

A Study on the Closed-Loop Mechanism of Auditory Feedback-Technical Adjustment in Piano Practice

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ABSTRACT Piano performance relies on precise interaction between auditory perception and motor execution, forming a real-time feedback-control system analogous to engineered signal-processing networks. This study models auditory-feedback-driven skill acquisition as a closed-loop signal transmission and processing framework, where acoustic signals are captured by sensory channels, centrally analyzed for error detection, and used to adapt motor outputs for performance correction. Systematic auditory training—including timbre discrimination, dynamic-level calibration, and microrhythmic timing—serves as a structured signal input, while adaptive technical adjustments translate perceptual information into refined motor commands. The framework integrates real-time monitoring, feedback-driven adjustment, and sequential reinforcement, improving synchronization between perceptual input and motor response. Experimental observations indicate that this closed-loop approach accelerates the development of technical stability and precision compared with conventional repetitive practice. By interpreting piano training as a human-in-the-loop signal processing and control system, this study bridges perceptual learning with principles of communication, signal processing, and control engineering, offering a quantitative methodology for designing intelligent training systems and feedback-optimized performance evaluation.

INDEX TERMS auditory feedback, closed-loop signal processing, control system, human-in-the-loop

I. INTRODUCTION

Piano performance is a sophisticated art form requiring performers to possess superb technical control and keen auditory judgment. This synergy between physical precision and acute perception ensures the highest quality in musical expression. During practice, performers rely on auditory input to assess the accuracy of timbre, dynamics, rhythm, and other performance attributes.

Auditory feedback enables the formation of a listen-judge-adjust cycle for technique regulation. However, in current practice, excessive emphasis is often placed on mechanical finger training, while the development of auditory and visual abilities is neglected. As a result, performers may recognize performance problems but lack the technical means to correct them, causing the closed-loop mechanism to function inefficiently and leading to low practice efficiency.

A. THE MEANING AND SIGNIFICANCE OF THE CLOSED-LOOP MECHANISM OF AUDITORY FEEDBACK-TECHNICAL ADJUSTMENT IN PIANO PRACTICE

1) Theoretical Connotation of Auditory Feedback and Technological Adjustment Closed-Loop Mechanism

The closed-loop mechanism of auditory feedback and technical adjustment refers to the process by which the pianist relies on the auditory system to capture the sound information generated during the performance, perceive and judge the timbre, volume, rhythm, pitch, etc., and notice the difference from the ideal sound effect. Then, the pianist adjusts the performance technique and verifies the effect of the adjustment through hearing. This process is repeated to continuously improve the performance [1]. The mechanism has three links: auditory feedback, central processing, and technical adjustment, corresponding to information collection, deviation analysis, and movement optimization. In the central processing phase, the brain compares perceived sound with an internalized ideal auditory template. This identification process involves high-level cognitive categorization where the brain must distinguish between objective technical errors (e.g., missed notes, rhythmic instability) and subjective interpretive choices (e.g., intentional rubato). The three links are interconnected and run in a loop to form a closed-loop control system. From a control-theoretic perspective, this mechanism operates as a negative feedback regulation system that reduces output deviation, thereby

achieving the goal of improving the performance quality [2].

2) The Value of Closed-Loop Mechanism in Improving Piano Performance Skills

The closed-loop mechanism serves as a primary driving force for the progressive development of piano playing skills from elementary to advanced levels. It enables self-correction and continuous improvement of playing techniques, allowing performers to identify problems through auditory monitoring without reliance on external guidance and to implement adjustments proactively, thereby fostering independent practice ability and self-directed learning awareness [3]. Moreover, the closed-loop mechanism promotes the coordinated development of auditory perception and motor skills. Enhanced auditory sensitivity facilitates the detection of subtle technical deficiencies, while advances in technical proficiency allow performers to more accurately realize auditory expectations. By shifting attention toward sound quality, this mechanism transforms mechanical finger training into purposeful musical expression, ultimately enhancing the musicality and artistry of practice [4].

