Motor performance in violin bowing: Effects of attentional focus on acoustical, physiological and physical parameters of a sound-producing action

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ABSTRACT
Violin bowing is a specialised sound-producing action, which may be affected by psychological performance techniques. In sport, attentional focus impacts motor performance, but limited evidence for this exists in music. We investigated the effects of attentional focus on acoustical, physiological, and physical parameters of violin bowing in experienced and novice violinists. Attentional focus significantly affected spectral centroid, bow contact point consistency, shoulder muscle activity, and novices’ violin sway. Performance was most improved when focusing on tactile sensations through the bow (somatic focus), compared to sound (external focus) or arm movement (internal focus). Implications for motor performance theory and pedagogy are discussed.

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Introduction
The rich, expressive sound of the violin has been described as imitating the quality of the human voice (Deutsch, 2011). Learning to produce this sound requires highly specialised fine motor skills, developed over years of practice (Konczak et al., 2009), and while mathematical understanding of bowed string motion is well documented (e.g. Schoonderwaldt, 2009a), little is known about how psychological performance techniques affect these skills. A human’s motor control of a musical instrument exists within a cognitive system involving thoughts and mental processing (Desmet et al., 2012), meaning that a musician’s psychological approach to performance may explicitly or implicitly influence their physical manipulation of sound. In sports research, a wealth of studies have found that motor skill performance can be improved by focusing attention on the environmental effects of an action compared to focusing on internal movement processes (for a review see Wulf, 2013), but little is known about these effects in instrumental music-making. Violin playing offers a particularly interesting context to explore this topic due to the sophisticated psychomotor skills required for sound manipulation. The current study explores the effects of the psychological performance strategy ‘focus of attention’ (FOA) on the system of sound production in violin playing, by investigating changes in sound quality (acoustical analysis), instrument movement (motion capture), and physiological muscle activity (electromyography).

The action-sound chain
In describing the process of sound-producing actions, Jensenius (2007) depicted an action-sound chain of cognition in which neurological activity in the brain leads to physiological muscle activity, physical movement of limbs, mechanical control of the instrument and eventually acoustical impacts on the environment (Figure 1). In the current study, we investigate how an additional psychological element, such as a performance psychology technique, may influence sound production. Thus, the action-sound chain provides us with a useful framework for exploring the effects of FOA on violin sound production. We investigate the effects of differing attentional foci on physiological, physical and acoustical aspects of violin tone production, measured respectively through electromyography of muscle activity in the bowing arm, motion parameters of the violin and bow, and computationally extracted timbral features of sound.

Acoustic features of violin sound
Defining acoustic parameters to measure tone quality can be a complex endeavour. Perceptions of musical timbre
are complex and multifaceted (e.g. Alluri & Toiviainen, 2009), and in terms of violin sound, the challenge of providing quantifiable acoustic measures of tone quality is considerable (Giraldo et al., 2019). Nonetheless, acoustic features of string sound can provide information about the means of sound production. For example, the root mean square (RMS) of an audio signal provides a measure of overall energy in the sound wave, and is calculated by squaring, averaging, and then taking the square root of the signal amplitude (Lartillot & Toiviainen, 2007). The RMS of an audio signal is commonly considered to provide information about the loudness of the sound (Hove et al., 2019). Roughness is another acoustic feature, which gives a measure of sensory dissonance (Eerola et al., 2012), or the ‘noisiness’ of a tone (Liew et al., 2018). The perception of roughness is caused by the phenomenon of ‘beating’ between sinusoids, which can originate from harmonic dissonance between two tones, or, as is relevant to the current study, timbral dissonance (Sethares, 2005), within an individual tone. As roughness has been associated with perceived unpleasantness (Liew et al., 2018), we might expect higher roughness to indicate lower quality of violin tone. A third acoustic feature widely considered to be an important aspect of timbre perception is spectral centroid which is a mathematical measure of the geometric centre of the distribution of a sound wave’s spectrum (Lartillot & Toiviainen, 2007). Spectral centroid can be considered a measure of the perceptual ‘brightness’ of tone (Edgerton et al., 2014; Schoonderwaldt, 2009b), and as violins with higher brightness have been judged as better quality by experts (Łukasik, 2005), a higher spectral centroid might indicate better quality violin tone.

**Physical and physiological aspects of violin bowing**

In physical terms, sound production on the violin is controlled via three main parameters: bow speed, bow force (downward pressure on the string), and the distance between the bow’s position of contact with the string and the violin bridge (i.e. bow contact point, Perez-Carrillo, 2016; Schoonderwaldt, 2009b). Within this dynamic system of sound creation, violinists manipulate these parameters to achieve artistic expression, while simultaneously maintaining a delicate balance between parameters to maintain tone quality. Thus, subtle alterations to bowing variables can affect the sound produced. For example, it has been shown that the spectral centroid of a violin tone is mainly controlled through bow force (Schoonderwaldt, 2009b), while the volume of playing tends to be controlled through the bow contact point. Optical motion capture technology can be used to measure aspects of bow control as motor performance outcomes at the physical stage of sound production. Kinematic parameters of bow velocity and acceleration, as well as positional data of bow contact point, provide information about the performer’s approach to sound production, as well as their spatial and temporal motor control abilities. For example, a fundamental technical skill in learning to use the violin bow is the ability to keep the bow parallel with the violin bridge, which can be measured through the consistency of the bow contact point.

A violinist’s mechanisms of bow control are situated within the musician’s whole body, therefore it is considered important that the whole body is able to move freely so that stiffness and excess muscle tension are avoided (Medoff, 1999; Roos, 2001). For example, in cello playing, head and torso movements contribute to the player’s ability to generate fluid bowing and good quality sound (Rozé et al., 2020). This finding highlights how overall freedom of body motion might impact sound quality. Thus, a measure of whole-body motion such as instrument sway may be considered an important global aspect of the physical stage of sound-production. Further, more static postures have been found to be associated with increased pain, while increases in micro movements are associated with less pain (Vergara & Page, 2002), indicating that postures which are ‘too still’ may negatively impact the body.

In addition, the physiological stage of sound production can be investigated using electromyography (EMG), which measures small electrical currents in muscles, caused by muscle contraction (Reaz et al., 2006). EMG muscle activity can provide information about energy expended through muscle use – another important aspect of the motor control system. Excess muscle tension is a common health issue among instrumental musicians.
Focus of attention in motor skill performance

In order to explore how a change in psychological approach might affect the system of sound production, the field of sports performance psychology provides an appropriate paradigm. Research on the topic of focus of attention (FOA) in sport has shown that the object of a performer’s thoughts can affect their motor performance. In this paradigm, performers are given verbal instructions as to which aspect of a motor action they should think about while performing. Types of FOA have been categorised as either ‘internal’ (focusing on the internal body movements required to perform the task), or ‘external’ (focusing on the effect of the task in the external environment, Wulf & Lewthwaite, 2016). An internal focus instruction directs attention within the body (and must explicitly refer to the body, e.g. ‘focus on your arm’), while an external focus instruction directs attention outside of the body (and must not explicitly refer to the body, e.g. ‘focus on the sound’ Wulf, 2013). Results widely show that an external focus produces superior performance for many types of gross motor skills (e.g. Neumann, 2019; Wulf, 2013). This phenomenon is explained by the constrained action hypothesis (CAH, McNevin et al., 2002; Wulf et al., 2001) which states that an internal focus brings conscious attention to automatic movement mechanisms which would normally operate at the implicit level, disrupting automaticity and leading to impaired motor performance.

