# Immersive Visual Analysis of Cello Bow Movements

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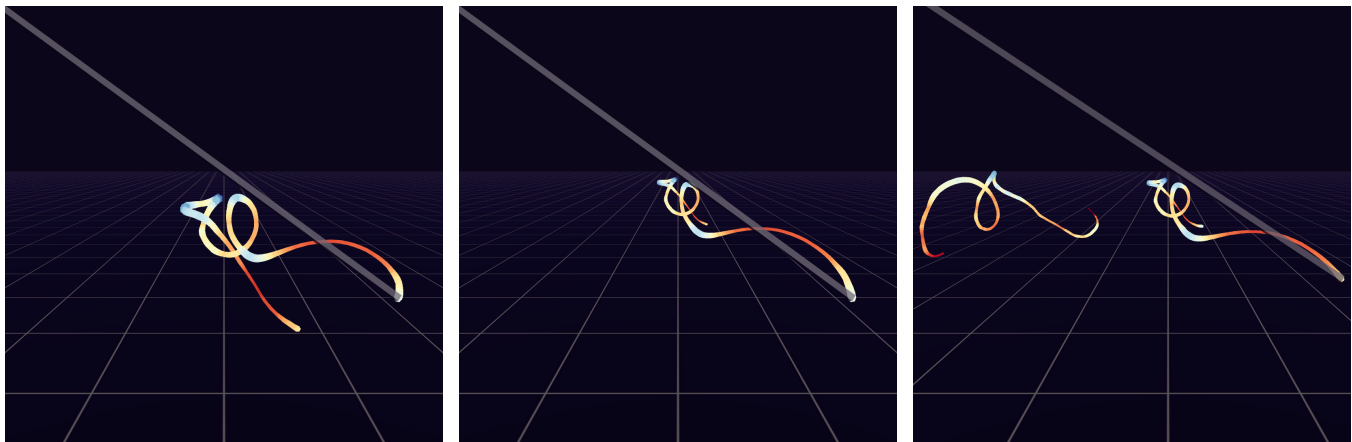
(a) A one-to-one mapping that shows the motion exactly as it was.

(b) Mapping time to a spatial dimension allows seeing longer recordings with less clutter.

(c) Simultaneous display of the current motion and a recording.

Figure 1: Comparison of visual encodings for bow movements. Here, color and thickness both indicate movement speed. We plan to also visualize played notes, loudness, and differences between recordings or live input and recording.

ABSTRACT

We propose a 3D immersive visualization environment for analyzing the right hand movements of a cello player. To achieve this, we track the position and orientation of the cello bow and record audio. As movements mostly occur in a shallow volume and the motion is therefore mostly two-dimensional, we use the third dimension to encode time. Our concept further explores various mappings from motion and audio data to spatial and other visual attributes. We work in close cooperation with a cellist and plan to evaluate our prototype through a user study with a group of cellists in the near future.

*All authors contributed equally to this work.

CCS CONCEPTS

• **Human-centered computing** → **Visualization**; Human computer interaction (HCI); *Visual analytics*; • **Applied computing** → Interactive learning environments.

KEYWORDS

Immersive analytics, virtual reality, cello, tracking, visualization, motion guidance

1 INTRODUCTION

Sheet music for cello pieces usually lacks instructions for how notes should be played. Deciding on the exact bow movements is therefore up to the musicians themselves. Since there might be very different ways to play the same piece, the analysis and comparison of different musicians' playing can reveal their strategies and differences and might help musicians try other movements and thereby improve or vary their playing.

Instrument playing is a physical activity in which positions and scales of movements have a meaning connected to our physical world. We therefore decided to use concepts from immersive and situated analytics for our design [15]. When looking at the bow movements of a cellist, we note that they are mostly restricted to a two-dimensional plane. This fact can be leveraged for visualization, as it allows us to map time to space, following an important visualization principle [24]. We thus use the third dimension by letting a line indicating the path of motion "fly away" from the observer.

