Accessible Wind Instruments:
Normalizing Breath Control Around Comfort

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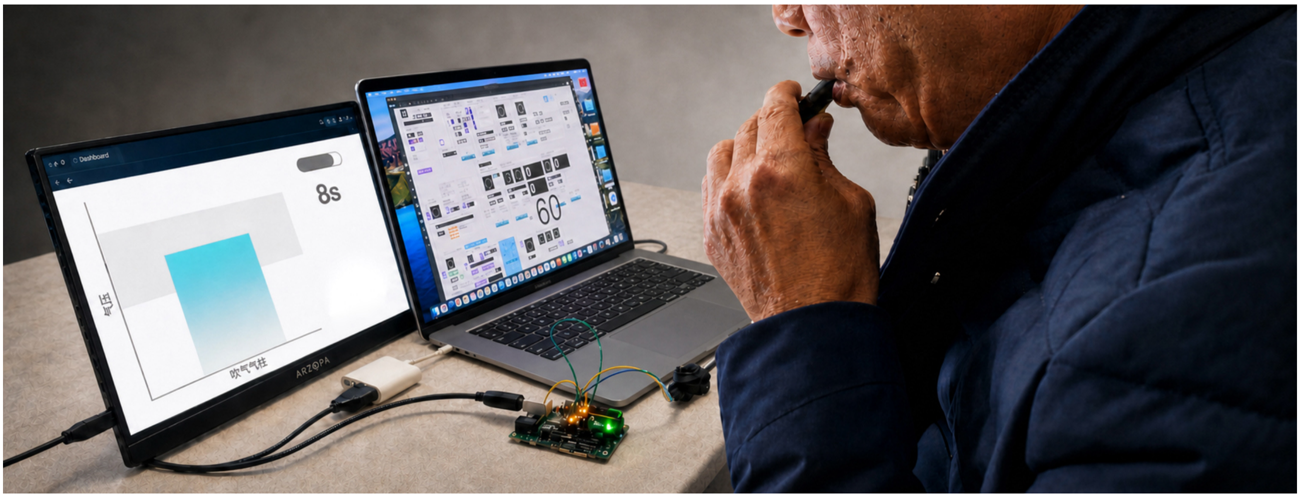

Figure 1: Experimental setup of the breath-interaction prototype used in the pilot study.

Abstract

Breath pressure is a core expressive input for digital wind instruments. However, differences in performers' breath capacity and control stability mean that some users may not access the full range of breath input values or may not sustain higher breath pressures for long periods. This can limit their access to the intended expressive range of the instrument. As part of the development of an accessible digital wind instrument, this paper introduces a normalized breath-pressure scale centered on long-duration comfort. Breath pressure is mapped to a unified control scale, aligning each user's comfort region into a common space while defining a personalized upper boundary to support comfortable and repeatable use. Implemented in a real-time Arduino–Max/MSP prototype, the approach allows mappings and task thresholds to be specified in terms of this normalized scale, reducing dependence on absolute pressure magnitudes. A small pilot with two older participants illustrates the workflow from calibration and normalized-scale task execution to descriptive analysis of task performance, fatigue ratings, breath signals, and brief post-task feedback. The main contribution is a prototype-level calibration logic organized around comfortable long-duration control, supporting a more interpretable task space for breath-based musical interaction.

Keywords

Breath interaction, Digital Wind Instrument, Normalization, Calibration, Inclusive Musical Interfaces

1 Introduction

Breath pressure is a core expressive input for digital wind instruments. Through breath control, performers articulate dynamic nuance—from gradual swells to sustained, steady tones. In real use, however, users differ greatly in breath capacity and control stability: some can sustain a steady airflow with ease, while others fluctuate more or fatigue faster. These differences are often more visible in older users, where age-related declines in respiratory strength and endurance can make sustained control harder [1][2]. Beyond physiological capacity, individual variation in interaction habits and blowing strategies further complicates control. Users may differ in embouchure, mouthpiece position and blowing intensity, meaning that even under identical instrument settings, the effective input range varies

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noticeably across individuals. Consequently, relying on a small set of standardized sensitivity presets may not accommodate the diversity of user capabilities.