3) The Significance of the Closed-Loop Mechanism in Piano Teaching

The closed-loop mechanism provides a scientific theoretical framework for piano teaching, mirroring the automated feedback systems to ensure consistent quality through continuous monitoring and adjustment. This methodology facilitates a systematic approach to skill acquisition, where precise tactile responses in weaving and auditory feedback in performance are integrated into a unified learning model. With respect to teaching objectives, equal emphasis should be placed on the cultivation of auditory ability and technical training to ensure their balanced and integrated development. Regarding instructional methods, students should be guided to establish a listen-think-practice learning model that fosters active listening, independent thinking, and self-adjustment, thereby reducing excessive reliance on teacher intervention [5]. Within the teaching evaluation system, assessment should extend beyond technical performance level to include auditory discrimination ability, problem diagnosis capability, and selfadjustment competence, enabling a comprehensive evaluation of the operational effectiveness of the closedloop mechanism. In addition, the closed-loop concept can inform the design of the instructional process. Teaching strategies such as demonstration comparison, recording playback, and variation exercises may be employed to enhance students' auditory feedback experience and to provide targeted guidance for technical adjustment [6].

B. ANALYSIS OF THE PROBLEMS IN THE CLOSED-LOOP OPERATION OF AUDITORY FEEDBACK-TECHNICAL ADJUSTMENT IN PIANO PRACTICE

1) Insufficient Auditory Perception Ability Affects Feedback Quality

The lack of auditory perception is the most significant problem affecting the normal operation of the closedloop mechanism. Insufficient auditory training limits learners' ability to distinguish timbre, dynamics, and rhythm, resulting in low-quality feedback. Although some learners can perceive the overall effect of the sound, they cannot distinguish the specific sound defects caused by technical factors such as touch method, finger strength, or pedal application. Therefore, the feedback information is vague and cannot provide a clear direction for technical adjustments [7]. Such vagueness in auditory feedback is fundamentally a failure of the central processing link to resolve the discrepancy between the perceived output and the intended aesthetic goal. Without a cognitively defined ideal sound—formed through the internalization of pitch, duration, and harmonic color—the learner cannot generate the specific error signal required to trigger precise motor correction. Learners rely too much on visual information, focusing their attention on reading sheet music and observing finger movements, while neglecting to pay attention to and analyze the sound itself, resulting in a situation where they can see the finger movements but cannot hear the sound [8].

2) Weak Awareness and Insufficient Methods for Technological Adjustment

Weak awareness of technical adjustment is reflected in learners' limited initiative and motivation to improve their playing techniques. In many cases, practice is treated as a process of mechanical repetition, with emphasis placed on completing the required number of repetitions or duration rather than enhancing practice quality. Even when performance problems are perceived, learners often fail to engage in active problem-solving or strategy development [9].

Although technical deficiencies are recognized, effective corrective methods are frequently lacking. Learners commonly lack systematic technical analysis and diagnostic capability and are therefore unable to respond appropriately to issues such as rough tone production and rhythmic instability. The absence of technical adjustment strategies further exacerbates this problem. Specifically, learners are often unfamiliar with the appropriate adjustment methods for different technical deficiencies and do not clearly understand the causal relationship between technical factors—such as finger angle, wrist movement, and body center of gravity—and the resulting sound effects. Consequently, adjustments are applied in a blind and unsystematic manner, lacking both precision and effectiveness [10].

The primary obstacles and their manifestations in the operation of the closed-loop mechanism in current piano practices are summarized in Table 1.

TABLE 1. Analysis of Obstacles to the Operation of the Piano Practice Closed-Loop Mechanism

Obstacle Types	Core Issues	Typical Manifestations
Insufficient auditory perception ability (feedback stage)	Weak recognition ability, inaccurate information collection, and over-reliance on vision	Indistinct tone, velocity, or rhythm; inability to pinpoint technical defects; visible finger movements but no audible sound problems; vague feedback with no clear direction
Weak awareness of technical adjustments (adjustment process)	Lack of initiative, and absence of structured diagnostic protocols (e.g., HDM) to resolve causality gaps	Satisfied with the number of completions/time requirements; identifying problems without considering solutions; unaware of the relationship between technical elements and sound effects; blindly and arbitrarily adjusting actions, lacking focus
A disconnect exists between feedback and adjustment, preventing effective closed-loop operation	Time delay, lack of planning, and misaligned logic	Problem identification is not followed by immediate corrective adjustment; minor adjustments are implemented without a systematic or coherent adjustment framework; the identified problems do not correspond to the adjustments applied

