Designing a Low-Cost Nasal Airflow Measurement Device for the Singing Studio

Project Report

Module BMPF7010D - Work-based Learning Project (Extended)

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I used AI as an assistant throughout this project, primarily to transcribe my dictation and take notes. I also used it to search for and verify sources, organize files, help write and review Arduino code, confirm numerical findings, troubleshoot/operate unfamiliar software, suggest structural, formatting, and grammatical changes, create tables, create a table of contents, and help format references.

Audio recordings, video recordings, and logged pressure traces supporting the measured results in Findings are available on request.

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Project Proposal

Context

The singing literature has established nasal airflow as a meaningful physiological parameter across genres, with Western classical singing the most studied. Professional singers have been shown to utilize nasal airflow during sustained vowel phonation and nasalized consonants (Birch et al., 2002; Tanner et al., 2005), and recent studies hypothesize that this may function as a semi-occluded pathway increasing vocal tract reactance, thereby potentially improving resonance and vocal economy (Vampola, Horáček and Laukkanen, 2021, 2024; Konrot et al., 2025). Despite growing interest in the field, research remains limited. In my view, this may stem from a lack of accurate, task-specific, and accessible tools, as most nasal emission instruments used in this area were developed for clinical speech pathology and are prohibitively expensive. My project aims to produce a low-cost prototype device that measures nasal airflow during singing responsively enough give teachers, researchers, and students tools to investigate its role outside a clinical setting. Instrumentation used in existing nasal airflow singing research will also be evaluated.

I am a practicing vocal coach and content creator, and my professional context provides direct access to the singing population as well as an applied motivation for developing accessible feedback tools. The prototype is not a substitute for lab-grade instrumentation, and no clinical application is intended, but it aims to put basic nasal airflow feedback within reach of singers, teachers, and researchers, and leaves open the possibility of later development into a calibrated research instrument.

Justification

Four things justify this project:

1. Proper usage of nasal airflow may improve vocal health (Vampola, Horáček and Laukkanen, 2021, 2024; Konrot et al., 2025), yet no affordable means exists for singers, teachers, and researchers to evaluate the parameter freely.
2. Recent technological advances and the availability of consumer-grade technology make a low-cost solution plausible for the first time.
3. Instrumentation in this literature falls into a small number of categories: microphone-based nasalance systems (Perna, 2008), thermistors (Farré et al., 1998), and direct airflow or pressure measurement (Tanner et al., 2005). No comparative evaluation of their relative accuracy or task-suitability for singing appears to exist.

4. A low-cost prototype can be developed further in future research, for example by calibrating it against values reported in the existing literature, or by using it to measure nasal airflow in singers in research and studio settings.

Intended Impact

The primary intended impact is to establish whether a low-cost, non-invasive device can detect nasal airflow during singing at a resolution useful to singers and teachers, distinguishing nasalized from non-nasalized production against its resting noise floor. If so, it could make basic nasal airflow feedback accessible to teachers, researchers, and students currently priced out of this measurement. Future iterations could add calibration permitting direct comparison with published values, but that is beyond this project's scope.

A secondary impact is a systematic comparative overview of instrumentation across the nasalance and nasal airflow literature in singing and speech, documenting device types, costs where reported, and methodological characteristics. This contextualizes the access barrier the prototype addresses and provides a resource for future researchers.

A third is the practical design knowledge generated by the build itself, including hardware and sensor selection, software decisions, and calibration challenges for future work, documented to inform low-cost device development for singing voice research. This reflects DBR's aim of yielding sharable design knowledge beyond the artifact produced (Design-Based Research Collective, 2003; Plomp, 2009).

Methodology

The methodology I will use is design-based research (DBR), which Plomp (2009, p.9) defines as “the systematic study of designing, developing and evaluating educational interventions... as solutions to such problems, which also aims at advancing our knowledge about the characteristics of these interventions and the processes to design and develop them.” DBR builds something to solve a real problem and studies the building process in order to learn from it. Here, the build is the prototype device and the problem is the absence of an affordable way for singers, researchers, and teachers to observe nasal airflow. Since no nasal airflow device built for singers exists, there is no established development path to follow and no way to specify the design fully in advance (Kelly, 2009, pp. 75–76). Sensor selection, tube placement, sampling rate and signal smoothing are decisions that can only be judged through building and testing.

Reeves' four-phase model provides the framework for my project (Reeves, 2006, cited in Plomp, 2009, p. 14). Reeves moves from analysis of practical problems to development of a

prototype, to prototype testing, to documentation and reflection, with each cycle feeding back into refinement of the problems, solutions, and methods themselves. DBR allows me to engineer a solution while studying it in a pragmatic manner (Cobb et al., 2003, p.9).

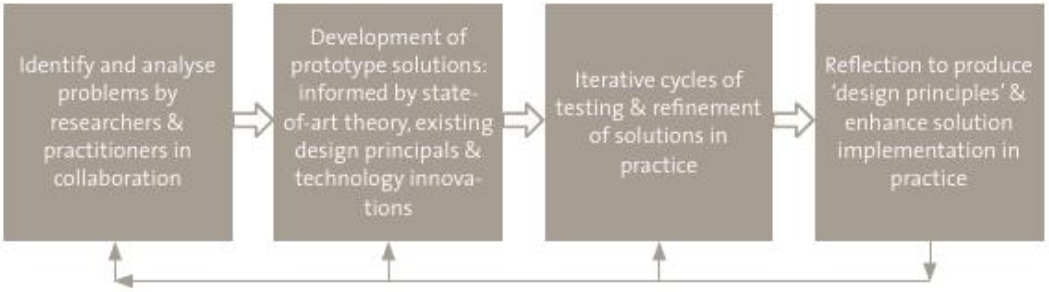


Figure P1. Refinement of problems, solutions, methods and design principles (Reeves, 2006, cited in Plomp, 2009, p. 14).

McKenney's (2001, cited in Plomp, 2009, p. 14) display of the CASCADE-SEA study plots a similar sequence to that of Reeves, with cycle width proportional to duration. My project follows the same time distribution: a short research survey, a longer stretch of design and testing, and a subsequently shorter time window spent in evaluation.