Some existing systems attempt to address this variability through calibration, for example by setting an upper limit from a user's maximum breath pressure, adjusting mapping sensitivity, or having users try repeatedly to find a start-blowing threshold and a usable input range [5][6][7]. These methods are useful for estimating upper capacity, but peak pressure mainly reflects what a user can reach momentarily, rather than what they can comfortably and repeatedly control in sustained use.

This motivates a different calibration logic: calibration remains necessary, but the mapping should be organized around each user's comfortable, repeatable control range for sustained use, rather than around peak pressure alone. Based on this idea, this paper introduces a normalized breath-pressure scale centered on long-duration comfort. The method identifies each user's comfortable breath reference and aligns it to the midpoint of a unified scale, then defines a personalized upper boundary so that the main control region does not sit near maximum effort while still preserving dynamic range. With these two anchors, raw breath pressure is mapped to a unified 0–100 scale, referred to in this paper as U-space. This allows task goals and thresholds to be specified in U-space rather than through user-specific absolute pressure values.

U-space provides a common reference for task design across users with different breath ranges. For example, the same long-tone task can be defined as "keep U within 45 to 55" for all participants, and a crescendo–decrescendo task can be described as "move U from 25 up to 60, then back to 25." This makes task instructions, logging, and comparison easier to keep consistent across participants.

This paper makes three main contributions: (1) a calibration method organized around comfortable long-duration pressure; (2) a personalized upper working boundary defined from peak-related information; and (3) a shared U-space that supports more interpretable and comparable task definition across users.

2 Related Work

Digital wind instruments use continuous controls such as breath, fingering, and mouth posture to support expressive playing. Commercial digital wind instruments usually treat mouthpiece breath pressure as the main continuous input and often combine it with bite or lip sensing for extra modulation such as vibrato, pitch bend, or timbre change [5][6][7]. Their working range is typically shaped through start-blow thresholds, upper limits, response curves, and sensitivity settings [5][6][7]. Such parameters are useful for adapting the instrument response, but they are often organized around sensor limits, fixed presets, or momentary peak output rather than around what a player can comfortably and repeatedly control during sustained use. This distinction matters because threshold and range settings shape both access and effort. If the start-blow threshold sits too close to a level that the user can only just sustain comfortably, activation can become fragile and sound may flicker on and off. If the main control range sits too close to a high-effort region, users may need to blow harder simply to maintain stable output. The key issue is therefore not to remove effort from musical interaction, but to avoid making high effort necessary for stable sound.

Although commercial digital wind instruments often provide calibration options, these settings may still be difficult to interpret for users with less technical knowledge. Parameters such as sensitivity, response curves, and thresholds are not always easy to relate to one's own capability. As a result, users may avoid changing defaults or may find it difficult to distinguish between personal control difficulty and a poorly matched configuration. Similar issues also motivated the design direction of the present prototype: a calibration approach that is easier to understand and easier to set around comfortable and repeatable breath control.

Research prototypes in the NIME literature also treat breath control and wind-instrument interaction as design problems that can be reconfigured rather than simply inherited from acoustic wind instruments. Scavone's The Pipe explored breath pressure as a core control input and demonstrated flexible mappings between breath and sound [3]. More recent accessible or alternative wind-interface projects, including KeyWI, the Augmented Flute for Beginners, and The Birl, address ease of use, feedback, alternative fingering/control strategies, and adaptive or learned mappings [8][9][10]. These works show that the design of the breath-control space is not only a sensing problem, but also an accessibility and mapping problem.

From a physiological perspective, if breathing loads stay close to or above the level that the respiratory muscles can comfortably maintain, fatigue becomes more likely. This can reduce the ability to generate and maintain breath pressure, increase pressure variability, and lower overall performance [11]. Studies of wind-instrument performance and wind players also show that respiratory function, breathing difficulty, and physical demands are relevant to performance quality and comfort [4][12][13]. This helps explain why control steadiness often drops and errors increase during longer wind playing. In this paper, stability refers to predictable control in interaction terms; it does not deny that instability can also have musical value in improvisation. For this reason, the comfort region is treated as an important reference in design and calibration, so that the main control space does not sit in a high-load region that may accelerate fatigue.

Taken together, prior work and early prototype observations point to the same design problem: the key issue is not only how to capture breath input, but how to define a control range that remains comfortable, understandable, and usable during longer and repeatable interaction.

