement before producing a note showed early signs of improvement, with somewhat fewer errors observed at this stage. However, this gain did not appear to be sustained: by lessons 7–8, the student's intonation was observed to become less stable again, and difficulties persisted throughout her playing. Even in first position, the student did not always produce the correct pitch on the first attempt and tended to play the wrong tone or semitone when accidentals were involved. This pattern was even more evident in passages involving position shifts and in other positions, where errors were frequent, and the student typically needed several attempts to adjust the pitch rather than producing it accurately from the start. When this happened, it appears to have been the teacher, rather than the student, who made the correction. On this basis, both raters rated all three parameters as *Absent* at the end of this phase.

During the intermediate period (lessons 9-16), the student's growing ability to anticipate correct finger placement was particularly evident in first and third positions, where errors became less frequent. By contrast, in second, fourth, and half positions, as well as in higher positions (from the fifth onwards), errors were observed both when playing steadily in these

positions and during shifts between positions. Regarding accidentals, some improvement in pitch accuracy was observed during the first lessons of this phase (lessons 9–10); however, by lessons 15–16, this improvement did not appear to have consolidated, and the student continued to show difficulty with finger placement in these passages. Similarly, when she had to play complex bow strokes (e.g., *balzato*, *spiccato*), slurred passages, or rhythmically complex passages, she tended to struggle with finger placement, resulting in more frequent errors. Meanwhile, self-regulation also appeared to emerge for the first time during this period, as the student began to attempt self-correction, especially in first and third position; however, these attempts remained fragmented and inconsistent, often interrupting the flow of her playing without reliably resolving the error. On this basis, the student's ability to anticipate correct finger placement was rated *Emerging* by both raters, while intonation consistency and self-regulation each reached only an *Absent*/*Emerging* boundary, reflecting the contrast between her strongest and weakest positions.

During this final period (lessons 17-24), the student tended to maintain accurate finger placement in first and third position, and appeared to show greater confidence in fourth position as well. These improvements seemed to have a direct effect on performance consistency: the student made fewer errors in these positions, and the flow of her playing was observed to improve accordingly. In the second and half positions, however, the student tended to make frequent errors and did not always produce the correct pitch on the first attempt, often needing several tries to find it. Improvements were observed in passages involving accidentals, although errors persisted, and accurate finger placement was not always achieved immediately. Passages involving complex bowing patterns or rhythmically demanding material also appeared inconsistent, frequently disrupting the fluency and continuity of performance. Self-regulation also showed further development during this period: building on the fragmented attempts at self-correction observed earlier, the student appeared to take more initiative when an error occurred, correcting herself with less hesitation, and, on a few occasions, resolved the error before the teacher had the chance to intervene — an outcome that had rarely occurred in the previous phase. On this basis, pitch anticipation was rated as *Developing* by both raters, while consistency of intonation and self-regulation each reached an *Emerging* level.

Audio recordings of individual practice

In the first lessons of this phase (lessons 1–4), the student appeared to anticipate correct finger placement with somewhat greater consistency, and intonation errors occurred somewhat less frequently. By lessons 7–8, however, it was observed that errors became frequent again during her practice sessions, and her intonation was often out of tune. Where video was available, additional signs of difficulty could be observed: she tended to move her hand hesitantly along the fingerboard, as though searching for the position rather than already knowing it, and she often looked down at her fingers while playing, rather than maintaining her gaze elsewhere. Throughout this phase, she also did not generally appear to notice when she played a wrong note, tending to continue playing rather than stopping, and her intonation tended to worsen further whenever complex bow strokes, slurred passages, or rhythmically complex passages were involved. On this basis, all three parameters were rated *Absent* at the end of this phase.

Throughout this second period (lessons 9–16), the student occasionally anticipated correct finger placement in familiar, fixed positions such as first and third, though even there her anticipation was not yet fully reliable. Difficulties appeared to persist in second, fourth, and half positions, as well as in higher positions.

She did not appear to notice or correct her own errors at all during this period, continuing to play through inaccuracies without stopping, and her intonation also tended to worsen whenever complex bow strokes, slurred passages, or rhythmically complex passages or with accidentals were involved, with little observable improvement in this respect. On this basis, pitch anticipation reached an *Emerging* level, and intonation consistency reached the *Absent*/*Emerging* boundary, while self-regulation remained *Absent*. During this final phase (lessons 17–24), it was observed that the student tended to anticipate correct finger placement more reliably in first and third positions, with somewhat greater confidence in fourth position as well, though second, half, and higher positions continued to generate frequent errors. She appeared to correct her own errors only occasionally during this period, without much confidence or consistency. Her accuracy with accidentals also appeared to improve somewhat: missed alterations — where the required sharp or flat was not applied at all — became less frequent, though the finger did not always land precisely once the alteration was attempted. Demanding passages

involving complex bow strokes, however, proved to remain challenging for her, and she appeared to struggle with finger placement. On this basis, pitch anticipation reached a *Developing* level, and intonation consistency reached an *Emerging* level, while self-regulation reached only an *Absent/Emerging* boundary.