McKenney (2001) illustrates in her study this cyclical process as follows:

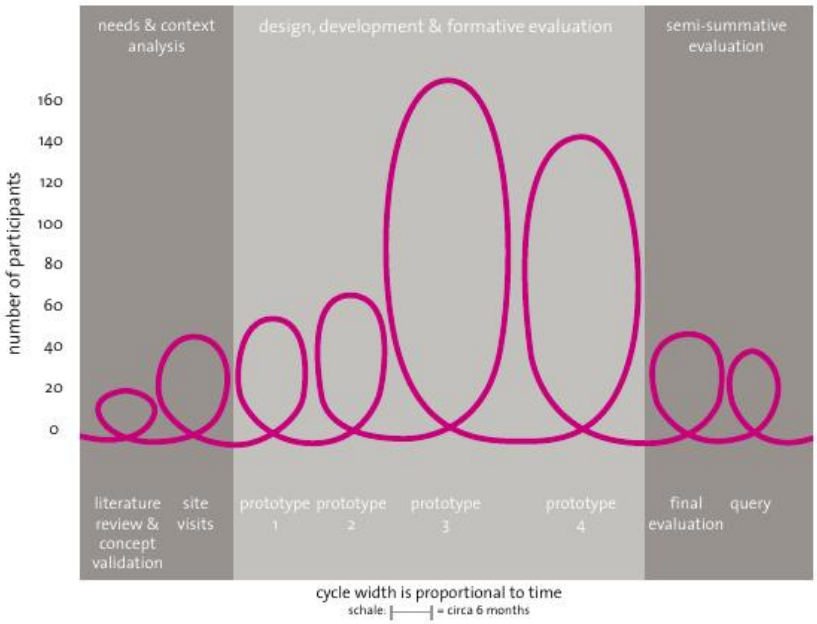


Figure 2: Display of the CASCADE-SEA study (McKenney, 2001)

Figure P2. Display of the CASCADE-SEA study (McKenney, 2001, cited in Plomp, 2009, p. 14).

Outlined Intention

The outline below follows the cycle Reeves describes, with time allocated across the steps in the proportions McKenney's display illustrates.

The full sequence runs across sixteen weeks *(this timeline is VERY off right now I need to go back and look at timelines)*

1. Initial survey of instrumentation used in nasal airflow research (weeks 1 to 4).
2. Initial device design informed by instrument survey (weeks 5 to 9).
3. Structured informal testing and refinement of the device (weeks 10 to 12).
4. Writing, full literature review, and finalization, including retrospective analysis of the device's efficacy and possible improvements (weeks 13 to 16)

My functioning prototype is an Arduino Uno R3 microcontroller paired with a Sensirion SDP810-125Pa differential pressure sensor, connected by a thin flexible tube at the nostril opening, outputting live differential pressure readings over USB to a laptop for viewing and logging. Testing confirmed that nasalized production yields a signal clearly separable from the device's resting noise floor.

I will be the sole participant in the study. Data evaluation will be descriptive: whether nasalized production yields a signal clearly separable from the resting noise floor, and whether that signal is repeatable across trials of the same task. Results will be presented as datasets (graphs and tables) of pressure change over time, showing the device's response across a range of nasal airflow, from slight leakage to fully nasalized consonants, alongside qualitative reflection on its usability in a studio setting.

Ethics and Insider Research

As an exploratory feasibility study with myself as sole participant, ethical considerations are limited in scope. The device is non-invasive: a small tube rests at the nostril opening without deep insertion. No medical or clinical application is intended, and it will not be used on other participants without full ethical review.

A further consideration is my dual role as designer and data collector. This is a dilemma inherent to design research, where the researcher is the “designer and often also evaluator and implementer”, which raises a potential conflict of interest (McKenney et al., 2006, cited in Plomp, 2009, p. 30). I will mitigate this by reporting the device's limitations transparently alongside its successes.

I am an insider researcher throughout, both as a vocal coach investigating a device intended for studio use and as the participant in testing. McKenney and Reeves (2012, pp. 17–18) describe a “co-learning agreement” model in which the practitioner operates as a “practitioner-researcher”. This proximity is a recognized challenge because the researcher is “intimately involved in the conceptualization, design, development, implementation, and researching”. Ensuring that my findings and implications are credible and trustworthy is an understood difficulty (Barab and Squire, 2004, p.10). -need some steps here to counteract that-

All data will be stored securely in accordance with institutional data management guidelines on a personal, secure device.

Expected Learning Outcomes

Upon completion of this project, I expect to have:

1. Developed a critical understanding of nasal airflow instrumentation in the singing literature, producing a comparative review that constitutes an original contribution in this area.
2. Acquired practical competence in electronics prototyping, including circuit design, sensor integration, and microcontroller programming, demonstrated through building a functioning device from consumer-grade components.
3. Gained experience in applying a design-based research methodology to a practical problem situated in a professional voice pedagogy context.
4. Developed skills in reflexive insider research practice, including awareness of the limitations and opportunities of my dual role as practitioner and investigator.

Part 1: The Problem and the Method

Introduction

Singers and teachers have debated nasal resonance for centuries (Stark, 1999). Recent evidence, however, suggests that classically trained singers often sing with an open velopharyngeal port (VP), even on vowels that do not require nasal coupling (Birch et al., 2002; Tanner et al., 2005). Research suggests that open port may enhance vocal resonance and efficiency (Vampola, Horáček and Laukkanen, 2021, 2024). However, the cost, limited customization, restricted data access, and invasiveness of velopharyngeal opening (VPO) measurement tools present barriers to studio use (Dewhurst et al., 2025; MicroTronics Corp., 2016; Cler et al., 2016; Birch et al., 2002). For example, a single commercial nasometer (an acoustic nasal emission detection device) costs “several thousand U.S. dollars” (Wang, L. et al., 2026, p. 2), and aerodynamic systems reportedly cost around $10,000 in 2016 (Cler et al., 2016, p. 1022). The PERCI-SAR system components total $16,895 in the manufacturer’s 2016 replacement-parts price sheet (MicroTronics Corp., 2016). This is because most VPO detection tools were developed for clinical speech application (Warren and DuBois, 1964; Niu, Kain and van Santen, 2006), not singing. Perna (2014, p. 409) argues that “The addition of the nasometer in the voice studio could prove to be additionally valuable both in finding an appropriate increase in nasalance for passaggio and in decreasing excessively nasal tone.”