3 Method

Figure 2 provides an overview of the prototype workflow, from breath-pressure sensing and Arduino-side preprocessing to Max/MSP-based calibration, U-space mapping, task execution, and data collection. In this workflow, breath-pressure input was first processed into a baseline-corrected signal and then mapped into U-space after participant-specific calibration. U-space was used as the shared control scale for task targets, control thresholds, user-interface feedback, sound response, and data logging. After calibration, two older participants completed the same interface-guided task workflow, including long-tone holding, crescendo–decrescendo control, rhythmic triggering, and free exploration. The collected data were then used for descriptive analysis of task performance, fatigue ratings, breath-signal patterns, and brief post-task feedback.

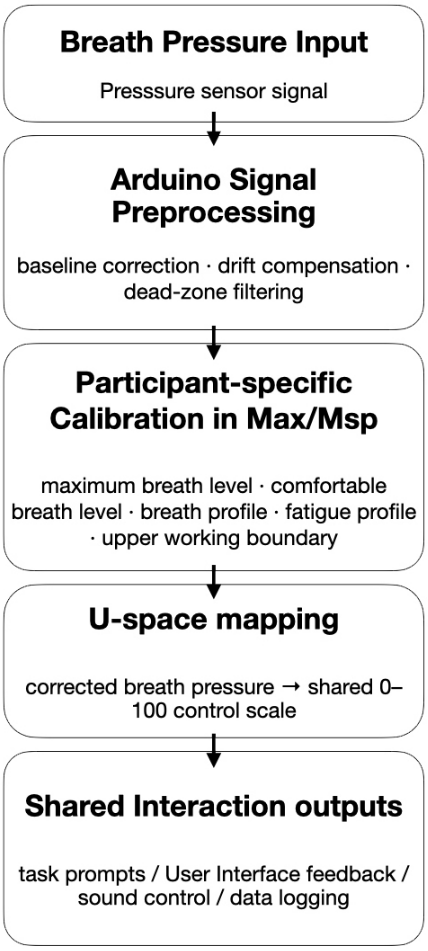

Figure 2: Prototype workflow for breath-pressure calibration and interaction.

Building on the workflow, the method was organized into two phases: Phase 1 established participant-specific calibration values and coarse profile groupings, which were then used to derive the personalized working boundary. Phase 2 observed how participants performed a common set of tasks in U-space after calibration.
The procedure involved four stages:

(1) Estimating a maximum breath reference for each participant.
(2) Estimating a comfortable long-duration breath reference that could be sustained with relative ease over time.
(3) Defining a personalized upper working boundary based on these two reference values, positioned below maximum effort.
(4) Mapping baseline-corrected breath pressure into U-space for task execution and analysis.

3.1 Participants

Two older adult participants took part in the pilot, both aged 63 at the time of the study. Neither had prior experience with wind instruments or related blowing-based musical performance. Both self-reported good general health and no known respiratory disease.

3.2 Calibration Procedure

Each participant first completed a calibration procedure with four tasks. After each calibration task, perceived fatigue was recorded on a 0–10 self-rating scale.
The calibration tasks were:

- a maximum-breath task used to estimate peak blowing capacity (Pmax);
- a comfortable-breath task repeated three times, from which the mean value was taken as the comfortable breath reference (Pcomf);
- a 10-second long-tone task used to observe sustained control and derive stability-related measures;
- a 10-second short-burst task used to observe how many clearly separated short blows could be produced within a fixed duration.

The fatigue ratings collected after each calibration task were used to derive a coarse fatigue profile for prototype calibration.

3.3 Breath and fatigue categorization

To support transparent parameter assignment, the prototype converted calibration results into two heuristic profiles: a breath profile and a fatigue profile. Here, “profile” refers to the label assigned after grouping the calibration indicators. The breath profile was used to select the boundary coefficient, which defined the upper working boundary as a proportion of each participant’s maximum breath reference, following the general idea of prescribing relative intensity from an individual maximum reference value [14]. The fatigue profile was based on 0–10 subjective fatigue ratings, following the general use of subjective fatigue scales to capture perceived fatigue [15], and was used to decide whether a more conservative boundary adjustment was needed. These profiles, cut-off values, and coefficients were used only as pilot-stage prototype settings and can be revised with further testing involving a larger group of older users.
The breath profile summarized usable breath range and control consistency. It was assigned from four calibration indicators: workspace ratio, long-tone variability, hold accuracy, and short-burst count. Here, the workspace ratio represented the remaining control margin above the comfortable breath reference and was calculated as:

$$WSratio = (Pmax - Pcomf)/Pmax$$

These indicators were converted into a simple heuristic score and used to assign one of three breath profile levels: B1 indicates a lower usable breath range, B2 indicates a moderate usable breath range, and B3 indicates a relatively higher usable breath range. The detailed scoring procedure is provided in Appendix One A.2.