Our approach works for both live and post hoc analysis and can show multiple recordings of the same or different players. Besides analysis, our display could be used for artistic performances, where the audience sees our 3D representation of the musicians' movements over time. Our current design uses virtual reality for ease of development, but future work will explore extensions to augmented reality, which would allow musicians and audience to see both instruments and visualization in the same space.

The authors of this paper have different backgrounds in the areas of visualization, immersive analytics, and general human-computer interaction. During our design, we collaborate closely with a cellist and follow guidelines from design study methodology [20], such as committing to regular meetings with this domain expert.

In summary, we contribute a new interface for immersive analysis of cellists' bow movements to allow studying and comparing movement patterns of one or more musicians. We explore possible data features we can measure or compute and then map to a range of visual markers and encodings. Our current prototype supports data collection and basic visualization. Future work includes further design exploration and an evaluation with a group of cellists.

2 RELATED WORK

A recent survey on music visualization [11] shows that despite a range of different applications such as visualization of instrument hardware, audio [4], sheet music [5, 16, 17], artist networks, and listening histories [3], there has still been little work in this domain. One task that has not been addressed much in this area is the analysis and visual comparison [6] of motion and exercise recordings. As data collected from playing music is personal to the musician, we consider our approach to be personal visualization [8].

Closest to our work are motion guidance visualizations. These systems show animated 3D paths that users need to follow along when learning motions such as dancing [27] or physiotherapy exercises [22]. Our primary tasks are more analytical, and as such we are interested in visualizations that can still provide motion guidance but at the same time allow for a better overview over entire motion sequences. To that end, we found inspiration in Ware et al.'s work [24], in which they — instead of using animation — map the 3D movements and behavior of whales onto paths that are augmented with textures and glyphs.

Work in the field of human-computer interaction addressed tasks such as assessing musicians' playing and providing respective feedback. Augmented reality, for instance, has been used to display information on drum kits [26] and guitars [13]. *Let's frets!* [14] uses LEDs and touch sensors on the fretboard to display and check exercises. Other approaches [10, 28] use sensor measurements in order to adapt the tempo or difficulty of exercises, or to allow users to

Figure 2: We currently track position and orientation of the bow through a VR controller fixed to it.

control effects [9]. Colored sheet music [2, 7, 21] can highlight mistakes and compare student's and teacher's recordings. *Strummer* [1] teaches users to play guitar chords and uses audio to check for correctness. *Soloist* [23] creates overviews of instructional videos for guitar players and extracts the played notes from audio through *CREPE* [12], so users can visually compare their playing to the instructor's. Our work focuses on different tasks, data, and instruments and extends this set of previous work.

3 DESIGN & IMPLEMENTATION

Inspired by Munzner's nested model [18], we structure this section into use cases and tasks, tracking and data, and visualization. Our current design uses virtual reality (VR) to allow for more immersion [15] and better embedding [25] than desktop interfaces, and a less distracting environment [19] and easier development than an augmented reality (AR) interface. We display sheet music virtually and our domain expert confirmed that seeing the instrument is not important. An extension to AR is planned for future work.

3.1 Use Cases & Tasks

There are multiple educational use cases that we plan to support: In music schools, our approach could be used to record a teacher's motion that a student then plays back while trying to follow, to learn the recommended movements. Recordings could also be analyzed and compared retrospectively, for instance to find incorrect or very different sections. Students or self-taught learners who own VR hardware could also do this at home once recordings made by others are available. Without access to others' recordings, students could still analyze their own playing and detect possible difficulties.

There are also uses cases apart from education: During a live performance, the musicians' movements could be visualized for the audience, for example through individual head-mounted displays or a 3D cinema canvas and glasses. Once recorded, the movements themselves could be displayed as an art installation, played back together with audio, and interacted with by visitors.