This project designs, constructs, and tests an affordable device specifically for singers called the NTAD (Nasal Tract Airflow Detector). The NTAD uses a non-invasive nasal cannula connected to a differential-pressure sensor and an Arduino controller. It detects nasal airflow indirectly by measuring pressure at the nares (Bunton, Hoit and Gallagher, 2011), with audio recorded separately. The main outputs of this project are the NTAD (Iteration 2.1) and the knowledge gained through the design-based research (DBR) cycle, including an adapted development cycle (Figure 10) and proposals for further development.

Aim and Objectives

Aim: To increase access to nasal airflow measurement within voice pedagogy by designing, building, and evaluating a low-cost prototype suitable for future use in the singing studio.

Objectives:

- Establish why measurements of nasal airflow are important to singers.

- Review existing instrumentation to determine if an accessible, low-cost option for singers is possible using literature-informed design criteria.
- Design and build a device using low-cost, commercially available components on the Arduino platform.
- Refine it through an iterative, DBR process.
- Test whether it can distinguish deliberate variation in nasal emission.
- Identify what future development cycles may entail.

Scope

I am a certified Complete Vocal Technique (CVT) teacher and teach contemporary commercial music (CCM) in a private studio. I also create educational vocal coaching content for YouTube. This report treats CVT as both a pedagogical framework and a body of published research, and I write about it as an insider. This project asks whether nasal emissions can be detected during singing using parts available to anyone. I built the NTAD, tested it on my voice, and evaluated it against criteria I developed. The project broadly follows Reeves' four-phase design-based research cycle (Reeves, 2006, cited in Plomp, 2009, p. 14; Figures 8a and 12).

The NTAD is not a clinical instrument, nor is that its intended use. It does not measure the size or shape of the velopharyngeal opening. The NTAD detects relative pressure at the nostril, which can then be converted into relative nasal flow through a simple formula. An emission above the NTAD's closed-port reading indicates that the port is open (Thompson and Hixon, 1979; Hoit et al., 1994; Bunton, Hoit and Gallagher, 2011).

Intended Impact: A device made from consumer-grade parts that can detect nasal emissions could make real-time, visual, pedagogically valuable VPO feedback accessible to more teachers and students (Lã et al., 2017; Lã, Sundberg and Granqvist, 2022). Additionally, insights from the design process itself are valuable and recognized as contributions within the Design-Based Research framework (Barab and Squire, 2004; Design-Based Research Collective, 2003).

Expected learning outcomes: a comprehensive understanding of nasal airflow measurement tools in the singing literature, practical skills in electronics prototyping and microcontroller programming, experience applying Design-Based Research, and the reflexive ability to balance the roles of both a practitioner and an investigator.

Literature Review

This review examines why nasal emission feedback might be useful for singers and provides a broad overview of existing instruments to familiarize me with the literature. It informs what the NTAD needs to do and addresses Reeves' first phase, analysis of the practical problem (Reeves, 2006, cited in Plomp, 2009, p. 14; Figure 12). This phase analyzes the problem outlined in my introduction in a pragmatic manner to establish the framework from which I can develop a proposed solution.

Literature Review Scope

My teaching is CCM, so I justify my literature selection by focusing on chest-dominant production techniques common in CCM. CCM research on VPO is limited, so I draw nearly exclusively from classical literature. Studies of tenor voices through and above the passaggio provide a useful comparison for my interest in chest-dominant, or mechanism 1 (M1), production (Perna, 2008, 2014; Roubeau, Henrich and Castellengo, 2009; Titze and Worley, 2009). I therefore give greater weight to studies of tenor voices, while recognizing that some studies on female singers report decreasing nasalance with rising pitch (Fowler and Morris, 2007, pp. 739, 744–745).

Included: Studies that intentionally investigated the VPO in singing published from 2000 onward with velopharyngeal status as the focus, not an incidental observation.

Excluded: Work published on investigating VPO in singers before 2000 and work that reports velopharyngeal opening in passing.

Admitted by exception: Older work introducing a technique still in use, such as Warren and DuBois (1964) on pressure-flow, and speech studies showing that nasal airflow is near zero when the port is closed, such as Thompson and Hixon (1979) and Hoit et al. (1994).

Supporting literature: Vocal tract acoustics, speech science, pedagogy, sensor engineering, sleep sensor literature, clinical practice, medical research, nasal airflow mechanics, and research methodology are cited as needed and not screened by date. For pedagogical claims or implications, prominent figures in the field are permitted, such as Vennard (1967), Titze (2007a, 2007b), and Bozeman (2021).

Grey literature: Manufacturer specifications and reputable, well-sourced material outside peer review, such as university physics pages and unpublished work by recognized figures like Rothenberg (2014).

The Velopharyngeal Port

The velopharyngeal port (VP) is the opening controlled by the velopharyngeal valve, formed by the soft palate and pharyngeal walls (Vennard, 1967). The port closes when the posterior velum lifts and moves back in a “knee-like” movement as the posterior and lateral pharyngeal walls contract to meet it (Kummer, 2011, p. 151; Figure 1a). During phonation, the VP opens and closes in varying degrees and shapes. This opening is referred to as the velopharyngeal opening (VPO), and it causes airflow to exit through the nose (Tanner et al., 2005). Greater VPO area is assumed to increase nasal airflow during singing, assuming all other vocal behaviors are constant (Warren and DuBois, 1964). A VPO was observed in many classical singers at some point within their recorded range in the studies reviewed in Tables 1 and 2. During sung tasks, the degree of opening appears to vary with vowel, pitch, volume, and register (Tanner et al., 2005; Jennings and Kuehn, 2008; Perna, 2014).