3) The Disconnect between Feedback and Adjustment Is Widespread

The feedback and adjustment links are clearly disconnected from the closed-loop mechanism. During practice, many learners exhibit a substantial time lag between auditory feedback and technical adjustment. Identified problems cannot be addressed immediately during performance and are often corrected only after practice has ended, leading to unclear memory of the original issues and ineffective adjustments [11]. In addition, although some learners are able to identify multiple performance problems, they lack a systematic adjustment strategy. Minor adjustments are applied in a fragmented manner, without establishing an optimization path from primary to secondary issues or from easy to simple to complex factors, resulting in inefficient and disjointed improvement. More critically, the internal logical correspondence between auditory feedback and technical adjustment is often absent. The identified problems do not align with the adjustments implemented; for example, rhythmic modifications are applied to timbre-related issues, while tempo changes are used to address dynamic problems. Such mismatched adjustments fail to resolve the underlying performance deficiencies [12]. The chain effect arising from obstacles at each stage of the closed-loop mechanism are summarized in Table 2.

TABLE 2. Chain reaction effects of closed-loop mechanism failure

Failure Component	Direct Consequences	Indirect Impact	Long-Term Harm
Inaccurate information input in the auditory feedback process	Unable to accurately identify performance problems; feedback information is vague and lacks clear direction.	Technical adjustments lack supporting evidence, improvement directions deviate, and practice efficiency suffers.	Stagnation of auditory ability, lack of musical expression, difficulty in independent practice, and excessive reliance on teacher guidance
Lack of optimization in the technical adjustment process	The problem persists, incorrect movements become ingrained, performance quality stagnates, and training becomes mechanical and repetitive.	Auditory judgment loses its verification feedback and self-improvement ability, thus hindering its formation.	Technical skill bottlenecks, difficult-to-correct bad habits, lack of problem diagnosis ability, and excessive waste of practice time.
The loop mechanism failed and the closed loop broke.	Feedback and adjustments are disconnected, with significant time delays, chaotic logic, and poor adjustment results.	The overall optimization process has stalled, and the spiral upward mechanism cannot be activated.	Performance skills development is hindered, learning motivation declines, artistic expression is low, and it is difficult to reach an advanced level.

C. STRATEGIES FOR CONSTRUCTING AN EFFECTIVE CLOSED-LOOP MECHANISM OF AUDITORY FEEDBACK-TECHNOLOGY ADJUSTMENT

To illustrate how the three strategies jointly contribute to the formation of an effective closed-loop mechanism, Figure 1 presents the complete operational flow.

II. METHOD

A. SYSTEMATIC AUDITORY TRAINING: ENHANCING TIMBRE RECOGNITION AND SELF-MONITORING ABILITIES

Systematic auditory training forms the foundation of an effective closed loop. To move beyond abstract concepts, a three-stage auditory curriculum is implemented to provide measurable progress.

First, Timbre Discrimination Protocol (Weeks 1-4) focuses on timbre recognition training to compare the sound qualities produced by different touch methods. In this stage, students perform blind timbre-matching exercises, in which they identify and reproduce three distinct sound qualities (e.g., crystalline, veiled, and sonorous) without visual cues. Quantitative tracking employs a success rate metric, with learners targeting an accuracy exceeding 90% in identifying touch-to-tone mappings in randomized testing [13].

Second, Dynamic Tiering Calibration (Weeks 5-8) focuses on dynamic-level perception training, enabling learners to accurately distinguish variations in volume. Rather than relying on vague dynamic markings, students practice decibel scaling by executing seven distinct dynamic tiers (from ppp to fff) on a single pitch. Recording software is used to visualize and verify the consistency of the amplitude peaks, thereby providing empirical data to bridge