Table 1: Data summary

Feature	Source	Example visual encodings
time stamp	time	1D space, animation, label
3D position	motion	1D, 2D, or 3D space
3D orientation	motion	texture, material, shape
speed of movement	motion	color, thickness, texture
speed of rotation	motion	color, thickness, texture
pitch / played note	audio	color, label
loudness	audio	color, thickness, texture
expected note	sheet music	color, label
expected loudness	sheet music	color, thickness, texture

3.2 Tracking & Data

Our implementation uses the Unity game engine for rendering 3D real-time visualization and an Oculus Rift S headset with controllers for output and interaction. For our current prototype, we taped one of the usually hand-held controllers to the bow (Figure 2), but we plan to switch to OptiTrack for our user study to reduce the bow's weight. We track the controller's 3D position and orientation 80 times per second (one sample each 12.5 ms) and store this information together with a time stamp. Additionally, we record audio and extract played notes with CREPE [12].

Table 1 summarizes the data features that we collect or compute for each time frame. For note and loudness, we can also compute the difference between actual and expected and visualize this value. In case we have multiple paths, we can compare them through differences at a certain point in time.

3.3 Visualization

Having these data features, we can now choose from a range of visual attributes to map them to. Our current design supports mapping the motion over time to 3D, such that the motion path is "flying away" from the user in a direction of choice, which is usually roughly orthogonal to the playing motion (Figure 1b). The speed of this 3D translation can be adapted. When set to zero, the motion is played back exactly as it was recorded (Figure 1a).

To show other data features together with time and space, we change the path's appearance at each time step. For example, we can vary the color and thickness based on the movement's speed or direction, or the audio's pitch or loudness. Further ideas for encodings include the path's shape (spiky, smooth, zigzag, ...) or texture and material (stripes, roughness, reflectance, ...), similar to related work [24].

For comparison between multiple recordings or a recording and the current hand motion, we can simply juxtapose or superimpose them (Figure 1c). Another interesting option would be to explicitly encode the differences [6], which is non-trivial for time-varying motion data and is left for future work at the moment. One approach would be a mapping from the Euclidean distance between the expected and actual position to a color. We could also apply encodings from previous motion guidance research [27], such as "rubber bands" connecting the actual position to the recommended one. A mapping to 2D paths in combination with multiples views

could show the motion from different perspectives and make comparison easier than the 3D view that suffers from occlusion and perspective distortion, especially when displaying more than two paths. Such comparative visualizations would allow, for example, to study different playstyles, such as playing a piece in a simplified versus the original way. Showing these paths side by side should clearly reveal differences.

Besides our visualization, we show a virtual representation of the bow for reference and plan to add a virtual cello. Sheet music can be displayed virtually as well, for use cases where the head-mounted display is worn during playing.

4 CONCLUSION

We propose a concept for visual immersive analysis of cello players' bow movements and explore different design aspects such as data collection, feature extraction, and visual encodings. During our design study process [20], we collaborate with a cellist as domain expert. Our current prototype already supports tracking and visualizing movement and speed in a 3D path's color and thickness.

Future work includes further exploration of the visual design space and an evaluation of effectiveness and usability in different use cases, which we plan to conduct as a user study with a group of cellists. We further plan to extend our approach to augmented reality, so players and audience are able to see each other and the instruments.

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REFERENCES

[1] Shunya Ariga, Masataka Goto, and Koji Yatani. 2017. Strummer: An Interactive Guitar Chord Practice System. In *International Conf. Multimedia and Expo (ICME)*. IEEE, 1057–1062. https://doi.org/10.1109/ICME.2017.8019338

[2] Shota Asahi, Satoshi Tamura, Yuko Sugiyama, and Satoru Hayamizu. 2018. Toward a High Performance Piano Practice Support System for Beginners. In *Asia-Pacific Signal and Information Processing Association Annual Summit and Conf. (APSIPA ASC)*. 73–79. https://doi.org/10.23919/APSIPA.2018.8659463

[3] Dominikus Baur, Frederik Seiffert, Michael Sedlmair, and Sebastian Boring. 2010. The Streams of Our Lives: Visualizing Listening Histories in Context. *IEEE Trans. Visualization and Computer Graphics (TVCG)* 16, 6 (2010), 1119–1128. https://doi.org/10.1109/TVCG.2010.206

[4] Jonathan Foote. 1999. Visualizing Music and Audio Using Self-Similarity. In *Proc. Seventh ACM International Conf. Multimedia (MULTIMEDIA)*. ACM, 77–80. https://doi.org/10.1145/319463.319472