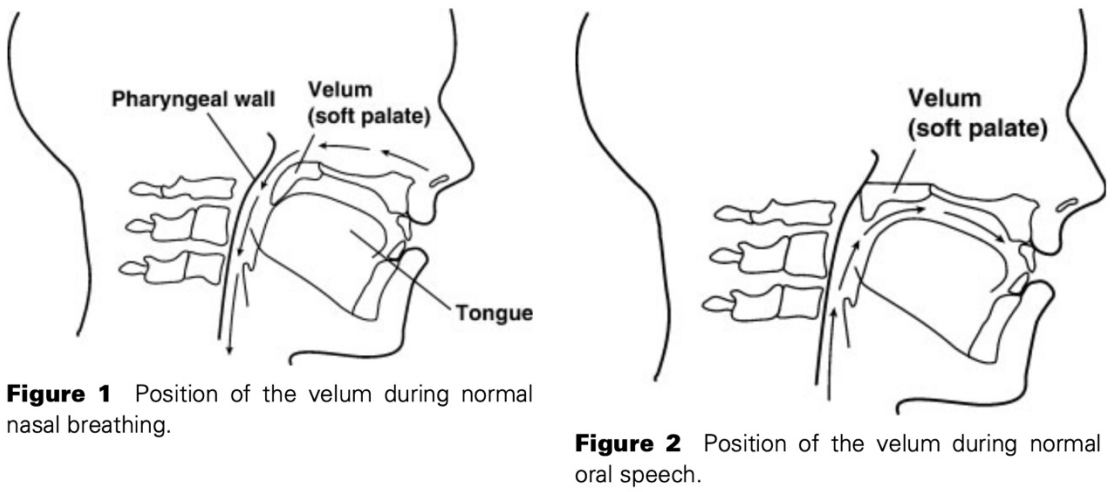


Figure 1 Position of the velum during normal nasal breathing.

Figure 2 Position of the velum during normal oral speech.

Figure 1a. Velar position during nasal breathing and oral speech (Kummer, 2011, p. 151, original Figures 1 and 2).

Common Misconceptions

The first common misconception is that a velopharyngeal port opening produces a “nasal tone,” typically described as harsh, strident, and bright. What is perceived here as “nasal” may actually be “excessive” twang (extreme narrowing of the epilaryngeal tube and pharynx) and/or the result of an “overly raised” laryngeal position (Perna, 2020; Perta, Bae and Obert, 2021; Saldías et al., 2021; Jelinger et al., 2024; Complete Vocal Institute, 2016).

Another common misconception is that raising the velum (soft palate) necessarily closes the VP, thereby reducing or eliminating nasal emissions. However, closure depends specifically on the movement of the posterior velum (not the soft palate as a whole) together with the pharyngeal walls (Kummer, 2011, p. 151; Figures 1a and 1b). Raising the soft palate can, however, contribute to a “darker” sound color (LoVetri, Lesh and Woo, 1999; Complete

Vocal Institute, 2026, p. 204). I suspect this darkening may also make the tone *sound* "less nasal" (less bright), which may partly explain the misconception.

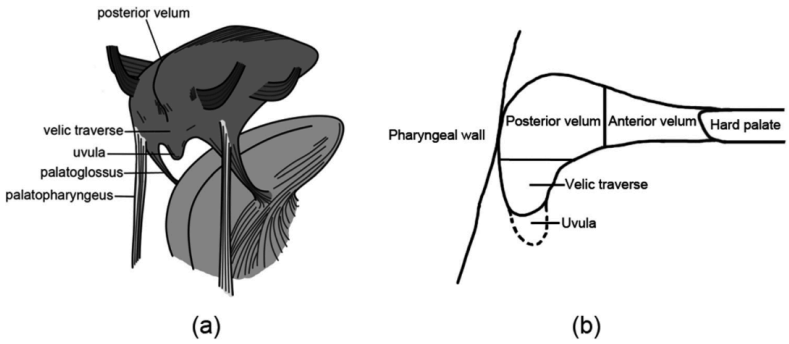


Figure 1b. The velum and tongue (Gick et al., 2013, p. EL209, original Figure 1).

Studying the Velopharyngeal Port

The velopharyngeal opening can be evaluated directly with imaging methods such as nasoendoscopy, X-ray, videofluoroscopy, or MRI, or indirectly by analyzing nasal emissions, including acoustic or aerodynamic (airflow and air-pressure) measures (Kummer et al., 2012; Blaylock, Goldstein and Narayanan, 2016). Many nasal-emission measurement systems in the singing literature capture both oral and nasal outputs, helping distinguish changes in nasal emission from changes in total emissions (Gill et al., 2020). The ratio of nasal output to the sum of nasal and oral outputs is called nasalance (Bundy and Zajac, 2006; Perna, 2008; Bunton, Hoit and Gallagher, 2011). A nasalance measurement above 0 suggests a possible VPO (Jennings and Kuehn, 2008). Nasalance alone, however, does not indicate the size of the opening. For more precise assessments of port behavior, such as VPO area estimates, measurements of nasal flow, nasal pressure, and oral pressure are required (Tanner et al., 2005; Martell, Lastowiecka and Bae, 2025).

Table 1. Imaging in the reviewed singing studies, 2000 to present.

Study	Instrument model	Interface
Birch et al. (2002)	Olympus ENF P3 nasopharyngoscope	Fiberscope
Echternach et al. (2021)	Olympus ENF GP; Photron Fastcam SA-X2	Endoscope

Table 2. Nasal emission literature in singing, 2000 to present.

Study	Instrument model	Interface	Measurement
Acoustic (Microphone-Based)			
Fowler and Morris (2007)	Glottal Enterprises OroNasal System	Divided vented mask	F0 nasalance
Perna (2008)	Glottal Enterprises Nasality Tutor	Divider plate	Acoustic nasalance
Jennings and Kuehn (2008)	Nasometer II 6400 (KayPENTAX)	Divider plate (headset)	Acoustic nasalance
Santoni et al. (2020a)	Nasometer 6450 (KayPENTAX)	Divider plate (headset)	Acoustic nasalance
Santoni et al. (2020b)	Nasometer 6450 (KayPENTAX)	Divider plate (headset)	Acoustic nasalance
Jayakumar et al. (2024)	Nasometer II 6400 (KayPENTAX)	Divider plate (headset)	Acoustic nasalance
Aerodynamic (Airflow)			
Birch et al. (2002)	Glottal Enterprises MS 100-R2	Divided mask	Nasal and oral airflow
Gill et al. (2020)	Glottal Enterprises flow mask; MS-110 interface	Divided mask	Nasal and oral airflow
Echternach et al. (2021)	Glottal Enterprises MS-110 PT-2E transducer	Divided mask	Flow nasalance
Jayakumar et al. (2024)	Glottal Enterprises Aeroview	Rothenberg mask	Nasal airflow
Orifice Area Estimation (Pressure-Flow)			
Tanner et al. (2005)	MicroTronics PERCI-SARS 3.22 heated pneumotachometer (Hans Rudolph)	Nasal tube; foam-tipped catheter in opposite nostril; oral catheter	Nasal airflow; oral and nasal pressure; estimated VPO area
Martell, Lastowiecka and Bae (2025)	MicroTronics PERCI-SAR HR7319-FP heated pneumotachograph	Nasal tube; foam-tipped catheter in opposite nostril; oral catheter	Nasal airflow; oral and nasal pressure; estimated VPO area
Aerodynamic (Nasal Pressure)			
This project **N**TAD	Sensirion SDP810-125Pa	Cannula	Nasal pressure