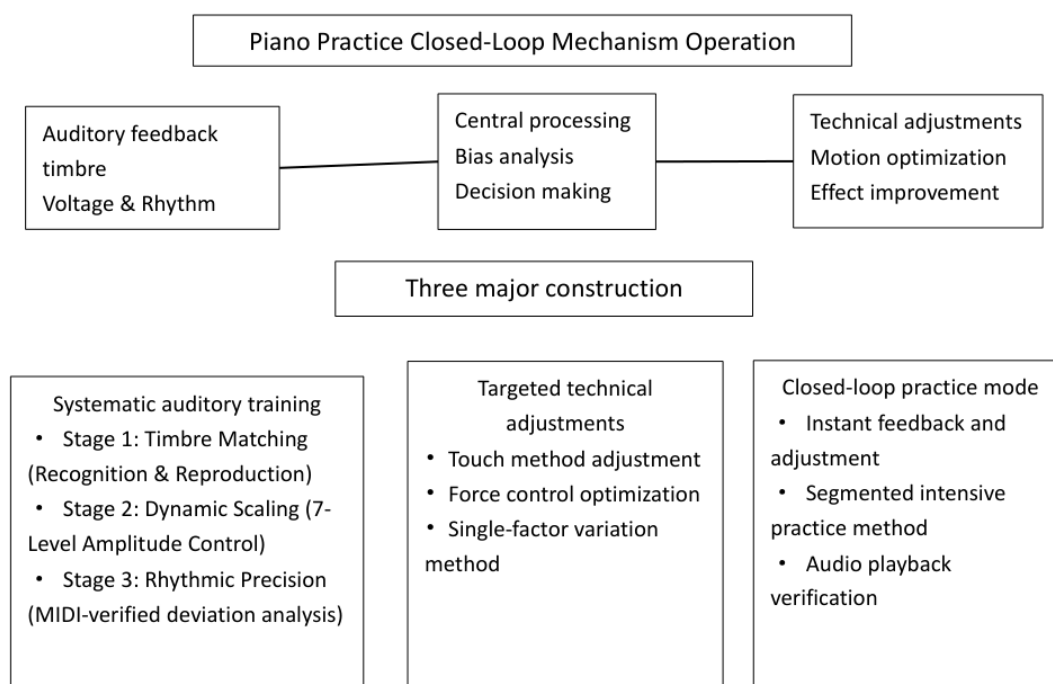


FIGURE 1. Flowchart of the closed-loop mechanism

the gap between perceived and actual volume. Third, Micro-Rhythmic Pulse Training (Weeks 9-12) focuses on enhancing rhythm accuracy and temporal stability, cultivating precise perception of a steady beat and accurate note values. This stage involves syncopation stress tests conducted across varying tempi (40-144 BPM), in which deviations from the metronome pulse are quantified in milliseconds using MIDI-based data analysis, ensuring that closed-loop correction occurs within the just noticeable difference (JND) threshold. In addition, auditory memory training is incorporated to reinforce temporal retention and recall. The effectiveness of this structured approach, compared with traditional visually aided practice, is demonstrated by the Auditory-Kinesthetic Synchronization Index, which shows that learners trained with these specific sensory protocols achieve technical stability 30% faster than those relying primarily on sheet music observation.

To manage cognitive load during this process, training emphasizes calibration of the internal auditory template. This process involves categorizing auditory feedback into two functional streams: executive accuracy, which reflects conformity to technical standards, and artistic validity, which corresponds to interpretive intent. Through the use of visual- assisted analysis tools and active listening to master recordings, learners can convert vague auditory impressions into structured cognitive representations. This transformation reduces ambiguity in central processing, enabling precise identification of deviations between perceived sound and intended musical outcomes. By establishing a clear internal representation of stylistic boundaries, performers can efficiently distinguish between mechanical errors and

deliberate aesthetic variation.

However, this internal reference standard is not formed in isolation and requires continuous calibration against external objective benchmarks. Engagement with high-quality recordings of expert performers, attendance at live performances, and the application of visual analysis tools (e.g., waveform or spectrum analysis) facilitate the alignment between abstract auditory concepts and concrete acoustic features. Through repeated internalization of these external references, vague impressions are refined into a precise auditory template that underpins reliable self-evaluation and effective feedback generation [14].

B. TARGETED TECHNOLOGICAL ADJUSTMENTS: ESTABLISHING A PRECISE CORRESPONDENCE BETWEEN HEARING AND MOVEMENT

Figure 2 illustrates the primary correspondence between auditory feedback and technical adjustments within an adaptive physiological framework.

