Student Conference Proceedings
Vol 2, No 1, 2026, Article ID 2712, 4 Pages

Student Conference Lübeck

Proceedings Article

The Effects of Sonification on Motor Control in Juggling: The Role of Proficiency

Saewon Jeong[a,*] · Mara K. M. Grothus[a*] · Andreas Sprenger[b] · Marcus Heldmann[b*]

[a]Study program Psychology - Cognitive Systems, Universität zu Lübeck, Lübeck, Germany
[b]Klinik für Neurologie, Universität zu Lübeck, Lübeck, Germany
[*]Corresponding author, email: saewon.jeong@student.uni-luebeck.de; marcus.heldmann@uni-luebeck.de

Received 23 February 2026; Accepted 22 June 2026; Published online 10 July 2026

Abstract

Real-time sonification—the transformation of movement into sound—is widely reported to facilitate motor control. However, its impact on complex upper-limb coordination remains underexplored, particularly regarding how individual proficiency influences feedback reception. We analyzed juggling variability across temporal, spatial, velocity, and coordination dimensions using wearable sensors that mapped vertical hand movements to changes in auditory pitch. Although no within-subject effects were observed, analysis revealed a distinct proficiency-dependent response. Sonification enhanced stability for lower-proficiency jugglers but acted as a rhythmic perturbation for higher-proficiency jugglers, consistent with the expertise reversal effect. Furthermore, spatial stability remained unaffected regardless of proficiency, likely due to the visual primacy regulating spatial trajectories in juggling. These findings demonstrate that the efficacy of sonification is both proficiency-dependent and dimension-specific. Strategic application of augmented feedback must therefore consider individual internal models and task-specific sensory constraints.

I. Introduction

Human motor control relies on the integration of visual, auditory, and proprioceptive information to regulate movement [1]. However, the functional role of each sensory modality is not fixed; rather, it is dynamically weighted according to task demands and individual skill levels. In this context, juggling provides a representative model, as it is a highly structured upper-limb task characterized by precise spatiotemporal organization [2, 3]. Its regulatory parameters span temporal, spatial, and dynamical dimensions that are influenced by both internal motor models and augmented external feedback [4, 5].

Real-time sonification—the systematic transformation of kinematic data into acoustic signals [6]—represents a prominent application of this augmented information. Auditory feedback is known to facilitate motor learning and rehabilitation, primarily by enhancing movement awareness. Given the auditory system's sensitivity to temporal regularity and its potential to reduce reliance on visual processing [5], sonification can contribute to stabilizing the rhythmic structures inherent in juggling. Despite its potential, existing research has predominantly focused on lower-limb dynamics, such as gait rehabilitation [6], while its application in complex upper-limb coordination remains relatively underexplored. This gap is critical in juggling, as the coordination of upper-limb segments is governed by distinct control strategies depending on proficiency [2]. Consequently, a systematic investigation is required to determine whether and how auditory feedback interacts differently with the multi-dimensional regulatory parameters of such a sophisticated task depending on performers' proficiency levels.

The efficacy of augmented feedback, such as real-time sonification, is not universal but is contingent on the performer's baseline proficiency. Previous research indicates that novices often benefit from additional sensory information, whereas experts may experience redundancy or even interference due to well-established internal control processes [5]. As movement patterns become increasingly refined with practice, the processing of external information shifts with the development of stable internal motor models. This skill-dependent interaction has been formalized as the *Expertise Reversal Effect*, which suggests that sensory cues providing essential scaffolding for novices may become redundant or even counterproductive for experts [7]. In the context of juggling, lower-proficiency performers, who still exhibit variability in their vertical rhythms, may benefit from sonification as an external temporal reference to stabilize their timing. Conversely, for higher-proficiency jugglers with automated motor representations, the same auditory feedback may induce conscious interference, disrupting intrinsic movement stability rather than enhancing performance. Accordingly, the effects of sonification in juggling should be examined not only in terms of whether it influences motor control, but also in relation to how its effects vary as a function of individual proficiency.