Acoustic Nasalance

Devices that measure acoustic nasalance are called nasometers. They use two microphones, one at the nose and one at the mouth, separated by a divider plate or a mask (Santoni et al., 2020b; Perna, 2020, p. 430; Figures 2 to 5). Commercial nasometers often filter both signals to a band centered near 500 Hz, which falls within the first formant range of most vowels (Bundy and Zajac, 2006, p. 691; Awan and Virani, 2013, p. 269). Readings can therefore vary with pitch and vowel even without a change in the VPO (Rothenberg, no date; Jennings and Kuehn, 2008, pp. 87–88; Perna, 2020, p. 431), and in singing they have also varied with loudness (Jennings and Kuehn, 2008, p. 85).

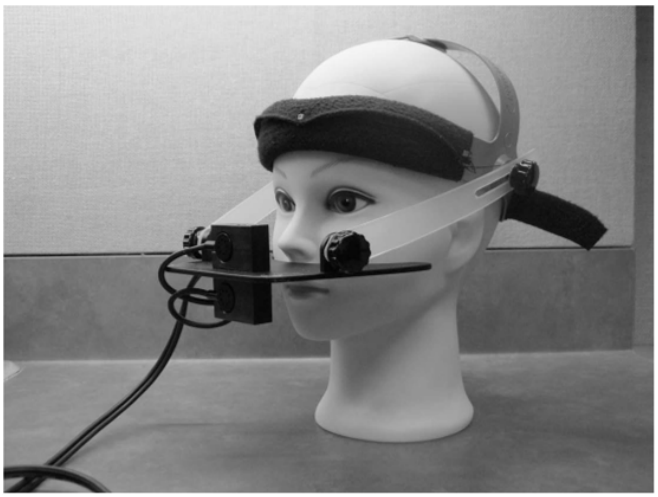


Figure 2. The Nasometer headset (Bressmann, 2021, original Figure 24.1).

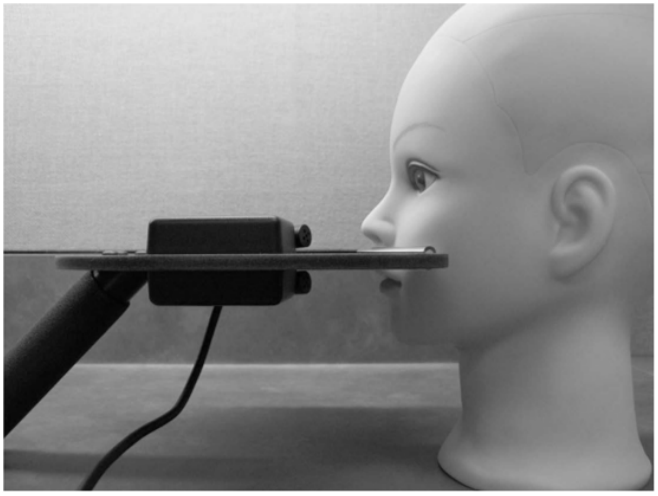


Figure 3. The Nasalance System with a separator plate (Bressmann, 2021, original Figure 24.5).

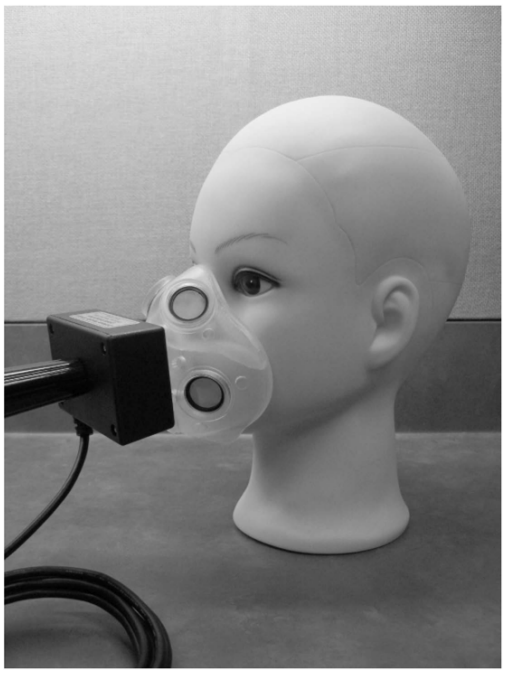


Figure 4. The Nasalance System with a face mask (Bressmann, 2021, original Figure 24.4).

Nasometer readings are also negatively affected by transpalatal signal transfer, in which oral energy reaches the nasal microphone through the palate even when the VP is closed. This can produce false-positive readings and higher-than-expected nasalance scores (Bundy and Zajac, 2006, p. 691; Rothenberg, no date). Jayakumar et al. (2024) also found no significant correlation between perceived nasality and either nasalance or nasal airflow among singers or non-singers. Readings also vary across commercial models (Awan and Virani, 2013; Bressmann and Tang, 2025).

Airflow

Airflow setups in the reviewed studies range from divided masks that measure nasal and oral flow together (Birch et al., 2002; Gill et al., 2020, p. 347) to tubing in one nostril that measures nasal flow alone, as in the pressure-flow studies (Tanner et al., 2005). In a divided mask, a plate at the upper lip separates the nasal and oral compartments (Rothenberg, 1977; Gill et al., 2020, p. 347; Figure 5).