Self-reflection interviews

Thematic analysis of the self-reflection interviews identified three recurring themes, emerging at different points across the intervention: the student's evolving sense of certainty about the target pitch, her spatial orientation on the fingerboard, and her trust in her own judgment when self-correcting. During the first lessons of this first period (lessons 1–4), a recurring theme in the student's self-reflection interviews was her uncertainty about what the note should sound like, which was linked to a repeatedly expressed difficulty in correcting her own errors. Regarding finger placement specifically, she described feeling more confident at the beginning, but by lessons 7–8, this had turned into confusion — particularly with accidentals, where she reported not knowing where to place her finger.

During the second part of the intervention (lessons 9–16), this earlier uncertainty about the target pitch had shifted into something more specific: the student described occasionally sensing that something sounded right, though this impression remained too inconsistent and unreliable for her to act on with any confidence. She also reported frequent confusion regarding spatial positions on the fingerboard, at times believing she was playing in one position while her hand was actually positioned elsewhere — confusion she linked directly to the full colour-coded tape system, which covered the entire fingerboard with a different colour for each pitch and which she described as overwhelming her capacity to process visual information while playing. Partway through this period, the full tape system was replaced with the simpler "Don't Fret" fingerboard marker.

By the final phase of the intervention (lessons 17–24), the student reported feeling more confident about where to place her fingers, which she attributed to the simpler "Don't Fret" markers introduced after the original tape system proved confusing. She also described feeling ready to self-correct during lessons, explaining that having the teacher there gave her confidence that she was judging the pitch correctly. She continued to report, however, that she did not yet fully trust her own ear when practicing independently.

Discussion

An important methodological consideration must be acknowledged before interpreting the findings: the participant was concurrently involved in two additional pedagogical interventions alongside the multisensory program examined here — one based on AI-assisted practice, another on embodied learning approaches. The specific contribution of the multisensory intervention, therefore, cannot be isolated, and any changes observed may reflect the combined influence of multiple forms of support, or interactions between them, rather than the multisensory strategies alone. The present study should accordingly be read as a descriptive account of learning within a complex educational environment, not a causal demonstration of the multisensory approach's effectiveness.

The findings of this study suggest that intonation control in a bowed-string player with dyscalculia can be improved through a multisensory pedagogical intervention. Indeed, targeting internal pitch representations and auditory–motor integration appeared to help strengthen some aspects of intonation control, while others remained more challenging.

Pitch anticipation showed the most consistent development, closely reflecting the transition from closed-loop to open-loop control (Schmidt & Wrisberg, 2000). In the lesson recordings, finger placement initially depended almost entirely on trial and error, before anticipatory behavior began to emerge in familiar positions (first and third), eventually becoming more consistently established there by the end. This suggests that a stable kinesthetic memory, the bodily sense of where the finger needs to be before the sound is heard (Keller, 2012), had begun to consolidate within those positions. Much the same pattern unfolded in individual practice, where early trial-and-error reliance likewise gave way, by the end, to more reliable anticipation in first and third position and growing confidence in fourth. The self-reflection interviews trace this same path: the student moved from not knowing what the target note should sound like to feeling confident about where to place her fingers.

Self-regulation showed clearer but more gradual development. In the lesson recordings, error correction was made entirely by the teacher at first, with no attempts by the student to identify or correct her own errors — a pattern that began to shift partway through the intervention, when fragmented attempts at self-correction first appeared (first and third position) before giving way by the end to more initiative, less hesitation, and the occasional correction made ahead of the

teacher. A similar but more delayed development was observed in individual practice. For much of the intervention, the student showed little evidence of independent error detection, beginning to correct herself occasionally in the final phase, with less confidence than in lessons. The self-reflection interviews trace this same trajectory: persistent difficulty correcting her own errors at the start gave way to a first form of intonational awareness — occasionally sensing that a note sounded right, though not yet trusting this enough to act on it — and, by the end, to feeling ready to self-correct in lessons specifically because the teacher's presence confirmed her judgment was right.

Consistency followed a path shaped by the other two. Errors occurred throughout the student's lesson playing, even in first position, at the outset, before shifting unevenly by the midpoint to reflect the growing contrast between her strongest and weakest positions, and finally giving way, as finger placement improved in first, third, and fourth position, to fewer errors and a more fluent performance overall. Individual practice followed suit, mirroring the early instability of lessons before reaching, by the end, the same level of improvement.

Several specific difficulties, however, persisted across the intervention and were not fully resolved by its end.

Second, half, and higher positions remained consistently more error-prone than first, third, and fourth position throughout all three periods, in both lessons and individual practice. This is plausibly linked to the finer spatial discrimination these positions require: as the distance between successive pitches narrows in higher positions, and as half position calls for the kind of intermediate, non-anchored spatial judgment that first do not, the magnitude-based spatial processing involved becomes correspondingly more demanding — precisely the kind of judgment that atypical intraparietal sulcus functioning, discussed in the theoretical framework, would be expected to compromise (Schwenzer & Mathiak, 2011; Kaufmann et al., 2008). First and third position, by contrast, are the most commonly used and earliest-practiced positions on the violin, and may simply have benefited from more repetition during the kinesthetic mapping strategy than positions reached later in a student's typical progression.