[5] Daniel Fürst, Matthias Miller, Daniel A. Keim, Alexandra Bonnici, Hanna Schäfer, and Mennatallah El-Assady. 2020. Augmenting Sheet Music with Rhythmic Fingerprints. In *5th Workshop Visualization for the Digital Humanities (VIS4DH)*. IEEE, 14–23. https://doi.org/10.1109/VIS4DH51463.2020.00007

[6] Michael Gleicher, Danielle Albers, Rick Walker, Ilir Jusufi, Charles D. Hansen, and Jonathan C. Roberts. 2011. Visual Comparison for Information Visualization. *Information Visualization* 10, 4 (2011), 289–309.

[7] Matsuto Hori, Christoph M. Wilk, and Shigeki Sagayama. 2019. Piano Practice Evaluation and Visualization by HMM for Arbitrary Jumps and Mistakes. In *53rd Annual Conf. Information Sciences and Systems (CISS)*. 1–5. https://doi.org/10.1109/CISS.2019.8692813

[8] Dandan Huang, Melanie Tory, Bon Adriel Aseniero, Lyn Bartram, Scott Bateman, Sheelagh Carpendale, Anthony Tang, and Robert Woodbury. 2015. Personal Visualization and Personal Visual Analytics. *IEEE Trans. Visualization and Computer Graphics (TVCG)* 21, 3 (2015), 420–433. https://doi.org/10.1109/TVCG.2014.2359887

[9] Jakob Karolus, Annika Kilian, Thomas Kosch, Albrecht Schmidt, and Paweł W. Wozniak. 2020. Hit the Thumb Jack! Using Electromyography to Augment the

Piano Keyboard. In *Proc. ACM Designing Interactive Systems Conf. (DIS)*. ACM, 429–440. https://doi.org/10.1145/3357236.3395500

[10] Jakob Karolus, Hendrik Schuff, Thomas Kosch, Paweł W. Wozniak, and Albrecht Schmidt. 2018. EMGuitar: Assisting Guitar Playing with Electromyography. In *Proc. 2018 Designing Interactive Systems Conf. (DIS)*. ACM, 651–655. https://doi.org/10.1145/3196709.3196803

[11] Richard Khulusi, Jakob Kusnick, Christofer Meinecke, Christina Gillmann, Josef Focht, and Stefan Jänicke. 2020. A Survey on Visualizations for Musical Data. *Computer Graphics Forum (CGF)* (2020). https://doi.org/10.1111/cgf.13905 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cgf.13905

[12] Jong W. Kim, Justin Salamon, Peter Li, and Juan P. Bello. 2018. CREPE: A Convolutional Representation for Pitch Estimation. In *International Conf. Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, 161–165. https://doi.org/10.1109/ICASSP.2018.8461329

[13] Markus Löchtefeld, Sven Gehring, Ralf Jung, and Antonio Krüger. 2011. GuitAR: Supporting Guitar Learning through Mobile Projection. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems (CHI EA)*. ACM, 1447–1452. https://doi.org/10.1145/1979742.1979789

[14] Karola Marky, Andreas Weiß, Andrii Matviienko, Florian Brandherm, Sebastian Wolf, Martin Schmitz, Florian Krell, Florian Müller, Max Mühlhäuser, and Thomas Kosch. 2021. Let's Frets! Assisting Guitar Students During Practice via Capacitive Sensing. In *Proc. 2021 CHI Conf. Human Factors in Computing Systems (CHI)*. ACM, Article 746, 12 pages. https://doi.org/10.1145/3411764.3445595

[15] Kim Marriott, Falk Schreiber, Tim Dwyer, Karsten Klein, Nathalie Henry Riche, Takayuki Itoh, Wolfgang Stuerzlinger, and Bruce H. Thomas. 2018. *Immersive Analytics*. Springer LNCS 11190.