Table 1: Prototype breath-profile labels and corresponding baseline coefficients.

Profile	Interpretation	Prototype Coefficient
B1	Lower usable breath range	kB = 0.6
B2	Moderate usable breath range	kB = 0.7
B3	Relatively higher usable breath range	kB = 0.8

The fatigue profile summarized subjective fatigue sensitivity during calibration. It was assigned from the average fatigue score across the calibration sub-tasks. Three heuristic levels were used: F1 indicates low fatigue sensitivity, F2 indicates moderate fatigue sensitivity, and F3 indicates high fatigue sensitivity. In this prototype, these levels were used mainly to support pacing decisions and, in the case of F3, to apply a more conservative boundary adjustment. The detailed procedure is provided in Appendix One A.3.

Table 2: Prototype fatigue-profile labels and corresponding boundary adjustments.

Profile	Interpretation	Boundary Adjustments
F1	Low fatigue sensitivity	kF = 0
F2	Moderate fatigue sensitivity	kF = 0
F3	High fatigue sensitivity	kF = 0.1

In this prototype, only high fatigue sensitivity led to a boundary reduction; F1 and F2 were kept separate mainly for descriptive interpretation and pacing decisions.

3.4 Personalized working boundary

After calibration, the assigned breath profile and fatigue profile were used to derive the personalized upper working boundary, Pfence. The breath profile first determined the baseline proportion of Pmax used to set this boundary; when subjective fatigue was high, the fatigue profile provided a more conservative adjustment. The purpose of this boundary was to keep the main control region below the participant's maximum breath reference, while still preserving usable workspace above the comfortable breath level.

The boundary coefficient, k, was calculated by combining the breath-profile coefficient and the fatigue-adjustment coefficient:

$$k = k_B - k_F$$

The breath-profile coefficient, kB, was selected from Table 1 according to the assigned breath profile. The fatigue-adjustment coefficient, kF, was selected from Table 2 according to the assigned fatigue profile. The personalized upper working boundary, Pfence, was then computed as:

$$P_{\text{fence}} = k \cdot P_{\text{max}}$$

3.5 Mapping to U-space

Once Pfence had been obtained, baseline-corrected breath pressure, P, was mapped to U-space. As shown in Figure 3, the scale used two anchors: each participant's comfortable breath reference, Pcomf, was aligned with the middle of the scale, U = 50, while the personalized upper working boundary, Pfence, corresponded to the upper end of the scale, U = 100. In this way, U = 50 represented a practical reference point near the center of the participant's comfortable and repeatable operating region.

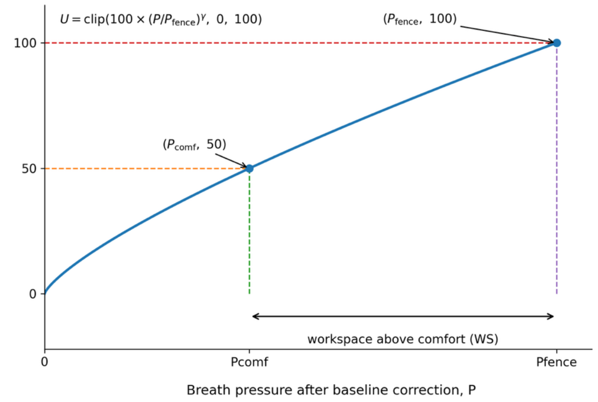

Figure 3: Schematic mapping from breath pressure P to U-space.