Building on the differential effects of internal and external foci, some studies have also shown a distance effect such that external foci further from the body (e.g. on a piece of equipment, Alishah et al., 2017; Bell & Hardy, 2009; McKay & Wulf, 2012; McNevin et al., 2002; Porter et al., 2012; Singh & Wulf, 2020). This shows that, in addition to differential effects of internal vs. external foci, various types of external foci may differently affect performance. Furthermore, an internal focus can produce measurable changes to motor behaviours such as less efficient muscle use (Vance et al., 2004), and changes to aspects of physical motion (Wulf & Dufek, 2009). These findings exemplify how a seemingly small change in psychological approach can impact both performance of a specific motor task, and measurable changes to the global motor control system.

Attentional focus in music

A few previous studies have laid important groundwork for understanding FOA effects in music-making. Duke et al. (2011) found an effect of attentional focus on skill transfer in a piano task, such that temporal evenness of playing two alternating notes was improved by focusing on either sound or the piano hammers (distant external foci), compared to the piano keys (proximal external focus) or the fingers (internal focus). These results were seminal in supporting the CAH for a musical task involving auditory feedback. Similarly, Atkins (2017) found that trained singers received higher expert ratings when performing under distal external foci compared to internal and proximal external foci, while Mornell and Wulf (2019) found that an external focus on musical expression compared to an internal focus on technical accuracy improved expert ratings of both musicality and technical accuracy for various kinds of expert instrumentalists.

On the other hand, some music studies have failed to replicate the FOA effects found in sport. Atkins (2017) found a main effect of FOA on expert ratings of untrained singers’ performances, but differences between the conditions were unclear. Contrary to the CAH, performances were most often ranked as best under an internal focus on feeling vibrations in the zygomatic arch (cheekbones), compared to feeling vibrations in the throat, focusing on a microphone, or focusing on a distal point on the wall. In this study, Atkins notes that the internal focus instructions introduced extra tactile sensory feedback (i.e. feeling vibrations in the body) rather than purely focusing on movement itself, and this aspect of the internal foci may have affected results. Indeed, the zygomatic arch focus might actually be considered an external focus, as it diverted attention away from the main source of motor activity (the larynx), and focused not on movement, but on tactile sensation. Similarly, two studies on woodwind playing also failed to support the CAH, with no significant effects of focus condition on performance outcomes (Stambaugh, 2017, 2019). Stambaugh likewise suggests that as tactile sensory feedback plays an important role in controlling woodwind sound production, any attention to tactile sensations brought about as a consequence of the internal focus instructions might have interfered with constrained action effects. Tactile sensory feedback refers to afferent touch sense information such as vibrations or pressure controlled by an efferent action, therefore providing guiding information for the control of that action. In instrumental music-making,
tactile sensory feedback might constitute feeling vibrations from the instrument, or changes in pressure or resistance depending on how the fingers interact with the instrument. It is also noted that basic sound production using woodwind instruments is more complex (i.e. involves the coordination of both hands and breathing) than previously tested tasks of piano playing and singing, which also may have affected results (Stambaugh, 2017). Although Mornell and Wulf (2019) found support for the CAH in a variety of instrumental performances, their conception of the external focus as ‘on musical expression’ and the internal focus as ‘on technical accuracy’ is not directly comparable with the other studies discussed here. Therefore, the current literature on FOA in music-making is lacking in evidence for the CAH in complex instrumental sound production. Furthermore, the potential influence of bringing attention to tactile feedback in instrumental playing warrants further exploration, as does the study of measurable motor outcomes such as muscle activity and motion features.

**Tactile sensory awareness in music performance**

In support of indications from previous FOA research in music that attention to tactile sensory feedback may be beneficial to performance, other areas of research similarly highlight the role of attention to body sensations. For example, somatic training methods such as the Alexander technique, Feldenkrais method, and body mapping are widely thought to improve performance and reduce the risk of injury through the cultivation of sensitivity to body sensations, muscle tension and movement habits (Davies, 2020; Lee, 2018; Slade et al., 2020). While some academics have argued that this somatic approach contradicts CAH theory because it focuses attention within the body, and on process rather than outcome (Ives, 2003; Shusterman, 2009), it has also been argued that the somatic approach, in fact, encourages external FOA, by focusing on the quality of movement, rather than movement itself (Mattes, 2016). In support of the somatic approach, studies have found that expert performers under pressure tend to focus on physical sensations such as breathing or posture (Buma et al., 2015; Kokotsaki & Davidson, 2003), and that attention to body sensations may play a role in preventing overuse injuries (Batson, 2007). As mentioned before, research has highlighted the importance to learning of tactile feedback for woodwind and brass players (Stambaugh, 2017, 2019), while string playing pedagogy also indicates the value of developing kinaesthetic sensing (i.e. awareness of body posture, movement, strength etc.), which is closely connected with tactile sensing, in cultivating good playing technique (Cotik, 2019). Therefore, attention to tactile feedback may influence the production of sound in string playing. To our knowledge, no previous study of FOA in music performance has investigated how focusing on tactile sensory feedback through an instrument might compare with internal and more distal external FOA.

**Expertise and FOA**

FOA research in sport has shown that the CAH applies to performers of various levels of expertise (Wulf, 2013). However, in a recent study it was shown that beginner volleyball players may benefit more from a proximal external focus (i.e. external to, but close to the body), and experts from a distal one (Singh & Wulf, 2020). The authors suggest that their proximal external focus which utilised *imagery* about arm angle without referencing arm movement per se, avoided constrained action by diverting attention away from motor mechanics, while also bringing awareness to action-execution technique. While experts were able to achieve their best performance by focusing distally on a target, beginners benefitted from the extra attention to technical detail allowed by the proximal external focus.

In musical tasks, interactions of FOA with expertise remain unclear. Atkins (2017) found beneficial effects of an external focus for trained singers, while Atkins (2017) found benefits of both external and internal foci for untrained singers. In contrast, Duke et al. (2011) found that less experienced pianists benefitted from a more external FOA, while expert pianists were unaffected. Violin bowing is a particularly complex motor skill, which beginners must accumulate at least 700 h of practice to achieve (Konczak et al., 2009). Thus, violin bowing is a particularly interesting context for exploring the effects of FOA and expertise.