The primary objective of this study is to investigate the effects of real-time sonification on juggling motor control strategies across four key dimensions: temporal, spatial, velocity, and coordination variability. Guided by previous findings on auditory feedback and the expertise reversal framework, we hypothesized that the impact of sonification would be proficiency-dependent. Specifically, lower-proficiency jugglers were expected to show reduced variability under sonification, whereas higher-proficiency jugglers were expected to experience weaker benefits or even increased variability. Furthermore, sonification was expected to preferentially influence rhythm-related parameters (i.e., temporal and velocity variability) rather than the spatial dimension.

II. Methods and materials

II.I. Participants

Seventeen healthy, right-handed volunteers (5 females, 12 males; Mean age = 24.71 ± 5.73 years) were recruited. Right-handedness was an inclusion criterion to minimize variability in motor dominance. All participants showed a baseline juggling proficiency of at least 15 consecutive catches in a three-ball cascade pattern. The study was conducted in accordance with established ethical guidelines, all participants provided written informed consent prior to the experiment.

II.II. Apparatus and Data Acquisition

Upper-limb kinematics were captured using an Inertial Measurement Unit (IMU)-based motion capture system (Xsens MVN, Xsens Technologies B.V., Enschede, The Netherlands). Eleven inertial sensors were placed at the head, sternum, pelvis, and bilaterally at the shoulders, upper arms, forearms, and hands. Data were sampled at 60 Hz. Full-body kinematics were reconstructed via the system's software (Xsens MVN Analyze 2019.2.1) and exported as C3D files, providing three-dimensional trajectories (x, y, z) of a 40-marker biomechanical model. Auditory feedback was processed via a Steinberg audio interface and delivered through stereo speakers at a consistent volume level.

II.III. Experimental Design and Procedure

A within-subjects design was employed in a controlled laboratory setting. Participants provided informed consent and completed a demographic questionnaire. Following sensor placement, a 1-minute familiarization period allowed participants to adapt to the physical constraints of the IMU sensors and the specific juggling balls used in the study. During this period no auditory feedback was given. The experimental task consisted of two conditions: (1) No-Sonification (control) and (2) Sonification (real-time auditory feedback). Each condition lasted 10 minutes, and the order of conditions was counterbalanced across participants to mitigate potential order effects. In the sonification condition, real-time auditory feedback was generated using Max 8 (v 8.5.3; Cycling '74). The vertical displacement (Z-axis) of the hands was mapped to a synthesized piano timbre. To ensure clear auditory separation, the right and left hands were assigned to distinct frequency ranges with a four-octave gap. The pitch was modulated according to the height of each hand. This mapping facilitated a real-time auditory representation of movement trajectories, establishing a direct correspondence between kinematic actions and sound.

II.IV. Data Processing and Statistical Analysis

Raw kinematic data were preprocessed in MATLAB (R2025b, MathWorks) by extracting the trajectories of three markers—the ulnar styloid, radial styloid, and the dorsal side of the hand—to derive a virtual hand centroid. Data integrity was maintained by interpolating missing values (0.01%–0.08% per trial) via the MoCap Toolbox [8]. Subsequently, high-frequency artifacts were removed using a second-order 15 Hz low-pass Butterworth filter with zero-lag technique [2]. For standardized comparisons, movement data were segmented based on the right-hand

DOI 10.18416/SCP.2026.2712

trajectory. An analysis window of 26 consecutive throws was defined, following an initial four-throw buffer to ensure motor stability. This 30-throw criterion represents the minimum performance threshold observed across all participants, ensuring a balanced within-subject design without data exclusion.

Movement stability was operationalized through four primary variables: temporal variability (coefficient of variation [CV] of inter-peak intervals), spatial variability (three-dimensional standard deviation [SD] of the hand centroid across the x, y, and z axes), velocity variability (CV of peak velocity as a proxy for force control), and coordination variability (SD of the discrete relative phase, ϕ). The effect of sonification was subsequently quantified using difference scores (Δ = Sonification − No-Sonification), with data normality verified through Shapiro–Wilk tests. Statistical analyses were conducted in R (v 4.4.3) with the significance level set at $\alpha = .05$. Differences between the Sonification and No-Sonification conditions were analyzed using paired-samples t-tests for parametric data (spatial and coordination variability) and Wilcoxon signed-rank tests for non-parametric data (temporal and velocity variability). Effect sizes were calculated using Cohen's d and matched-pairs rank-biserial correlations (r_B) for the respective tests. Additionally, the proficiency-dependent efficacy of auditory feedback was examined through correlation analysis, utilizing Pearson's r or Spearman's ρ to assess the relationship between the No-Sonification condition and sonification-induced changes (Δ).