A monotonic nonlinear mapping was used so that the response remained controllable around the comfort region while still allowing access to higher values near the personalized upper boundary. The mapping was computed as:

$$U = \text{clip}\left(100 \cdot \left(\frac{P}{P_{\text{fence}}}\right)^{\gamma},\ 0,\ 100\right)$$

Here, P is the baseline-corrected breath pressure at a given moment, Pfence is the personalized upper working boundary, and the clip function limits the output to the range from 0 to 100. The exponent γ controls the shape of the mapping curve and is calculated so that Pcomf maps to U = 50:

$$\gamma = \log(0.5) / \log(P_{\text{comf}} / P_{\text{fence}})$$

To make the prototype procedure explicit, the same boundary-setting and mapping process is summarized in Algorithm 1.

Algorithm 1: U-space boundary-setting and mapping procedure.

```
Input:
    Pmax     maximum breath reference
    Pcomf    comfortable breath reference
    B        breath profile
    F        fatigue profile
    P        baseline-corrected breath pressure at the current moment

1: Select the breath-profile coefficient kB according to B.
2: Select the fatigue-adjustment coefficient kF according to F.
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3: Compute the boundary coefficient:
    $k = kB - kF$
4: Compute the personalized upper working boundary:
    $Pfence = k × Pmax$
5: Compute the mapping exponent:
    $γ = log(0.5) / log(Pcomf / Pfence)$
6: Map the current breath pressure into U-space:
    $U = clip(100 × (P / Pfence)^γ, 0, 100)$

Output:
    U, a normalized control value from 0 to 100
```

3.6 U-space task demonstration

After calibration, participants completed a common set of short tasks in the newly defined U-space. These tasks included a 10-second long-tone task, a crescendo–decrescendo task, a rhythm-accuracy task, and a free-exploration task. This phase was used to observe how participants performed under a shared U-space task framework.

3.7 Data collection

Four forms of data were collected:

- raw breath-pressure signals recorded during calibration and task performance;
- derived calibration values and U-mapping parameters, including Pmax, Pcomf, breath and fatigue profile assignments, and Pfence;
- fatigue self-ratings recorded after each calibration sub-task and each U-space task;
- brief post-task verbal feedback.

These comments were used as interpretive support alongside the quantitative task data.

3.8 Data analysis

Data analysis in this pilot was descriptive and exploratory. The aim was not to test statistical differences, but to examine whether the comfort-centered U-space mapping could support a workable task framework for participants with different breath characteristics.

The analysis combined task performance, fatigue self-ratings, signal traces, and post-task feedback. Task performance showed whether participants could complete the same U-referenced tasks, while fatigue self-ratings reflected perceived effort during the tasks. Raw pressure traces and mapped U trajectories were examined to understand target entry, target maintenance, and changes in control over time. Post-task feedback helped interpret participants' perceived comfort, controllability, workload, and task difficulty.

For the long-tone task, the analysis focused on target-band hold accuracy and signal variability within the 10-second window. The crescendo–decrescendo task was examined by comparing the produced U trajectory with the intended task trajectory. The rhythm task focused on trigger accuracy and timing relative to the task prompt. Free exploration was used to observe how participants played or explored according to their own preferences during open interaction.

4 Implementation

The prototype implementation followed the pipeline shown in Figure 2. Breath pressure was measured using an MPX5010DP pressure sensor connected to an Arduino, sampled every 5 ms, and streamed to a host computer via USB serial.

On the Arduino side, lightweight preprocessing produced a timestamped, baseline-corrected pressure signal that remained close to zero at rest. This included rest-baseline estimation, drift compensation near rest, a small dead zone to suppress jitter, and short averaging to distinguish rest from blowing more reliably. In this study, this breath-pressure signal was the only input used for U-space mapping and task decisions.

In Max/MSP, the incoming pressure signal was used first for calibration and then converted into U-space after the calibration parameters had been set. The resulting U value drove the local dashboard, task prompts, thresholds, and sound control, so that visual feedback and audio response were based on the same control scale. Calibration parameters and task outcomes were logged for each trial under pseudonymous identifiers.

5 Illustrative example with two older participants

5.1 Calibration outcome

This section uses data from two participants to illustrate how calibration values and profile assignments shaped the final U-space mapping in practice.

Table 3: Summary of calibration outcomes.