In summary, sound production in violin playing is relatively well understood in terms of the mathematical relationships between bowing parameters and string motion, but little research exists on how psychological performance techniques may influence bowing action. A useful cognitive framework, the sound-producing action chain (Jensensius, 2007) depicts the various stages of sound production from neurological to acoustical, and we suggest that the additional psychological element should be explored. In sports research, such a psychological effect on motor performance has been observed in research on attentional focus. That is, motor performance is improved by adopting an external focus on task goals compared to an internal focus on movement processes (Wulf, 2013), a phenomenon explained by the Constrained Action Hypothesis (CAH) (McNevin et al., 2003; Wulf et al., 2001). Further, this constrained action effect has been shown to influence other aspects of the
motor system such as motion features, and muscle activity (Vance et al., 2004; Wulf & Dufek, 2009). However, evidence for these effects in music performance is limited. In addition, some evidence suggests that attention to tactile sensory feedback could be beneficial in instrumental music-making (Davies, 2020; Lee, 2018; Slade et al., 2020; Stambaugh, 2017), which may have implications for finding an optimal focus of attention for music performance.

The current study

The current study aimed to investigate how a psychological performance approach might affect motor skill performance during violin tone production. To this end, we applied the FOA paradigm founded in sports psychology to a simple violin sound production task, for both experienced players and complete novices. The selection of complete novices (i.e. participants with no prior string playing experience) was intended to create a high contrast in expertise between the two groups. For beginners, this early stage of learning is of great pedagogical importance, where teachers must take care to instil good technique to avoid the need for correction of bad habits later (Salzberg & Salzberg, 1981), while for experienced players, returning to basic technique such as open-string bowing is useful for maintenance of good playing technique. To gain a detailed view of effects on the motor system we examined outcomes at various stages of the sound-producing action chain (see Figure 1), namely physiological (EMG muscle activity), physical (technical bowing and scroll sway motion parameters) and acoustical (computationally extracted timbral features of the sound produced). While scroll sway may not be a direct physical aspect of sound production, it is considered here as part of the sound-producing action chain as whole-body motion may influence production and perceptions of sound (see Introduction).

We aimed to compare effects of internal and external foci with a novel 'somatic' focus which intended to bring awareness to tactile sensory feedback through the bow. The internal instruction aimed to bring attention to the internal mechanics of the task (arm movements), and the external instruction aimed to bring attention to the external goal of sound production. The somatic focus aimed to direct attention towards tactile sensations resulting from the action (i.e. feedback), through reference to the musical instrument. For this condition, performers were instructed to focus on ‘the resistance of the bow against the string’ with the reasoning that doing so would draw attention to tactile feedback from the bow such as vibrations and changes in tension. We considered this instruction to be the most naturalistic and straightforward way of achieving such a focus without introducing confounds between the different focus instructions (for example, number of words or degree of complexity of the instruction), the methodological importance of which has been discussed (Wulf, 2013). In this way, the somatic focus was intended to provide a focus grounded in bodily awareness through attending to fluctuations in touch sensations of the fingers on the bow, paralleling the kind of awareness which may occur as part of somatic training methods. This focus can be considered a type of external focus, as it does not refer directly to body movement (Wulf, 2013). The focus instruction details are displayed in Table 1.

We hypothesised that:

(1) Focus instructions would affect motor control of sound production at physiological, physical, and acoustical stages. In accordance with the constrained action hypothesis, we predicted that external and somatic foci would benefit motor performance relative to the internal focus. As a somatic focus has not been tested before in this context, we did not predict differences between somatic and external.

(2) There would be differences in performance outcomes and attentional focus effects between novices and experts.

The physiological, physical and acoustical stages of sound production were measured through surface EMG

| Table 1. Focus instruction details. |
|----------------------------------|---------------------------------|---------------------------------|------------------|
| Focus condition     | Verbal instruction | Description | References to focus concept |
| Internal            | Focus your attention on the movement in your right arm. | Directs attention to internal movement mechanisms and refers directly to the body. | Stambaugh (2019), Wulf (2013) |
| External            | Focus your attention on the sound you produce | Directs attention to the environmental effects of the action. Does not refer directly to the body. | Duke et al. (2011), Stambaugh (2019), Wulf (2013) |
| Somatic             | Focus your attention on the resistance of the bow against the string | A type of external focus as it directs attention towards the musical instrument, and does not refer directly to the body. Aims to bring attention to tactile feedback through the instrument. | Duke et al. (2011), Mattes (2016), Wulf (2013) |
sensors, optical motion capture, and music information retrieval, respectively.

Materials and methods

Participants

Thirty-three right-handed participants (18 female, mean age = 24.97 years, SD = 4.80) were recruited. One participant was excluded from the analysis as their level of training was not enough to be considered experienced, but too much to be considered a novice. This resulted in a sample of 32 participants (18 female, mean age = 24.94, SD = 4.87), all of whom were compensated €10 for taking part. All participants played a musical instrument (mean years played = 15.20, SD = 6.35). Sixteen participants comprised the novice group, having never played a string instrument before, and 16 qualified as experienced violin or viola players, having at least 7 years of training in their instrument. The novice participants were specifically required to have experience playing a non-string instrument, to ensure that they possessed basic musical spatial–temporal skills that would equip them for the task of learning foundational violin technique in a short training session.

Equipment and experimental set-up

The experiment was carried out in a 5 m × 5 m room outfitted with eight infrared-based motion capture cameras (Qualisys Oqus). All participants used the same violin, which was a Fastoso intermediate model which was mounted with an AKG Harman C411PP contact microphone. Red stickers were placed on the stick of the bow to mark the middle section of the bow. The sound was recorded via Audio Desk software and a MOTU 828MK3 audio interface, while motion capture data was recorded via Qualisys Track Manager (QTM) software. Audio and motion capture were synchronised via SMPTE timecode. Five reflective markers were placed on the violin and bow, as shown by the black markers in Figure 2 (right panel), from which we later derived position and motion data. Motion data of participants’ bodies were also collected, although they are not analysed in the current study. Therefore, it should be noted that participants wore motion capture jackets and caps during the experiment. The jackets were made of soft, flexible material, designed to allow considerable freedom of movement for studying wide ranges of motion, therefore, the jackets did not restrict performers’ motion in the current study.

Trigno Delsys wireless surface EMG sensors recorded muscle activity using QTM software in synchrony with the motion capture. The wireless EMG sensors were placed on the participant’s bicep, triceps, and deltoid muscles of the right arm (see Figure 2, left panel) and secured with strong adhesive Delsys stickers, prior to fitting the motion capture jacket. Care was taken to ensure EMG sensors were not disturbed by the jackets, through checking sensor position and the EMG signal. All fitting of equipment and placing of sensors and markers was carried out by the first author.