These masks must be tightly sealed and can cause user discomfort (Birch et al., 2002; Gill et al., 2020). Birch et al. (2002) reported that masks disturbed vocal production, disrupted feedback, and limited jaw movement. Masks can also leak at the rim when improperly sealed, so they may miss nasal flow (May and Scherer, 2018; Birch et al., 2002, p. 70). Phantom nasal flow of up to 30 mL/s has also been recorded, likely from articulator movement, and its effect on singing recordings remains uncertain (Fisher and Swank, 1997, cited in Bundy and Zajac, 2006; Rothenberg, no date).

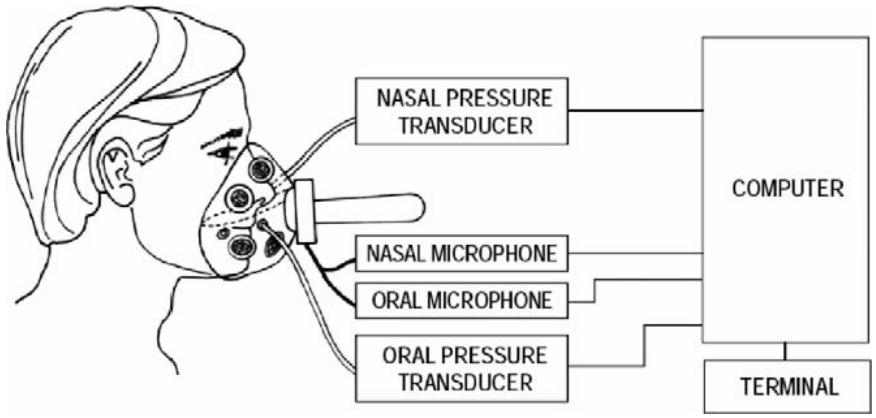


Figure 5. The OroNasal Nasality System divided mask (Bundy and Zajac, 2006, p. 694, original Figure 1).

Orifice Area Estimation

Pressure-flow devices record nasal and oral pressures and nasal flow, then estimate orifice area using an orifice equation (Warren and DuBois, 1964; Figure 6). Of the studies reviewed here, only Tanner et al. (2005) and Martell, Lastowiecka and Bae (2025) collected sufficient data to estimate VPO area in this way. Despite their comprehensive scope, both rely on an equation that Pelorson (2001) challenged. The equation was modeled on abrupt, sharp-edged openings; rounded openings were overestimated by up to 100% in Pelorson's mechanical model (Pelorson, 2001, pp. 185–187). Unfortunately, of the studies reviewed, only Birch et al. (2002) appear to have observed VPO shapes in singing, and the effect of those shapes remains unexamined (Figure 7a).

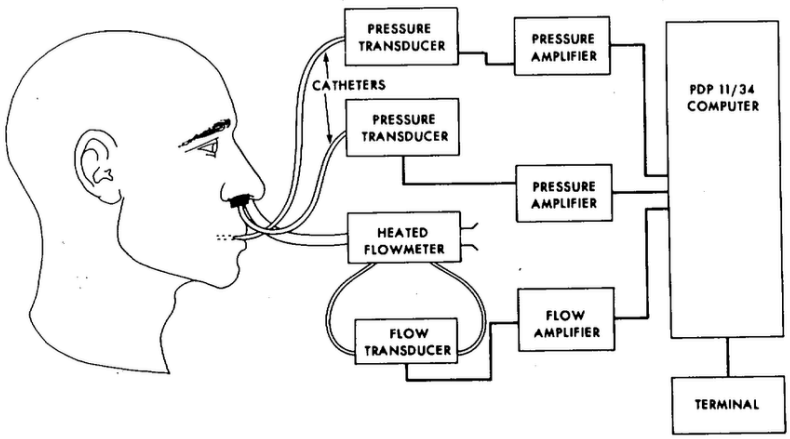


Figure 6. The pressure-flow technique (Warren et al., 1985, p. 12, original Figure 1).

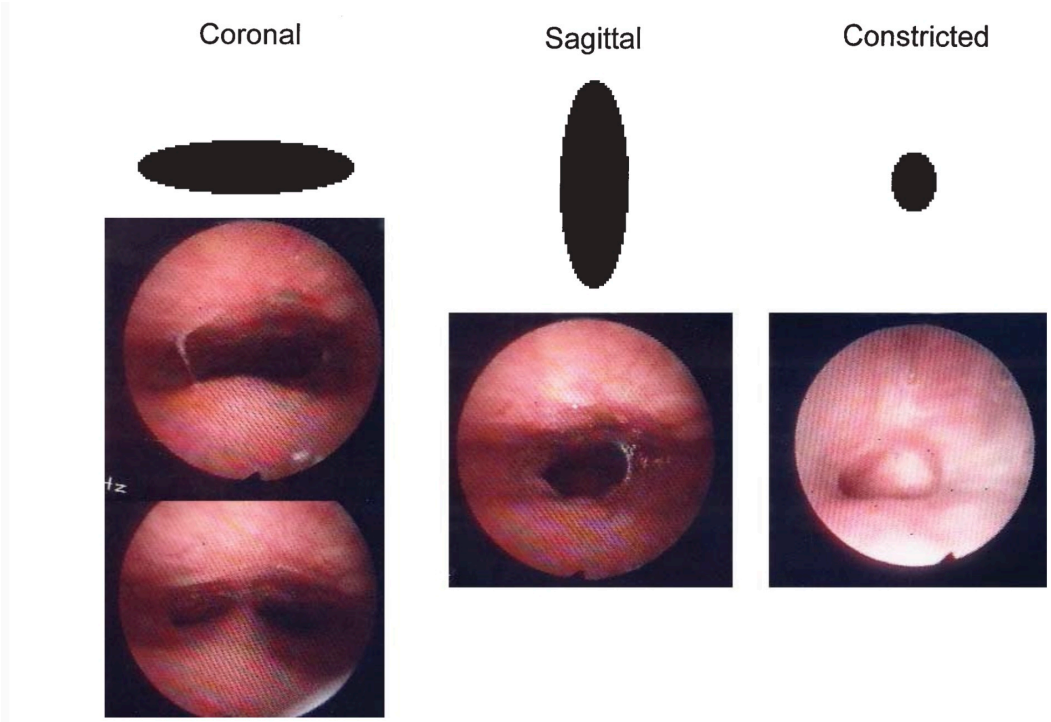


Figure 7a. Coronal, sagittal and constricted velopharyngeal openings observed in singers (Birch et al., 2002, p. 66, original Figure 5).