III. Results and discussion

III.I. Absence of Uniform Sonification Effects

To assess the impact of real-time sonification, we examined whether the difference scores (Δ) for each kinematic variable significantly deviated from zero. As summarized in Table 1, the analysis of the full sample revealed no statistically significant differences between conditions across all measured dimensions ($p > .05$). This lack of significance at the aggregate level indicates that the auditory feedback did not induce a uniform or consistent shift in juggling stability across all participants.

Table 1: Comparison of movement variability between sonification and no-sonification conditions

Variable	No-Sonification	Sonification	Difference	p-value	Effect Size
temporal	4.48 (1.23)	4.89 (1.98)	0.41 (2.26)	0.831	-0.052
spatial	54.00 (15.1)	57.93 (18.6)	3.93 (18.0)	0.382	0.218
velocity	5.40 (1.85)	5.18 (2.02)	-0.22 (2.12)	0.309	-0.247
coordination	10.70 (3.92)	11.45 (2.77)	0.74 (3.15)	0.347	0.235

Note. Values in the No-Sonification, Sonification, and Difference columns are reported as mean (SD).

However, velocity variability demonstrated a modest decrease, despite the absence of significant overall effects ($m_{\text{diff}} = -0.22$, $\text{SD}_{\text{diff}} = 2.12$; $r_B = -0.25$). This suggests that the real-time auditory feedback may have served as a subtle guide for stabilizing the force applied to each throw. As illustrated by the individual slopes in Figure 1, the response to sonification was highly variable across participants, with some showing improved stability while others experienced disruption. These findings suggest that the effects of sonification may be masked when averaging across the entire sample, highlighting the need for a more detailed analysis based on individual proficiency levels.

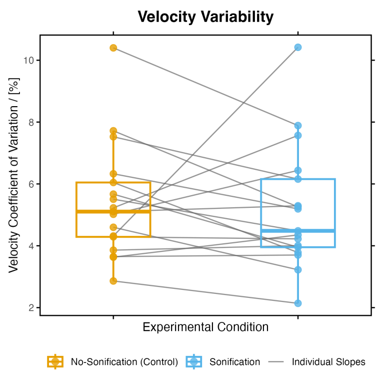

Figure 1: Velocity variability across experimental conditions.

III.II. Proficiency-Dependent Modulation of Movement Variability

Specifically, correlation analysis between variability in the control condition (No-Sonification) and sonification-induced changes in variability (Δ) revealed strong negative relationships across temporal ($\rho = -0.57$, $p = .017$), velocity ($\rho = -0.65$, $p = .005$), and coordination ($r = -0.71$, $p = .001$) metrics. These findings indicate that the impact of sonification varied by individual proficiency, as illustrated in Figure 2.

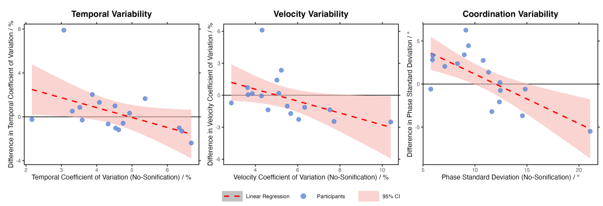

Figure 2: Relationship between control variability and sonification-induced changes in movement metrics.

Consistent with the hypothesized *Expertise Reversal Effect*, this proficiency-dependent pattern suggests that additional sensory information can become redundant or even disruptive for individuals with well-established motor schemas [7]. For lower-proficiency jugglers, sonification likely functioned as a regulatory signal, provid-

DOI 10.18416/SCP.2026.2712

ing a rhythmic reference to stabilize their kinematic patterns. Conversely, for higher-proficiency jugglers with robust internal models, the real-time auditory information acted as a rhythmic perturbation [5]. This external feedback may have induced conscious monitoring of otherwise automated processes, thereby compromising the intrinsic stability. While these kinematic findings establish a clear objective basis for proficiency-dependent interference, future studies should integrate subjective reports to further validate the underlying cognitive processes.