Procedure

Before the start of the experiment, participants gave written informed consent in accordance with the Local Ethics Committee guidelines, and filled out a brief demographic questionnaire including their musical training history. Next, EMG sensors were positioned over the belly of the muscle, parallel to muscle fibres, in accordance with SENIAM guidelines (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles, see www.seniam.org). The signal to noise ratio was then visually checked for each muscle using the SENIAM recommended movements. Next, participants were outfitted with the motion capture jacket, cap, and markers, and

Figure 2. The left panel shows placement of EMG sensors on the bicep, triceps (long muscle head) and deltoid (medial muscle-head) muscles. The right panel shows motion capture markers placed on the participant’s body, violin, and bow, with X, Y and Z axes depicted in the bottom left corner.
there was a short training session in which novices were taught the basics of holding the violin and bow and how to carry out the experimental tasks (see below), while experienced violinists were simply taught the experimental tasks. This training was led by the first author who is an experienced violin teacher, and care was taken to ensure that basic bowing technique was adequately established. For novices, this session lasted approximately 15–20 min, and for experienced violinists, approximately 10 min. Participants were instructed to keep their visual gaze on the violin A-string during the task.

Participants performed 4 bows (starting on a down-bow) on the open A-string (tuned to A4) in response to a metronome, set to 30 bpm (IOI = 2000 milliseconds (ms)). Participants were instructed that the goals of the task were: (1) to play in time with the metronome, (2) to use the middle section of the bow as defined by the stickers, and (3) to play with a good sound. A good sound was defined as: (1) consistent volume and tone quality, (2) avoiding scratching, scraping or squeaking sounds, (3) smooth bow changes. They were instructed to create a resonant tone at a medium mezzo-forte dynamic.

In an initial practice round, participants carried out the task with no focus instruction. The task was then performed under three focus conditions, counterbalanced in order across participants: internal focus, external focus, and somatic focus. For each condition, participants performed three trials of the task. Before each new focus condition, participants sat quietly for one minute to minimise carry-over effects between conditions. Focus instructions were given verbally, and reinforced for each repetition of the task. After each focus condition, participants were asked to verbally report what they had been thinking about, to provide an indication of how well focus instructions were followed. After the experiment was complete, participants were debriefed about the purpose of the experiment.

Data analysis

Ability to follow the focus instruction

One methodological issue with the FOA paradigm is that it is difficult to know if participants followed the focus instructions. Most FOA studies simply assume that instructions are followed correctly. Therefore, to provide an indication of how well participants followed the focus instructions we inspected the reported thoughts after each condition. The data consisted of one comment for each condition (3 comments) per participant, yielding 96 comments in total. Participants’ answers were transcribed and coded by the first author as either providing evidence that the instruction was followed (1) or not (0). Comments were coded with a 1 if the participant reported: (a) that they were thinking about the object of the focus instruction or that they were thinking about ‘the focus’, or (b) if they directly reported being able to do the focus, enjoying the focus or trying to do the focus.

Comments were coded with a 0 if participants (a) directly reported difficulty with the focus instruction or (b) if their reported thoughts were completely irrelevant to the focus, implying distraction. The purpose of this analysis was to provide an overall indication of how well focus instructions were followed, but not to provide criteria for judging individual participants. For example, because this data is limited in its’ ability to truly assess the degree to which a person focuses on a certain object, we do not use these data as a basis for exclusion or further analysis. Also, even though a participant might have exhibited difficulties following the focus instructions, they may have still been affected by the instructions at an implicit level. Ninety-three percent of the overall comments were coded with a 1, indicating a high rate of success. Overall, 5 participants received a 0 code for one condition out of three, and 1 participant received a 0 for two conditions. No participant received a score of 0 for all three conditions.

Tempo and bow speed checks

The bowing task conditions were devised so as to control, across focus conditions, for tempo (by indicating the tempo with a metronome) and speed of bow used (by indicating the amount of bow to be used with stickers on the bow). However, participants may have deviated from the intended parameters. Therefore, to check that there were no systematic deviations of these variables across focus conditions which might influence results, we ran mixed ANOVAs on the outcome variables ‘length of task’ (i.e. mean time taken to complete a trial), and bow velocity. The within-participants factor was condition, and the between-participants factor was expertise. Effects of Focus Condition and Expertise are displayed in Table 2. There were no significant interaction effects. As there was no significant difference in these variables between focus conditions, we deemed it unnecessary to further statistically control for length of task or speed of

| Table 2. Effects of focus condition and expertise on length of task and bow velocity. |
|------------------------------|-------|-----|-----|
|                              | F value | P value | \(\eta^2_p\) |
| **Length of task**           |        |       |     |
| Effect of condition          | 0.53 (1.32, 39.62) | .521 | .02 |
| Effect of expertise          | 3.64 (1, 30) | .066 | .11 |
| **Bow velocity**             |        |       |     |
| Effect of condition          | 1.04 (1.60, 47.86) | .348 | .03 |
| Effect of expertise          | 1.58 (1, 30) | .218 | .05 |

= Mauchley’s test of sphericity was significant (p < .001), so the Greenhouse-Geisser corrections are reported.
bow in the rest of the analyses. Regarding small deviations in length of recordings, many of the outcome variables are expressed as mean or standard deviation values over time, meaning that small variations in length should not affect results.

Audio
Audio files were first segmented using SMPTE timecode to match the time series of the motion capture recordings. Audio was then processed using the MIR (Music Information retrieval) toolbox (Lartillot & Toiviainen, 2007) and custom code in MATLAB software. Each audio clip was trimmed from the start to the end of the audio waveform to exclude silence. All trials were visually inspected for signal quality, and 16 trials (4.6% of total trials) were excluded from the analysis due to pops/cracks in the audio signal. If more than two trials per condition were deemed poor quality, the participant was excluded completely from the analysis. Two participants were fully excluded on this basis, and an additional participant was excluded because their original audio files were lost. This resulted in a total of 29 participants for the audio analysis.

Segmentation of the audio signal. In order to assess tone quality on the steady part of the sound without the bow changes, we segmented the audio into 'bow' and 'bow change' sections. The locations of bow changes were detected using the MIRpeaks function, which identifies the time points at which an audio signal peaks or troughs. In this case, identifying the troughs in the signal revealed the time at which the bow changed direction. Visual inspection and parameter adjustments for each recording ensured that these time points were correctly identified. The 'bow change' sections comprised a window around the bow change (defined as 20% of the length of the previous bow), and 'bow' sections consisted of the rest of the signal. Therefore, the size of the bow change window applied was not the same across recordings, but was adjusted based on the individual timing of each bow. This allowed a fair analysis, ensuring that the bow change sections represented consistent proportions of each recording. For example, if one recording was performed slightly quicker than another, the bow change window would be smaller to more accurately represent the time in which the bow change took place. The percentage size of the window was chosen based on a visual inspection of the data and was deemed to be an appropriate window size. A segmentation example is displayed in Figure 3. MIR features were then applied only to the 'bow' sections, to give an indication of the quality of the sound regardless of the bow changes.