Participant	A	B
Gender/Age	F/63	M/63
Pmax	250	392
Pcomf	54	42
Breath Profile	B2	B2
Fatigue Profile	F2	F2
Pfence	175	274

5.2 Participant A (female)

Participant A had an maximum breath reference, Pmax = 250 and a comfortable breath reference of Pcomf = 54, giving a measured workspace ratio of 0.784. Her long-tone variability was CV = 0.16, with a hold accuracy of 67%, and she produced 55 bursts in the short-burst task. Under the heuristic scoring procedure, these values led to a B2 breath profile.

Her fatigue ratings after the four calibration tasks were 2, 0, 8, and 3, giving a mean fatigue score of 3.25. This corresponded to a moderate fatigue profile, F2.

Using the boundary-setting rules, B2 assigned a baseline breath coefficient of kB = 0.7, while F2 applied no additional reduction, kF =

0. The combined coefficient was therefore k = 0.7, giving a personalized upper working boundary of Pfence = 175. This value was then used as the upper anchor for Participant A's U-space mapping.

5.3 Participant B (male)

Participant B had Pmax = 392 and Pcomf = 42, giving a workspace ratio of 0.893. His hold accuracy was 78%, with higher long-tone variability, CV = 0.22, and a short-burst count of 31. Under the heuristic scoring procedure, these values also led to a B2 breath profile.

His mean fatigue score was 3.75, corresponding to the F2 fatigue profile. The same B2/F2 assignment therefore resulted in the same combined coefficient, k = 0.7. However, because his Pmax was higher, this produced a higher personalized upper working boundary of Pfence = 274.

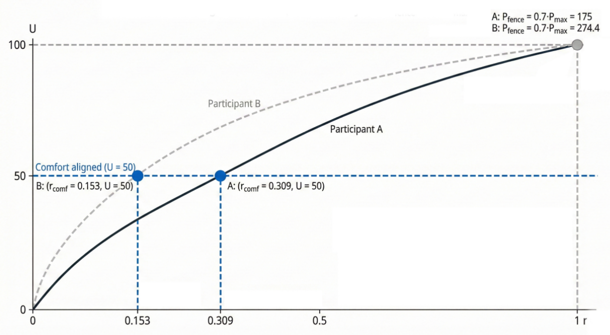

Figure 4: Individualized mapping curves from normalized pressure ratio to U for Participants A and B.

Using the values in Table 3, Figure 4 shows the individualized mapping curves for the two participants. Although both were assigned the same B2/F2 profiles, their mappings differed because their Pmax, Pcomf, and Pfence values were different. Their comfortable breath references also appeared at different positions on the normalized pressure-ratio axis: 0.309 for Participant A and 0.153 for Participant B. In U-space, however, both Pcomf values were aligned with U = 50, and both Pfence values were aligned with U = 100. This shows how the mapping used the same U-space anchors while adapting the pressure-to-U transformation to each participant.

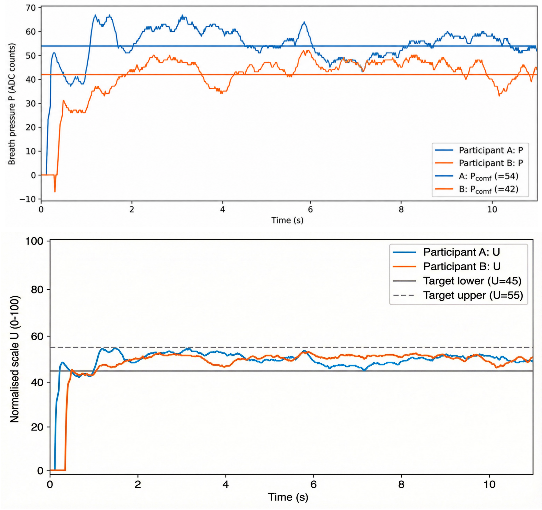

Figure 5: Long-tone task comparison before and after U-space conversion.

Figure 5 compares the same long-tone task before and after U-space conversion. In raw pressure units, the two participants produced different pressure magnitudes, meaning that a single absolute pressure target would not represent the same effort demand for both users. After conversion to U-space, both trajectories could be interpreted against the same target band, U = 45–55. This illustrates how U-space provided a common reference scale for the task while still making individual control differences visible.