III.III. Dimension-Specific Limits on Spatial Variability

In contrast to the temporal, velocity, and coordination measures, spatial variability did not show a significant correlation with individual proficiency levels ($r = -0.38$, $p = .131$). One possible explanation is that spatial aspects of juggling rely strongly on visual information [4]. Precise throwing and catching are supported by continuous visual monitoring of ball trajectories; in such visually dominated control dimensions, auditory feedback may provide functionally redundant information that fails to be integrated into the existing visual control [5]. Furthermore, as the present study quantified integrated 3D spatial variability to reflect the multi-dimensional nature of juggling, the specific mapping of feedback to vertical (Z-axis) movement may have selectively influenced rhythmic and force-related parameters rather than 3D spatial precision.

Consequently, the present findings indicate that proficiency-dependent effects were not evident for hand-level spatial variability under the current experimental conditions. Future research investigating vision-restricted conditions or multi-dimensional mapping strategies may clarify whether sonification plays a compensatory role in spatial control across all dimensions.

IV. Conclusion

This study investigated the multi-dimensional effects of real-time sonification on juggling motor control. Although the intra-individual responses across sonification conditions did not manifest as a uniform trend, significant response patterns were identified through an in-depth analysis accounting for individual proficiency levels. Specifically, sonification served as a stabilizing reference for lower-proficiency jugglers but acted as a rhythmic perturbation for higher-proficiency jugglers, providing robust empirical support for the Expertise Reversal Effect. Furthermore, the lack of spatial response confirms that the efficacy of auditory feedback is dimension-specific, as spatial trajectories in juggling remain governed by visual primacy. These results indicate that for augmented feedback to be effective, it must be strategically aligned with the performer's internal models and the task's modality-specific constraints. To better define the boundaries of auditory-motor integration, future studies should combine subjective reports with multi-dimensional mapping strategies or vision-restricted tasks. These insights will guide the development of proficiency-dependent, personalized feedback systems for high-performance motor skills.

Acknowledgments

The work has been carried out at the Klinik für Neurologie, Universität zu Lübeck.

Google Gemini (Gemini 3.1 Pro) was used as an aid for coding and troubleshooting in MATLAB and R.

Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

References

[1] M. S. Gazzaniga, R. B. Ivry, and G. R. Mangun, Cognitive Neuroscience: The Biology of the Mind, 5th ed. New York: W. W. Norton & Company, 2019, ISBN: 9780393603170.

[2] M. Zago, I. Pacifici, N. Lovecchio, M. Galli, P. A. Federolf, and C. Sforza. Multi-segmental movement patterns reflect juggling complexity and skill level. *Human Movement Science*, 54:144–153, 2017, doi:10.1016/j.humov.2017.04.013.

[3] A. A. M. van Santvoord and P. J. Beek. Spatiotemporal variability in cascade juggling. *Acta Psychologica*, 91:131–151, 1996, doi:10.1016/0001-6918(94)00044-1.

[4] R. Huys and P. J. Beek. The coupling between point-of-gaze and ball movements in three-ball cascade juggling: The effects of expertise, pattern and tempo. *Journal of Sports Sciences*, 20(3):171–186, 2002, doi:10.1080/026404102317284745.

[5] R. Sigrist, G. Rauter, R. Riener, and P. Wolf. Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review*, 20(1):21–53, 2013, doi:10.3758/s13423-012-0333-8.

[6] T. H. Nown, P. Upadhyay, A. Kerr, I. Andonovic, C. Tachtatzis, and M. A. Grealy. A mapping review of real-time movement sonification systems for movement rehabilitation. *IEEE Reviews in Biomedical Engineering*, 15:310–323, 2022, doi:10.1109/RBME.2021.3121544.

[7] S. Kalyuga, P. Ayres, P. Chandler, and J. Sweller. The expertise reversal effect. *Educational Psychologist*, 38(1):23–31, 2003, doi:10.1207/S15326985EP3801_4.

[8] B. Burger and P. Toiviainen, Mocap toolbox: A matlab toolbox for computational analysis of movement data, in *Proceedings of the Sound and Music Computing Conference*, 172–178, 2013.