MIR (Music Information Retrieval) features. Based on previous literature, we selected three MIR features to measure acoustic qualities of the sound produced during the task (see Table 3): spectral centroid, roughness, and RMS (see Introduction for detailed descriptions). While these three measures are not exhaustive of the possible changes to tone quality which could occur, they were considered to be the most relevant, easily interpretable acoustic features to violin sound production technique. For further details of feature derivation see the MIR Toolbox manual (Lartillot & Toiviainen, 2007). Each feature was derived using a windowed analysis (window length = 25 ms, overlap = 12.5 ms), from which the mean and standard deviation over time were calculated.

Motion capture
In QTM software, data were labelled and trimmed via a visual inspection from the start to the end of the bowing action. Finishing gestures at the end of bowing were excluded, as the aim was to examine the kinematics of technical bow movements during sound production. Gaps were filled in QTM using either linear interpolation, or the relational gap-fill method, which employed linear interpolation within a local coordinate system defined by the available violin markers. Most gaps were less than 10 frames (0.05 ms) long, and the maximum filled gap was 75 frames (0.38 ms) long. All gaps were carefully visually inspected to ensure appropriate gap filling, and any trials with too much missing data were excluded from analysis (see below). The violin scroll marker was used to indicate instrument sway, while technical aspects of sound production were derived from the bow markers. Data were then processed in MATLAB using the Motion Capture Toolbox (Burger & Toiviainen, 2013). For analysis of the bow, data were converted to a local co-ordinate system in which data were expressed in relation to the violin with the X-axis parallel to the violin bridge (see Figure 4), and the origin positioned at the lower left corner of the violin. This controlled for movement of the violin and individual height differences. For analysis of bow motion, two secondary markers were created by averaging the two bow markers to create a mid-bow marker, and averaging the two markers at the lower bout of the violin to create a ‘mid-base’ marker, which served as a reference for the bow contact point measure (see below). One participant was excluded from the scroll sway analysis due to a completely missing scroll marker in their motion data. From the bow measures, two trials (from two separate participants, 0.6% excluded trials) were excluded due to poor quality recordings (i.e. missing trajectories).

Bow contact point. The contact point of the bow refers to the bow’s positioning on the string relative to the bridge.
We calculated the mean contact point as the difference between the mean position of the mid-bow in the Y-dimension (i.e., perpendicular to the violin bridge), and the mean position of the mid-base in the Y-dimension, in millimetres (mm). Smaller values represent playing closer to the bridge, and bigger values further from the bridge. Consistency of contact point was calculated as the standard deviation of the position of the mid-bow in the Y-dimension.

**Scroll sway (freedom of motion).** We calculated scroll sway in the medio-lateral axis (mm), as a measure of freedom of overall body motion. Scroll sway was operationalised as the standard deviation of the scroll marker position data in the Y-axis. This approach to deriving sway has been used successfully in previous research on body sway (i.e., Riley et al., 1999). Scroll sway was derived from the global coordinate system to represent a wider range of motion including both upper body and violin motion. As the measure used was standard deviation of position data, individual differences in the angle of the violin to the body would not influence the measure. Similarly, as only Y-axis information was used, differences in participant height or arm length would also not affect the measure.

**Bow acceleration.** Acceleration of the bow was derived from the three-dimensional position data, in millimetres per second squared (mm/s²) and then the Euclidean norm was derived to provide one value across three dimensions. These values were then averaged over time.

**Electromyography**

EMG data were band-pass filtered at 20–450 Hz within the wireless sensor, and further processed using custom software in MATLAB. All data were visually inspected, and 4 trials containing large artefacts were excluded from the analysis (0.3% total excluded trials), although no participants had more than one trial per condition excluded. Data were mean centred and full-wave rectified. A moving RMS filter was applied with a window of 50 ms and overlap of 25 ms, and data was normalised (max–min) to control for individual differences. The mean RMS value was then calculated in millivolts (mV), to represent the power of muscle activity during each trial, and values were averaged across trials.
focus condition, Bonferroni-corrected post-hoc pairwise comparisons were conducted. To follow up interaction effects of condition with expertise, simple effects analyses were carried out, testing for the effect of condition in each expertise group separately.

**Results**

**Acoustic features**

For mean spectral centroid, a main effect of Focus Condition was found ($F(1.52, 38) = 3.65, p = .047, \eta^2_p = .13$), with Bonferroni-corrected pairwise comparisons revealing that the somatic condition ($M = 1439.30$ Hz, $SE = 55.07$ Hz) resulted in significantly higher spectral centroid compared to internal ($M = 1327.16$ Hz, $SE = 24.91$ Hz; $p = .045$), with no significant differences to external ($M = 1341.97$ Hz, $SE = 34.69$ Hz). This result implies a brighter tone quality in the somatic condition (Figure 5).

No main effects of Focus Condition were found for SD spectral centroid ($F(2,52) = 1.60, p = .212, \eta^2_p = .06$), mean RMS ($F(1.54,41.49) = 0.25, p = .720, \eta^2_p = .009$), SD RMS ($F(1.38,40.12) = 0.95, p = .366, \eta^2_p = .03$), mean roughness ($F(1.63,40.83) = 0.19, p = .782, \eta^2_p = .008$) or SD roughness ($F(1.43,35.85) = 0.44, p = .580, \eta^2_p = .02$). No significant interactions were found. However, significant Expertise effects were found for all MIR variables apart from the mean spectral centroid (Table 4), indicating that experienced violinists played quieter and with less roughness than novices, and had higher consistency than novices in all acoustic features.

**Motion capture**

**Bow contact point**

For mean contact point, there was no effect of Focus Condition ($F(2,56) = 1.29, p = .284, \eta^2_p = .04$), and no interaction effect. There was an effect of Expertise ($F(1,28) = 24.84, p < .001, \eta^2_p = .47$), such that experienced violinists ($M = 141.15$ mm, $SE = 1.97$ mm) had a contact point further from the bridge compared to novices ($M = 127.72$ mm, $SE = 1.84$ mm).

For SD contact point, there was a main effect of Focus Condition ($F(1.60, 48.12) = 4.98, p = .016, \eta^2_p = .14$), and no interaction effect. There was no effect of Expertise ($F(1,30) = 0.71, p = .406, \eta^2_p = .02$). For the effect of Focus Condition, pairwise comparisons showed a significant difference between external and somatic ($p = .042$), such that standard deviation of contact point was lower in somatic ($M = 6.042$ mm, $SE = 0.35$ mm) than external ($M = 7.07$ mm, $SE = 0.48$ mm). These results indicate that the consistency of bow-string contact point improved in the somatic condition compared to the

![Figure 4. Motion capture violin markers. The grey markers indicate the physical markers placed on the violin and bow, and the black markers indicate the ‘virtual’ markers used for bow analysis. The markers are: (1) left base, (2) right base, (3) scroll, (4) bow heel, (5) bow point, (6) bow mid, (7) mid base.](Image)
external condition. There were no significant differences compared to internal ($M = 6.17 \text{ mm}, SE = 0.40 \text{ mm}$, Figure 5, right panel).