A related difficulty concerned accidentals, closely tied to a feature of the visual support system used early in the intervention: the original colour-coded tape system marked finger positions only for natural notes, leaving no reference — and no marker to rely on — when an accidental was required, plausibly accounting for the categorical errors observed under it, where the alteration was missed altogether. The subsequent

"Don't Fret" system added semitone lines, offering for the first time a visual reference for the half-step adjustment an accidental requires, and accuracy improved somewhat in both lessons and individual practice by the end — though incompletely, since difficulties with accidentals persisted in both sources through the final phase, suggesting the simplified reference alone was not sufficient to resolve a difficulty tied to the additional spatial-numerical demand an alteration imposes.

This same episode points to a broader risk in designing multisensory interventions for learners with dyscalculia. The original tape system, though intended to help, appeared in practice to generate more cognitive load than it relieved: the student's own account of confusion about her spatial position, and of feeling overwhelmed by visual information while playing, suggests that tracking colour, shape, and pitch simultaneously exceeded what she could manage. This matches what the theoretical framework predicts about working memory in dyscalculia: holding several visual cues in mind at once, as the original tape system required, is exactly the kind of task that atypical intraparietal sulcus functioning makes harder. The fact that a simpler system worked better for her suggests that how much a visual tool asks the learner to track matters more than how much musical information it manages to encode.

Complex bow strokes, slurred passages, and rhythmically demanding patterns continued to disrupt her playing in both lessons and individual practice even in the final phase, despite the broader gains in consistency — consistent with the idea that tasks not yet fully automatic draw on limited attentional resources, leaving fewer available for pitch accuracy even in otherwise improving positions (Blanchet & Assaiante, 2022).

Progress, moreover, was not always linear: pitch anticipation and consistency both improved in lessons 1–4, but this gain had not held by lessons 7–8, when difficulties returned across much of her playing. This may reflect a partial response to the kinesthetic mapping strategy alone, introduced before the auditory-motor loop's other component — a stable internal image of the target pitch — had developed enough to sustain it; without that foundation, an early gain in spatial anticipation may not have withstood the rising technical demands of the repertoire.

Finally, self-regulation remained markedly more fragile in individual practice than in lessons, never progressing beyond an Absent/Emerging boundary even by the final phase — consistent with the student's own account of sensing, but not yet trusting, when a note sounded right, and of feeling ready to self-

correct in lessons only because the teacher's presence confirmed her judgment, while still distrusting her own ear alone. Self-regulation, in other words, appears to depend not only on the auditory and spatial foundations of the other two parameters but also, at this stage, on external validation that unsupervised practice could not provide.

Taken together, these findings remain encouraging. Pitch anticipation and consistency showed substantial improvement, while self-regulation gradually emerged as the student became increasingly aware of responding to intonation errors. However, this capacity remained considerably stronger in lessons than in individual practice, suggesting that the gains achieved had not yet fully transferred beyond the supported learning environment.

Limitations

Several limitations should be considered when interpreting these findings. First, this study is based on a single case, and the findings cannot be assumed to generalize to other bowed-string players with dyscalculia, whose neurocognitive profiles and educational histories may differ considerably. The findings should therefore be understood as offering an in-depth, context-specific account of one learner's developmental trajectory, rather than as evidence of a universally effective intervention. Second, the home recordings of individual practice were heterogeneous in both format and frequency: they alternated between audio and video, were captured with different equipment (a smartphone rather than the dedicated camera used for lessons), and were made only occasionally rather than systematically. This variability resulted in considerable differences in recording quality, at times limiting the clarity of the observations available for analysis, and meant that the sample of individual practice available for each period was less complete and less standardized than that available for lessons. Third, the original tape system was modified partway through the intervention rather than held constant, complicating any attribution of the gains observed to a single, stable protocol rather than to the protocol as it evolved. Finally, six months may not be enough for these gains — particularly in self-regulation, the least developed parameter — to consolidate into fully automatic, independent skills.

Conclusion

This study set out to explore how intonation control might be supported in bowed-string players with dyscalculia, through an intervention designed around the specific neurocognitive vulnerabilities associated with this learning profile. What emerges most clearly is that progress in intonation control is not a single, unified process: its components followed their own developmental timelines, with some showing earlier and more substantial gains than others. The practical implication extends beyond this case: interventions for learners with dyscalculia may need to be differentiated, rather than treating intonation as a single uniform target.

More broadly, this case contributes to a small but growing body of work on the intersection between dyscalculia and music education — an area still largely underexplored despite its relevance to many young musicians' everyday experience.

Future research should examine these processes across larger samples and over longer periods of time in order to determine whether the patterns observed in this study — namely uneven, layered development and persistent challenges in self-regulation — represent broader characteristics of learners with dyscalculia or are specific to this individual case.

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