[16] Matthias Miller, Alexandra Bonnici, and Mennatallah El-Assady. 2019. Augmenting Music Sheets with Harmonic Fingerprints. In *Proc. ACM Symp. Document Engineering (DocEng)*. ACM, Article 17, 10 pages. https://doi.org/10.1145/3342558.3345395

[17] Matthias Miller, Hanna Schäfer, Matthias Kraus, Marc Leman, Daniel A. Keim, and Mennatallah El-Assady. 2019. Framing Visual Musicology through Methodology Transfer. abs/1908.10411 (2019). arXiv:1908.10411 http://arxiv.org/abs/1908.10411

[18] Tamara Munzner. 2009. A Nested Model for Visualization Design and Validation. *IEEE Trans. Visualization and Computer Graphics (TVCG)* 15, 6 (2009), 921–928. https://doi.org/10.1109/TVCG.2009.111

[19] Marc Satkowski and Raimund Dachselt. 2021. Investigating the Impact of Real-World Environments on the Perception of 2D Visualizations in Augmented Reality.

[20] In *Proc. 2021 Conf. on Human Factors in Computing Systems (CHI) (CHI '21)*. ACM, Article 522, 15 pages. https://doi.org/10.1145/3411764.3445330

[20] Michael Sedlmair, Mariah Meyer, and Tamara Munzner. 2012. Design Study Methodology: Reflections from the Trenches and the Stacks. *IEEE Trans. Visualization and Computer Graphics (TVCG)* 18, 12 (2012), 2431–2440. https://doi.org/10.1109/TVCG.2012.213

[21] Graeme Smith and Andrew Johnston. 2008. Interactive Software for Guitar Learning. In *Australasian Computer Music Conf. (ACMC)*. Australasian Computer Music Association.

[22] Richard Tang, Xing-Dong Yang, Scott Bateman, Joaquim Jorge, and Anthony Tang. 2015. Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises. In *Proc. ACM Conf. Human Factors in Computing Systems (CHI) (CHI '15)*. ACM, 4123–4132. https://doi.org/10.1145/2702123.2702401

[23] Bryan Wang, Meng Yu Yang, and Tovi Grossman. 2021. Soloist: Generating Mixed-Initiative Tutorials from Existing Guitar Instructional Videos Through Audio Processing. In *Proc. 2021 CHI Conf. Human Factors in Computing Systems (CHI)*. ACM, Article 98, 14 pages. https://doi.org/10.1145/3411764.3445162

[24] C. Ware, R. Arsenault, M. Plumlee, and D. Wiley. 2006. Visualizing the Underwater Behavior of Humpback Whales. *Computer Graphics and Applications (CG&A)* 26, 4 (2006), 14–18. https://doi.org/10.1109/MCG.2006.93

[25] W. Willett, Y. Jansen, and P. Dragicevic. 2017. Embedded Data Representations. *IEEE TVCG* 23, 1 (2017), 461–470. https://doi.org/10.1109/TVCG.2016.2598608

[26] Tetsuo Yamabe, Hiroshi Asuma, Sumire Kiyono, and Tatsuo Nakajima. 2011. Feedback Design in Augmented Musical Instruments: A Case Study with an AR Drum Kit. In *17th International Conf. Embedded and Real-Time Computing Systems and Applications (RTCSA)*, Vol. 2. IEEE, 126–129. https://doi.org/10.1109/RTCSA.2011.27

[27] Xingyao Yu, Katrin Angerbauer, Peter Mohr, Denis Kalkofen, and Michael Sedlmair. 2020. Perspective Matters: Design Implications for Motion Guidance in Mixed Reality. In *International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 577–587. https://doi.org/10.1109/ISMAR50242.2020.00085

[28] Beste F. Yuksel, Kurt B. Oleson, Lane Harrison, Evan M. Peck, Daniel Afergan, Remco Chang, and Robert J.K. Jacob. 2016. Learn Piano with BACh: An Adaptive Learning Interface That Adjusts Task Difficulty Based on Brain State. In *Proc. 2016 CHI Conf. Human Factors in Computing Systems (CHI)*. ACM, 5372–5384. https://doi.org/10.1145/2858036.2858388