**Scroll sway**
For scroll sway, there was no main effect of Focus Condition ($F(2,54) = 1.33, p = .273, \eta^2_p = .05$), but there was a significant effect of Expertise ($F(1,27) = 11.04, p = .003, \eta^2_p = .29$), and an interaction effect ($F(2,54) = 3.93, p = .025, \eta^2_p = .13$). Experienced violinists ($M = 10.86 \text{ mm}, SE = 0.91 \text{ mm}$) displayed more scroll sway than novices ($M = 6.78 \text{ mm}, SE = 0.82 \text{ mm}$). Following up the significant interaction effect, simple effects analysis showed a significant effect of Focus Condition for novices ($F(2,30) = 6.33, p = .005, \eta^2_p = .30$), and no effect for experienced violinists ($F(2,24) = 1.70, p = .204, \eta^2_p = .12$). Pairwise comparisons for the novice group revealed significantly more scroll sway in the somatic condition ($M = 7.92 \text{ mm}, SE = 0.75 \text{ mm}, p = .003$) compared to internal ($M = 6.26 \text{ mm}, SE = 0.64 \text{ mm}$), while the difference between somatic and external ($M = 6.16 \text{ mm}, SE = 0.82 \text{ mm}$), was approaching statistical significance ($p = .050$, Figure 6).

**Bow acceleration**
There was no main effect of Focus Condition on mean acceleration ($F(1,47,41.16) = 2.12, p = .144, \eta^2_p = .07$), and no further interaction or Expertise effects. For SD acceleration, there was no main effect of Focus Condition ($F(1,08,29.18) = 1.51, p = .231, \eta^2_p = .05$). There was a significant effect of Expertise ($F(1,27) = 6.24, p = .019, \eta^2_p = .19$), such that experienced violinists ($M = 712.54 \text{ mm/s}^2, SE = 67.35 \text{ mm/s}^2$) had more variable bow acceleration than novices ($M = 470.32 \text{ mm/s}^2, SE = 69.72 \text{ mm/s}^2$), and there was no further interaction effect.

**EMG**
A main effect of Focus Condition was found for the deltoid ($F(1,35,40.50) = 6.34, p = .010, \eta^2_p = .17$) and

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**Figure 5.** Left panel: Effects of focus condition on mean spectral centroid. Right panel: Effect of focus condition on standard deviation of bow contact point. * denotes a statistically significant difference, $p < .05$. Error bars indicate standard error of the mean. Descriptive statistics broken down by expertise and focus condition are provided in the supplemental materials.
Figure 6. Significant effect of focus condition on scroll sway for novices. * denotes a statistically significant difference, $p < .05$. Error bars indicate standard error of the mean.

the triceps ($F(2,58) = 4.01, p = .023, \eta^2_p = .12$) muscles, with no Expertise effects or interactions (Figure 7). For the deltoid, Bonferroni corrected pairwise comparisons showed a significant difference between internal ($M = 36.46\text{mV}, SE = 4.33\text{mV}$) and somatic ($M = 33.16\text{mV}, SE = 3.89\text{mV}, p = .023$), while the difference between external ($M = 33.29\text{mV}, SE = 3.87\text{mV}$) and internal was approaching significance ($p = .056$). These results indicate that deltoid muscle activity was significantly reduced under somatic focus compared to internal. For the triceps, pairwise comparisons showed no significant differences after Bonferroni correction, although the highest muscle activity was again observed in the internal condition ($M = 5.20\text{mV}, SE = 0.45\text{mV}$), with somatic ($M = 4.86\text{mV}, SE = 0.42\text{mV}$) and external ($M = 4.85\text{mV}, SE = 0.42\text{mV}$) being descriptively very similar (Figure 7). This non-significant trend reflects a similar pattern to the deltoid muscle.

For the bicep muscle, there was no effect of Focus Condition ($F(2,60) = 0.33, p = .719$), no interaction effect, and no effect of Expertise ($F(1,30) = 3.84, p = .060$, Figure 7).

Relationships between variables

As a final step, we explored relationships between physiological and physical variables with audio, in an attempt to gain insight into the mechanisms of sound-production. To this end, we ran correlation tests comparing (a) EMG activity of the three muscles and (b) motion capture variables (bow velocity, acceleration, contact point, and scroll sway) with audio variables RMS, spectral centroid and roughness. Correlations were run on mean measurements only, not standard deviations. For these purposes, the motion data was segmented to match the audio signal processing so that only motion during the bowing
sections was represented. As some variables were not normally distributed, we applied Spearman’s correlations. For the EMG correlation block, the alpha threshold for significance was adjusted to $p = .005$ (9 correlations) and for the motion capture block, alpha was adjusted to $p = .004$ (12 correlations). We found no significant correlations between either EMG activity or motion features after alpha correction. This indicates that the audio measures were not directly related to either muscle activity or motion features.

**Discussion**

This study investigated effects of the psychological performance technique attentional focus on several stages of sound-producing action in both novice and experienced violinists, comparing effects of three attentional foci – internal (on arm movement), external (on sound), and somatic (on bow-string resistance, see Table 1). We found significant effects of focus of attention (FOA) on the spectral centroid of violin sound, consistency of bow contact point, novices’ violin scroll sway, and EMG activity of the deltoid and triceps muscles. These results suggest that a change in psychological approach can impact motor control of sound production at several stages of the action-sound chain (see Figure 1), including an aspect of global motor behaviour (novices scroll sway). On the other hand, we found no effects of FOA for acoustic features RMS (i.e. loudness) or roughness, bow acceleration, or bicep muscle activity. In partial support of our first hypothesis, we observed, on the whole, performance improvements under somatic focus compared to internal. However, we did not observe any performance benefits of the external focus relative to internal, suggesting that the somatic focus on bow-string resistance was more beneficial to performance than the external focus on sound. Our second hypothesis was partly supported, with Expertise significantly affecting several outcome variables (acoustic features, bow acceleration, bow contact point, and scroll sway). However, we found an interaction effect of Expertise and Focus Condition, for the outcome measure violin sway only, suggesting that FOA effects on all other outcome variables were largely independent from expertise.

**Acoustical outcomes**

We found a significant main effect of focus condition on the acoustic stage of sound production. Results showed that spectral centroid increased under a somatic focus on bow-string resistance, relative to an internal focus on arm movement. In contrast, we found no effects for RMS or roughness. As spectral centroid is widely agreed to be associated with perceived brightness of a sound (e.g. Trapasso, 2013), and violins with higher brightness have been judged as better quality by experts (Łukasik, 2005), we deemed a higher spectral centroid to indicate an improvement in tone quality. This finding thus partially supports our first hypothesis that performance outcomes would improve under somatic focus compared to internal. As the somatic focus constitutes a specific type of external focus, this is in line with the *Constrained Action Hypothesis* (CAH), previous research in sport (e.g. Neumann, 2019; Wulf, 2013; Wulf & Lewthwaite, 2016) and music (Atkins, 2017; Duke et al., 2011; Mornell & Wulf, 2019). However, we unexpectedly found no evidence of performance benefits under the external focus on sound compared to the internal focus. This result does not support the CAH.