5.4 Descriptive U-space task outcomes

Table 4 summarizes the U-space task outcomes and post-task fatigue ratings. In the long-tone task, both participants achieved slightly higher target-band accuracy in the U-space task than in their calibration long-tone reference. Post-task fatigue ratings remained low or decreased: Participant A's fatigue rating was lower than in the calibration long-tone reference, while Participant B's remained low. The rhythm and free-exploration tasks were completed with no or minimal reported fatigue. Overall, the two participants completed the same U-space task set but showed different control patterns. Participant B showed steadier control in the structured tasks, whereas Participant A showed more fluctuation in the trajectories but responded more positively during free exploration.

Table 4: Summary of U-space task outcomes

Task	Participant	Outcome	Fatigue
Long-tone	A	Accuracy = 74%; CV = 0.15	5
Long-tone	B	Accuracy = 79%; CV = 0.19	3
Cresc.–decresc.	A	Rising–falling pattern; visible fluctuation	6
Cresc.–decresc.	B	Rising–falling pattern; relatively stable control	3
Rhythm	A	Trigger accuracy = 79%	0
Rhythm	B	Trigger accuracy = 90%	0
Free exploration	A	Easy; good control; willing to continue	0
Free exploration	B	Not difficult; stable control was challenging	0

6 Implications

A key implication of this work is that task comparability can be framed around comfortable and repeatable breath control rather than absolute pressure magnitude. In this pilot, U-space acted as a shared reference for describing and interpreting the same tasks across participants with different breath-pressure ranges.

Organizing the control space around comfortable long-duration use also changes where the main operating region sits. By placing each participant's comfortable breath near the middle of the shared scale, the main control region remains closer to a breath level that the participant can maintain rather than being pushed toward near-maximum effort. At the same time, the personalized upper boundary preserves workspace for stronger expressive input above the comfortable breath level.

Using the same U scale for interface feedback, task prompts, thresholds, and sound response also supports clearer interaction. It allows what participants see and hear to be linked to the same control value, which may reduce the need to interpret separate visual, task, and sound-control scales.

7 Limitations and future work

This study was a small feasibility-oriented pilot. Its purpose was to examine whether the proposed workflow could operate in a real prototype, from calibration and profile assignment to U-space mapping, task interaction, and data logging. The two-participant example was therefore used to illustrate how the workflow operated in practice, rather than to provide statistical evidence of effectiveness.

Several limitations remain. First, each participant completed only one session on a single day. It is not yet clear whether key variables used for U-space mapping, such as Pmax, Pcomf, and fatigue ratings, remain stable across days or repeated sessions. Future studies should include repeated sessions to distinguish day-to-day state changes from the usability of the mapping method itself.

Second, the current task set is still prototype-oriented and assumes that participants can maintain a basic level of breath control. For users who cannot comfortably sustain a 10-second long tone, the sustained calibration steps and related tasks may need to be shortened or adapted. The crescendo–decrescendo task also raised a practical issue: one participant found it unintuitive to raise breath to a target level and then immediately ease off in a slow and controlled way. Future versions may therefore need simpler task formats and more gradual transitions.

Third, the current grouping and boundary rules, including the B/F labels, coefficient choices, and fatigue-based boundary adjustments, should be understood as early pilot settings. As the study expands to larger samples, repeated sessions, and more playing-like tasks, these rules will need to be revisited, tested, and refined.

Future work should also address learning effects. Some improvements may result from participants becoming more familiar with the tasks and feedback, rather than from the mapping itself. Later studies should therefore separate task familiarization from the usability of the mapping and feedback. Future implementation could also explore AI-supported assistance, such as flagging when recalibration may be needed or suggesting more conservative boundary settings when fatigue-related signals appear. The aim would be to reduce manual tuning while keeping the control logic interpretable.

8 Conclusion

This paper presented a comfort-centered normalization method for breath interaction in digital wind instruments. The method uses each participant's comfortable long-duration breath as the central reference point and uses maximum-breath information to define a personalized upper working boundary. In this way, different raw breath-pressure ranges can be mapped into a shared U-space task framework without relying on a single absolute pressure target.

The Arduino–Max/MSP prototype and two-participant example illustrated how the workflow operated in practice, from calibration and profile assignment to U-space mapping, task interaction, and data logging. The results illustrate how U-space can support more consistent task description and interpretation across users with different breath characteristics, while still preserving visible differences in individual control patterns.