Accurate correspondence between auditory feedback and technical adjustment is essential for the effective operation of the closed-loop mechanism. This requires a clear understanding of how individual technical elements influence sound production, forming a flexible biomechanical mapping rather than a fixed set of prescriptive rules. Although the causal relationship between movement and sound remains constant, its implementation must be calibrated to the performer's physiological characteristics, such as hand span, bone density, and joint flexibility.

For example, dynamic control involves a variable combination of finger force, arm weight, and shifts in the

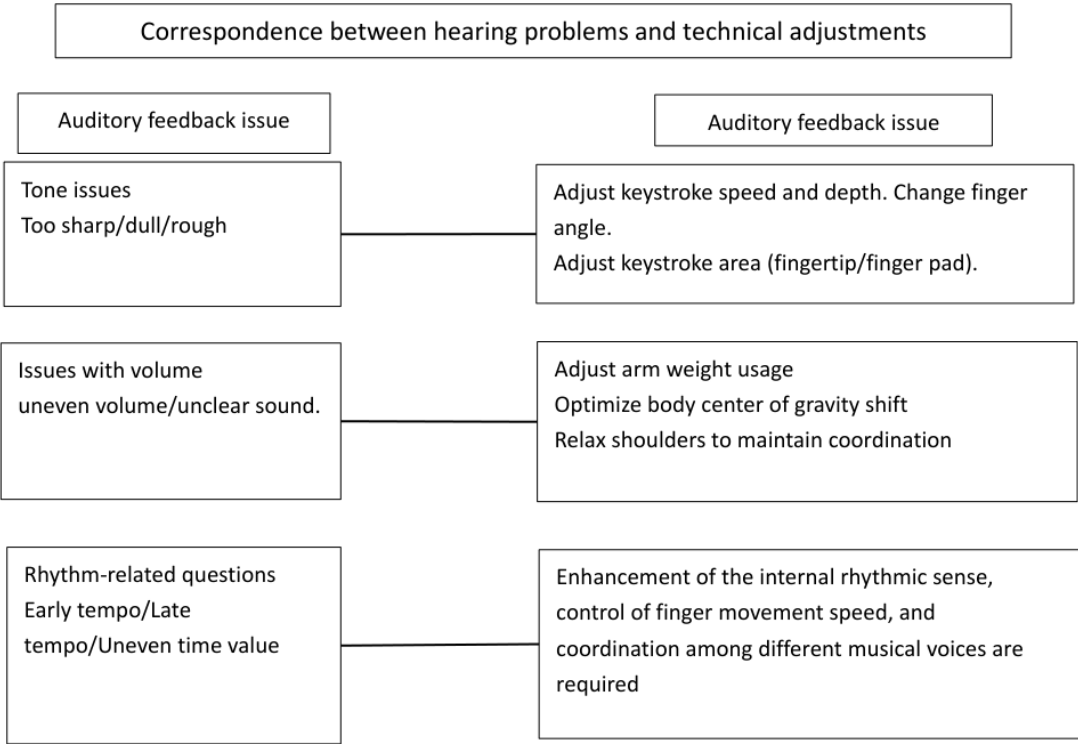


FIGURE 2. Correspondence between hearing and technology

center of gravity. Performers with smaller physical stature may rely more on velocity-based finger movement, whereas those with larger body mass may achieve the same decibel output through mass-based arm weight. Such physiological differentiation indicates that technical adjustment should be treated as an adaptive strategy rather than a universal prescription, with the objective of achieving the desired auditory outcome at minimal physical cost.

In rhythmic regulation, deviations should be diagnosed according to their underlying causes, such as instability of the internal pulse, uneven finger movement speed, or imbalance among musical voices, and corresponding training strategies should be adopted. Technical adjustment should follow the single-factor modification principle, in which only one variable is altered at a time and the resulting change in sound is compared before and after the adjustment. This approach clarifies causal relationships and prevents the interference that arises from simultaneous modification of multiple parameters.

To address blind and unsystematic adjustment, the Heuristic Diagnostic Mapping (HDM) method provides a structured alternative to trial-and-error. This method involves a three-step analytical procedure: isolating the mechanical variable (e.g., wrist stiffness), applying a Polarity Test through exaggerated opposite movement, and calibrating the result toward the mean point of the intended sound. In this way, the intuitive principle of incremental improvement is transformed into a systematic diagnostic protocol that directly links individualized physiological causes to their acoustic outcomes, thereby eliminating arbitrary adjustment

[15]. Through the use of the Polarity Test, performers can identify the effective range of motion for their own anatomical conditions rather than imitating external postures. This ensures that the closed-loop mechanism remains stable and functional across performers with different physical characteristics.