These results can be considered in terms of the distance effect that performance improves as FOA gets further from the body, which was supported by Duke et al. (2011) for a keyboard task, and Atkins (2017) for singing. Previous studies in music have defined a focus on sound as a more distant external focus relative to a focus on the musical instrument (Duke et al., 2011; Stambaugh, 2017), and following this rationale, the current study’s external focus may be considered more distal than the somatic focus. Our findings then, would not support a distance effect, as the focus on sound did not improve performance compared to the focus on bow-string resistance. Indeed, more distal external foci may not always produce the best performance results. Singh and Wulf (2020) found that a proximal external technique-based focus was more beneficial than distal external for those lacking in expertise (Singh & Wulf, 2020). Similarly, the somatic focus may afford the benefit of drawing attention away from movement mechanisms (avoiding constrained action) while also bringing awareness to bow technique. However, while our findings do not support the distance effect, neither do they refute such an effect. For example, it is possible that participants experienced the sound of the violin as closer than the bow-string resistance. Further research could explore how performers experience the closeness of different foci in musical tasks.

Unlike Singh and Wulf (2020), our findings for tone brightness applied to both experienced violinists and novices, but this may be a reflection of the complex nature of violin tone production, which is characterised by the careful balancing of several bowing parameters (Edgerton et al., 2014), and control of several degrees of freedom of motion (Konczak et al., 2009). The complexity of this motor skill may imply that even for experienced
players, bowing movements are not fully automatised, meaning that an optimal external focus should bring attention to the technical means of sound production, rather than the sound itself. Additionally, our results may have been different if we had a higher level of expertise in our sample. Another point to note about this finding is that spectral centroid in violin sound has been shown to be mainly influenced by bow force (Schoonderwaldt, 2009b), thus increased pressure of the bow into the string under the somatic focus may have underpinned this effect. Future studies should attempt to verify this by measuring changes in bow force due to attentional focus, which may be achieved through the use of specially designed systems for tracking bowing parameters (Pardue et al., 2015).

In contrast, we found no effects of FOA on RMS (i.e. loudness) or roughness (i.e. sensory dissonance) of sound produced. These contrasting findings reflect the multifaceted nature of even a simple string instrument sound production task in that there is a myriad of sound features which may or may not be affected. That we observed effects of attentional focus for spectral centroid and not the other features, indicates that bowing mechanics may be altered in a way that changes one aspect of tone but not others. This is consistent with mathematical understandings of bowing mechanics as a dynamic and complex system (e.g. Edgerton et al., 2014). Further research should explore the bowing features which might control the roughness of violin sound. Overall, our results indicate that a somatic focus on bow-string resistance during violin playing can affect the acoustical output of the sound-producing action via an increase in the brightness of tone produced, but not through the RMS or roughness of the sound.

MIR feature selection is clearly an important process in the current paradigm, as the features chosen for analysis may define whether or not effects are observed. We based our feature selection on previous research, and aimed to select features that were reasonably well understood in terms of their perceptual attributes, but it is unlikely that FOA would affect all aspects of sound produced by a musician, and it is possible that other MIR features would have produced different results. As there is currently no standard acoustic measure to represent violin tone quality as a totality, it was a necessary limitation to focus on a select few features of tone. Further research exploring FOA in more expressive musical tasks with a fewer number of trials could utilise perceptual ratings. Nonetheless, the use of MIR features in the current study provides a reliable and quantifiable way of measuring changes in the mechanics of sound production, and is an important contribution to this field of research.

**Physical outcomes**

To assess the effects of FOA on the physical stage of the sound-producing action, we examined technical bowing parameters of bow acceleration, bow contact point and violin sway. We found a main effect of focus condition on the consistency of bow contact point, such that bow contact point was less variable in the somatic condition relative to external. This finding indicates that a change in psychological approach may influence physical aspects of sound-producing motor control. In line with pedagogical perspectives, we considered the lower standard deviation of bow contact point observed in the somatic condition to indicate an improvement in bow control (Fischer, 1997). This result does not support our first hypothesis, as there were no differences relative to the internal focus, but rather points to a benefit of the somatic focus over the external focus. This is in line with our previous suggestion that the somatic focus encouraged awareness of bow technique, and strengthens our proposition that a focus on bow-string resistance might be more helpful to violinists’ tone production than a focus on the sound itself. Indeed, this effect may be driven by increased attention to tactile feedback from the instrument, supporting Stambaugh’s (2017, 2019) suggestion that awareness of tactile feedback is important for instrumental musicians and may be a contributing factor to FOA effects.

We found no effects of FOA on bow acceleration or mean bow contact point. A possible reason for the lack of any effect here may have been the very controlled nature of the task, which left little room for variation in bow acceleration. More variability in these parameters might have been observed in more complex, less controlled musical tasks, or with non-musician participants.

Results further demonstrated that attentional focus significantly affected novices’ freedom of body motion, as measured by micro changes in violin scroll sway. Novices’ instrument sway significantly increased under somatic focus compared to internal, while experts were unaffected. The systematic changes in sway observed here, were a matter of millimetres in magnitude, suggesting changes in micro-motion rather than large swaying motions which could be disruptive to playing technique. As freedom of body motion is considered a positive pedagogical outcome (Roos, 2001), inhibiting overall body motion has been shown to negatively impact music performance (Rozé et al., 2020; Turner & Kenny, 2011), and increases in micromotion while sitting have been associated with reductions in pain (Vergara & Page, 2002), we interpreted increased instrument sway as representing subtle relaxations of posture and thus an improvement in freedom of body motion. This finding therefore partially supports our first hypothesis, with freer motion in
the somatic focus relative to internal focus. Experienced violinists exhibited significantly more sway than novices overall, meaning that novices’ sway behaviour became closer to that of experienced players under the somatic focus, and supporting the interpretation of this effect as a performance improvement. This result supports previous findings that constrained action under an internal focus can lead to global changes in motor behaviour – i.e. changes to movement that are not specific to the part of the body focused on for the task (Wulf & Dufek, 2009). Indeed, it is argued that somatic training methods encourage reductions in stiffness through attention to subtle body sensations (Mattes, 2016), and our finding that the somatic focus increased sway may reflect similar mechanisms. Further research could build on this finding by exploring how changes in instrumental sway behaviour may affect perceptions of performance, or how FOA might affect larger gestural behaviour in expressive music performance.