The VPO's Functional Role in Singing

Whether singers benefit from a VPO during sung vowels remains unclear (Birch et al., 2002, p. 70; Gill et al., 2020, p. 346). One common theory in the literature is that an adequately shaped VPO may create acoustic conditions conducive to more efficient phonation by adjusting the vocal tract's first formant (F1) (Echternach et al., 2021; Vampola, Horáček and Laukkanen, 2021, 2024).

Nonlinear source-filter theory proposes that standing waves in the vocal tract can either aid vocal fold vibration via inertive reactance or hinder it through compliant reactance (Titze, 2008; Titze and Worley, 2009). The vocal tract can become more inertive as a harmonic approaches it's formant from below (Titze, 2008). "The inertive vocal tract (IVT) assists the vocal folds in vibration because the supraglottal pressure driving the air column is in phase with the velocity of the vocal folds" (Titze, 2001, p. 521). An inertive vocal tract lowers the pressure needed to start and sustain vocal fold vibration (Titze, 2001, p. 522) and may increase sound intensity at the same subglottal pressure (Titze, 2008, p. 2743).

Vampola, Horáček and Laukkanen (2021, p. 2154) report that the VPO acts "by raising the lowest [vocal tract] resonances," increasing vocal tract reactance near register transitions. In their model, these effects help ease passage through the first resonance and, consequently, the register transition, by lowering F1's amplitude (dampening) and increasing its frequency (Vampola, Horáček and Laukkanen, 2021). Echternach et al. (2021, p. 500.e9) concluded that "nasalance can be used in order to stabilize oscillatory regularity and open quotient in

male singers for singing across the passaggio," consistent with the rise in nasalance that Perna (2008) recorded after the tenor passaggio transition and with the VPO that Birch et al. (2002, p. 70) found near the passaggio in all three tenors they studied. These findings suggest that a VPO may favorably influence vocal efficiency (Vampola, Horáček and Laukkanen, 2021, 2024) and strengthen the singer's formant cluster (Vampola, Horáček and Laukkanen, 2024).

The Singer's Formant

The singer's formant is a prominent peak in the radiated spectrum between approximately 2 and 4 kHz (Martell, Lastowiecka and Bae, 2025; Figure 7b), produced when the third, fourth, and fifth formants cluster together (Sundberg et al., 2007). Singing energy in this region matters because it helps classical singers to be heard more easily over an ensemble (Jennings and Kuehn, 2008). Several studies indicate that nasal coupling may increase spectral energy in the singer's formant cluster (Sundberg et al., 2007; Gill et al., 2020; Vampola et al., 2020; Vampola, Horáček and Laukkanen, 2024). This increase in singer's formant energy may reflect greater vocal efficiency from a more inertive vocal tract (Vampola, Horáček and Laukkanen, 2024). Nasal resonance may also contribute directly to the perception of the singer's formant through similarities in the spectral patterns of vowels with high nasalance and those associated with the singer's formant (Titze, 1987, cited in Jennings and Kuehn, 2008).

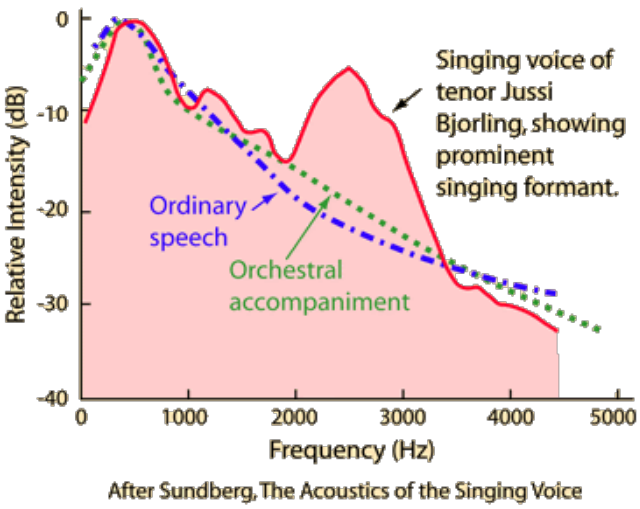


Figure 7b. Singer's formant (Nave, no date, adapted from Sundberg, 1977).

Limits of the Evidence

The argument that a velopharyngeal opening improves vocal economy draws on vocal source-filter nonlinearity theory (Titze, 2008; Titze and Worley, 2009). However, Titze's (2008, p. 2744) model does not include nasal coupling, so sound exits only at the mouth. A

semi-occlusion at the VPO adds a parallel path, with sound radiating from both the nose and mouth (Vampola et al., 2020; Bunton and Story, 2012). This parallel path has far less evidence supporting its mechanism (Vampola et al., 2020; Vampola, Horáček and Laukkanen, 2021, 2024). Echternach et al. (2021) found that increased nasalance through the passaggio was associated with stabilization of the open quotient in only four of eight professional male classical singers. Even the single-path nonlinear model has conflicting findings. Sundberg, Lã and Gill (2013, pp. 278, 288) found that “regardless of whether the first formant was slightly lower, slightly higher, or right on a partial, the properties of the voice source did not seem to be affected,” and that formant tuning occurred in only two of eighteen cases. They further suggested that “a singer’s formant cluster can be produced without the help of nonlinear source-filter interaction.”

The question remains as to why singers seem to use a VPO during singing, particularly near and above the tenor passaggio (Birch et al., 2002, p. 70; Perna, 2008; Echternach et al., 2021, p. 500.e9; see Pedagogical Implications: The VP as an Articulator). Better, more accessible ways of measuring it may help answer that question. This project attempts to develop an affordable studio instrument to help address that issue. Methodology outlines how I approached its development and how I evaluated the device.

Methodology

This chapter explains the requirements I set for the device, the tasks used to assess them, and how testing informed further design changes. This is how I approached Reeves' second phase, development of a solution (Reeves, 2006, cited in Plomp, 2009, p. 14; Figure 12). This phase uses existing research to develop a response to the problem of inaccessable and unaffordable nasal emissions detection for singers.