As an early feasibility demonstration, this work requires further testing with larger samples, repeated sessions, and more playing-relevant tasks. Future work will refine the profile and boundary rules and examine how comfort-centered breath normalization can support more accessible and interpretable breath-based interaction in digital wind instruments.

Ethical Standards

This work involved human participants. All participants provided informed consent prior to participation and were informed about the study procedure, the data to be collected, and their right to withdraw at any time without penalty. Data were handled to protect participant privacy (e.g. using pseudonymous identifiers and restricting access to the research team). The study procedures followed applicable institutional and national ethical guidelines.

Use of AI assistance: Generative AI tools were used only to support English-language editing/translation of author-written text and to redraw figures from the authors' hand-drawn sketches. The authors reviewed and verified all AI-assisted outputs and take full responsibility for the final manuscript.

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A Appendix One

A.1 Variables used in the calibration and U-space mapping

Variables	Meaning	Role
P	Baseline-corrected breath pressure	Real-time input for U-space mapping
Pmax	Maximum breath reference	Upper reference; used for workspace ratio
Pcomf	Comfortable breath reference	Comfort anchor; mapped to U=50
Hold accuracy	Proportion of time within target band	Indicates control accuracy
CV	Coefficient of variation in long-tone task	Indicates long-tone stability
Short burst count	Number of separated bursts in 10 seconds	Indicates short-burst control ability
Workspace ratio	Breath range remaining above comfort	Used for breath-profile scoring
Breath profile	Heuristic breath range/control category	Used to select kB
kB	Breath-profile coefficient	Sets baseline upper-bound coefficient
Fatigue profile	Heuristic fatigue-sensitivity category	Determines fatigue adjustment
kF	Fatigue-profile coefficient	Reduces upper boundary if fatigue is high
Pfence	Personalized upper working boundary	Upper reference for U-space
γ	Nonlinear mapping exponent	Ensures Pcomf maps to U=50
U	Normalized U-space value	Shared 0–100 control scale

A.2 Breath-profile scoring

Input:

```
  Pmax, Pcomf, CV, hold accuracy, short-burst count

1: Compute the workspace ratio:
     workspace ratio = (Pmax - Pcomf) / Pmax
2: Score the workspace ratio:
     if workspace ratio < 0.70, score = 0
     if 0.70 ≤ workspace ratio < 0.80, score = 1
     if workspace ratio ≥ 0.80, score = 2
3: Score the long-tone variability:
     if CV ≥ 0.20, score = 0
     if 0.10 ≤ CV < 0.20, score = 1
     if CV < 0.10, score = 2
4: Score the hold accuracy:
     if hold accuracy < 0.40, score = 0
     if 0.40 ≤ hold accuracy < 0.70, score = 1
     if hold accuracy ≥ 0.70, score = 2
5: Score the short-burst count:
```

```
    if short-burst count $< 20$, score $= 0$
    if $20 \le$ short-burst count $\le 40$, score $= 1$
    if short-burst count $> 40$, score $= 2$
6: Compute the total breath-profile score:
    total score = workspace score + CV score + hold-accuracy score + short-burst score
7: Assign the breath profile:
    if $0 \le$ total score $\le 3$, assign B1
    if $4 \le$ total score $\le 6$, assign B2
    if $7 \le$ total score $\le 8$, assign B3
8: Select the breath-profile coefficient:
    if $B = B1$, $kB = 0.6$
    if $B = B2$, $kB = 0.7$
    if $B = B3$, $kB = 0.8$

Output:
    B, the assigned breath profile
    kB, the breath-profile coefficient
```

A.3 Fatigue-profile scoring

```
Input:
    fatigue scores

1: Compute the mean fatigue score:
    mean fatigue score = average of fatigue scores after calibration sub-tasks
2: Assign the fatigue profile:
    if mean fatigue score $< 3$, assign F1
    if $3 \le$ mean fatigue score $< 7$, assign F2
    if mean fatigue score $\ge 7$, assign F3
3: Select the fatigue-adjustment coefficient:
    if $F = F1$, $kF = 0$
    if $F = F2$, $kF = 0$
    if $F = F3$, $kF = 0.1$

Output:
    F, the assigned fatigue profile
    kF, the fatigue-adjustment coefficiet
```