**Physiological outcomes**

Our first hypothesis was also partly supported for the physiological stage of the sound production task. In line with previous research that an external focus promotes more efficient muscle use (e.g. Marchant & Greig, 2017; Neumann & Brown, 2013; Vance et al., 2004), we found significantly reduced muscle activity in the deltoid muscle (shoulder) under somatic focus (a type of external focus) compared to internal. This, to our knowledge, is novel evidence of this physiological effect in a music task. In somatic training methods, it is thought that attending to body sensations can reduce excess muscle tension, and it has further been suggested that this process is underpinned by the CAH (Mattes, 2016). Our findings tentatively support this, as the somatic focus, which aimed to bring awareness to tactile sensations (i.e. body sensations) through the violin bow decreased muscle activity in the right shoulder. Further research could explore how FOA affects muscle activity in specific muscles known to be problematic for certain instruments, and how this might be useful in preventing playing-related injuries.

However, we found no significant effects of FOA for the bicep muscle, and the main effect on the triceps muscle did not yield significant pairwise comparison results (employing Bonferroni correction). We suggest that the reason these muscles were not affected by attentional focus may have been because they followed an alternating activation pattern which allowed rest periods in which excess tension could dissipate. These rest periods may have negated any over-activation effects caused by the internal focus. Future research might further investigate how muscle activation patterns mediate increases in EMG activity as a result of constrained action.

**Expertise effects**

Our second hypothesis was that performance outcomes and effects of FOA would be different for experienced players and novices. This hypothesis was supported for several acoustic features, showing that, compared to novices, experienced violinists’ sound was characterised as significantly less variable in spectral centroid, roughness and RMS, indicating greater control of sound consistency. Experienced players also played significantly quieter than novices and with less mean roughness, and their bow technique was characterised with higher variability of acceleration and a bow contact point further from the bridge. Also, experienced players’ violin sway was greater than novices, indicating greater freedom of overall body motion. This distinct characterisation of experienced and novice players, even for a very simple task, is in line with evidence that violin bowing is a highly complex motor skill which may take years to master (Konczak et al., 2009). These findings can inform future studies that require parameters with which to measure the quality of violin playing or to define violin expertise. In particular, lower mean roughness, lower standard deviation of MIR features, and higher violin sway may be useful features for characterising experienced players.

Our hypothesis that the effects of FOA would be mediated by expertise was supported only for the violin sway measure. On all other measures, no interaction of expertise and condition was observed. First, we suggest that the interaction effect of expertise and condition for instrumental sway might indicate that the experienced violinists had learned to integrate sway behaviour with their playing in such a way that it would be unaffected by constrained action. Experienced players were likely very comfortable with the violin posture and found the bowing task relatively easy, meaning that even under an internal focus, their overall body motion remained free. On the other hand, novices were unfamiliar with the playing posture and may have therefore been more susceptible to constrained action effects on their swaying behaviour. Secondly, the lack of interaction effects in other measures supports previous findings in sport that the CAH may affect motor performance regardless of expertise (Wulf, 2013). However, as discussed earlier, our findings generally point to performance benefits under a somatic focus on bow-string resistance for both novices and experienced players rather than an external focus on sound, and we believe that this is due to the complex nature of the sound production task, which requires attention to...
technical means of sound production rather than to the end goal of sound itself. So, the lack of expertise effects observed here may be due to the complex nature of violin tone production, and indeed, a sample of violinists with a wider range of expertise (i.e. elite solo performers) may yield different results. A final point to note on expertise is that it has been shown that training in certain musical skills, such as focussing on various instruments in an orchestra simultaneously, affects attentional capacities (Wöllner & Halpern, 2016). In this study, conductors had better divided attention skills compared to pianists, while more experienced musicians outperformed less experienced ones. In the current sample it is unknown if the experienced violinist group had better attentional capacities than the other group, and therefore, might have been better at following the focus instructions. Future research using this paradigm could take individual differences in attentional capacity into consideration.

**Relationships between variables**

As a final exploratory measure, we investigated the relationships between physiological muscle activity and motion variables with MIR features. We observed no significant correlations between motion or EMG measures and audio features, showing that the measures taken at different stages of the sound-producing action chain represent distinct aspects of the action. Although it may seem surprising that bow motion features did not correlate with MIR outcomes, these relationships may require measurement of other variables such as bow force, and flatness of bow hair, in order to understand them fully. While previous research has suggested that bow contact point is related to loudness (i.e. RMS, Edgeron et al., 2014), the lack of this relationship here might be explained by a lack of variation in these parameters due to the strict nature of the task. Gaining a full picture of how motion and physiological parameters contribute to violin sound production would be a useful topic for further research.

**Limitations**

Several limitations of the current study should be considered. Firstly, the task used was a reductive technical exercise not representative of the full scope of what music performance encompasses. Nonetheless, the exercise was a realistic one, important to the early stages of learning to play the violin, and has provided key findings which can inform the further study of more expressive, complex musical tasks. It should also be noted that the current study examined only *performance* effects of FOA, not *learning* effects. Exploring FOA effects on the learning of violin bowing skills would be a suitable topic for further research. Furthermore, the novices used in the current study had only a short training session, and it is possible that providing a longer time to establish bow technique for novices would show different results. Finally, the current study took place in a laboratory, where participants were required to wear various body sensors, which is undoubtedly an unusual music performing environment, and results may differ in a more naturalistic setting. Future research could thus build on the current findings by aiming to replicate them outside of the laboratory, with more complex, expressive musical tasks.

**Conclusions**

This study provides novel evidence that the psychological performance approach of attentional focus can affect physiological, physical, and acoustical aspects of motor control during a violin sound production task, in both experts and novices. Results also showed that attentional focus affected a more global aspect of motor control, namely freedom of body motion measured through instrument sway, for novices but not experts. Our findings provide support for the constrained action hypothesis in violin sound production (a continuous instrumental sound production task), in line with previous FOA research in sport. Under the assumption that a focus on sound can be considered more distant from the body than a focus on bow-string resistance, our results indicate no evidence for the distance effect (that more distal foci produce better performance), although further research is needed with more clearly evidenced definitions of what constitutes a distant focus in a musical task. Nevertheless, our findings indicate that the complex motor skills of violin tone production benefit from a somatic focus on bow-string resistance which allows attention to the technical means of sound production (Singh & Wulf, 2020), compared to an internal focus on movement mechanisms. Furthermore, the performance benefits we found of the somatic focus, may support putative mechanisms of somatic training methods for improving performance by encouraging awareness of body sensations and movement habits (Mattes, 2016). We additionally found that attentional effects were modulated by expertise only for the freedom of body motion measure, indicating that aspects of attentional focus effects on sound production may occur regardless of violin playing expertise. Future research on this topic should investigate the effects of attentional focus on expressive musical outcomes, and in situations of psychological pressure, as well as possible connections of attentional focus effects on muscle activity with playing-related injuries.
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