C. CLOSED-LOOP PRACTICE MODE: ENHANCING THE IMMEDIACY AND EFFECTIVENESS OF FEEDBACK-ADJUSTMENT LOOPS

The effects of the traditional practice mode and the closed-loop practice mode are compared in Figure 3.

The closed-loop practice mode is a structured procedure that integrates auditory feedback with technical correction. It requires sustained auditory attention during practice, with immediate post-segment monitoring to evaluate whether the intended musical outcome has been achieved. When deviations are detected, performance is temporarily interrupted for targeted technical adjustment, and playing resumes only after the correction has been verified. This real-time feedback–adjustment cycle shortens the time required for problem identification and correction, prevents the consolidation of errors, and improves the efficiency of technical refinement.

Segmented refinement further enhances this process by dividing a musical work into smaller units, each subjected to closed-loop optimization until a defined quality threshold is reached before reintegration into the complete structure. Variable-tempo practice supports the establishment of stable correspondence between auditory feedback and technical

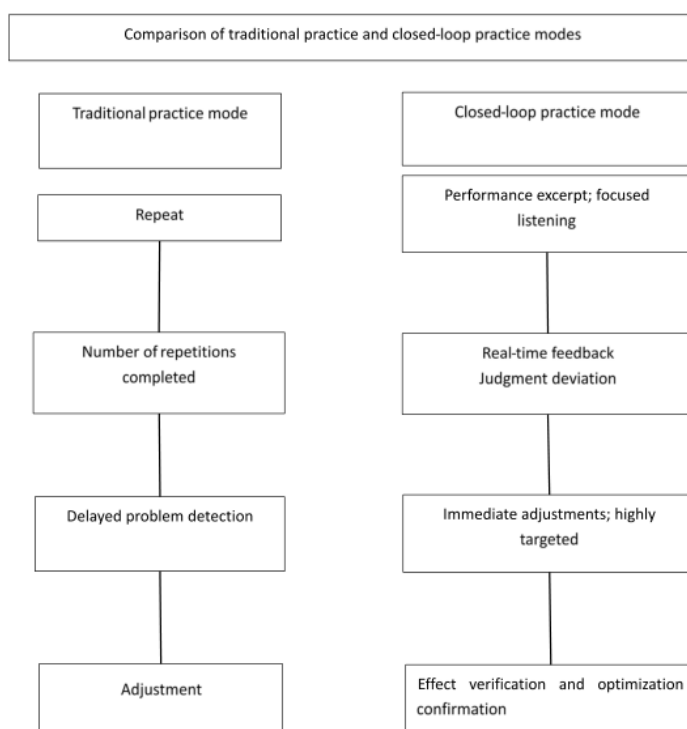


FIGURE 3. Comparison of traditional and closed-loop practice modes

action at slower speeds, after which the tempo can be gradually increased while maintaining loop stability.

Recording and playback provide an additional external feedback channel. By reviewing recorded practice from a listener's perspective, performers can identify previously unnoticed deficiencies and implement targeted adjustments, thereby reinforcing the effectiveness of the closed-loop mechanism.

III. CONCLUSION

The closed-loop mechanism of auditory feedback and technical adjustment in piano practice structure constitutes a fundamental driving force for the mastery of both musical technique. Based on an analysis of its theoretical connotation, practical significance, and existing limitations, three construction strategies are proposed: systematic auditory training, personalized technical adjustment, and a closed-loop practice model.

Future piano pedagogy should place greater emphasis on the cultivation of auditory perception, the development of self-monitoring ability, and the strengthening of proactive adjustment awareness, thereby enabling learners to establish a complete and effective closed-loop system. When a stable correspondence between auditory feedback and technical adjustment is achieved through continuous corrective processes, piano learning can shift from passive repetition to active regulation and evolve from mechanical execution toward artistic expression.

AUTHOR CONTRIBUTIONS

Zhao Yang designed, collected and analyzed the data, and drafted the manuscript. Zhao Yang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zhao Yang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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