Insider Research, Reflexivity and Ethics

I am an insider researcher because I researched my own work as a singing teacher, drawing on my experience as a singer and teacher to develop and test the NTAD prototype (Costley, Elliott and Gibbs, 2010, pp. 18–19). I had a clear bias in favor of this device working well, as I designed it, was the only participant, and evaluated it. I openly acknowledge this bias and make my best efforts to recognize and identify where it may have affected my work. Because I knew my beliefs could influence the results, I used existing literature to help limit bias in my methodology design. The limitations section below addresses the practical risks of evaluating my own device under Self-experimentation.

Developing the NTAD also involved significant self-experimentation. Self-experimentation involves researchers conducting experiments on themselves (Weisse, 2012). I served as the sole device developer, task designer, evaluator of device performance, and participant in task execution. Self-experimentation has precedent in singing voice research. Schutte, Stark and Miller (2003, pp. 495–496) measured one of their own authors, a tenor and singing teacher, and described him as "a sophisticated subject" who could link the measurements to deliberate changes in his technique. While I would not describe myself in quite the same way, my position was similar. As both an insider and as someone conducting a self-experiment, I could judge comfort during singing as well as interference with the task, and I had some reasonable degree of control over my VPO.

Ethics: I was the sole participant, with no involvement from students or third parties. The project adhered to the University's research ethics framework, and I obtained ethical approval before beginning development and self-testing. I tested the interface configurations individually.

Safety was the top priority in every design and iteration. To ensure ethical compliance, I evaluated comfort and made it a primary focus during task execution. I discontinued testing whenever I felt tired, chose not to continue, or experienced even mild discomfort. For example, before any sensor testing, I tried the Y-adapter alone (Iteration 1.1), felt mild discomfort, and did not test it further. I also used a new cannula/tubing for each test session

and kept brief notes in a Word document during development. I carried out the project in my home teaching studio in the United States as a self-employed practitioner. Findings are to be considered tentative.

Paradigm

This project adopted Dewey's pragmatism (Dewey, 1938), an instrumentalist paradigm that evaluates ideas by their practical effectiveness (Bannen, 2018, pp. 18, 25). Dewey's "end-in-view" is an aim that guides action (Dewey, 1925, cited in Bannen, 2018, p. 18). My end-in-view was a non-invasive, low-cost device that visualizes nasal airflow during singing. I evaluated each design through testing, tasks, and practical use, and I used my observations to guide the next iteration. Dewey treats inquiry as an active process that can change the situation being studied (Godfrey-Smith, 2002, cited in Bannen, 2018, p. 28). In this project, self-experimentation informed changes to the device, my practice, and the questions I took back to the literature. In line with Dewey, who did not reject an independent reality (Godfrey-Smith, 2002, cited in Bannen, 2018, p. 27), I adopted a realist ontology. I believe the velopharyngeal port exists in a definite state (shape and degree of opening, for example), whether measured or not, and that the VPO affects singing even if its exact mechanism is unclear (Birch et al., 2002, p. 70; Echternach et al., 2021, p. 500.e9; Gill et al., 2020, p. 346). My methodology and NTAD design led to deeper insights into the problem and a more refined prototype.

Design-Based Research

Design-Based Research (DBR) designs, deploys, and refines an intervention through cycles to solve a problem and develop knowledge during and after the process (McKenney and Reeves, 2013). DBR fits problems that must be solved and studied simultaneously (Cobb et al., 2003, p. 9). I used three different literary DBR cycles in this project and one adapted design. Each design served a different purpose in developing the project and provided a free, experimental, introductory experience using DBR cycles (Figure 12).

The report as a whole follows Reeves' four phases (Reeves, 2006, cited in Plomp, 2009, p. 14; Figures 8a and 12). These are analysis of the practical problem, development of a solution, iterative testing and refinement in practice, and reflection to produce design principles. Figure 12 maps these phases onto the report.

The full NTAD development process from 0 to 2.1, reported in Findings, followed McKenney and Reeves (2012, p. 77; Figure 8b), who divide a DBR macro-cycle into analysis and exploration, design and construction, and evaluation and reflection. Its two outputs, a maturing intervention and theoretical understanding, are reflected here in Iteration 2.1 and

the interpretation of the VP as an articulator developed through practice and a final literature review. This process helped me stay organized during iterative testing, help ensure I produced useful data, and avoid getting caught up in never-ending development or overly exhaustive prototype testing and data analysis.

For the individual iterative redesign cycles, I began with a six-phase model of focus, understand, define, conceive, build, and test (Easterday, Rees Lewis and Gerber, 2014; Figure 9). I revisited these phases throughout my process, ensuring more structured literature reviews and design changes as problems arose. Over the iterations, I adapted this model into a development cycle, shown in Figure 10, which reflects the actual process I undertook. Each design iteration produced (0, 0.1, 0.2, 1.1, and 2.1) was considered one completed development cycle. I developed this model and did my best to integrate it before the final, formal, measured testing phase. Figure 12 outlines the overall iterative process, showing how the five individual NTAD development cycles fit within the broader DBR framework of Reeves (2006, cited in Plomp, 2009).

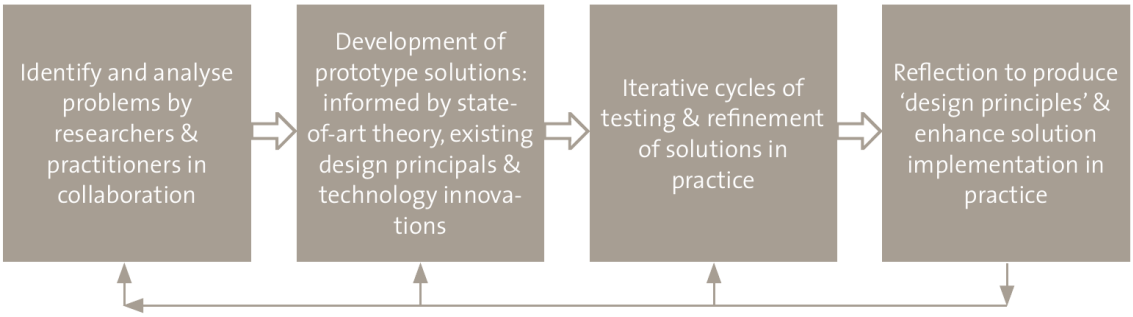


Figure 8a. Reeves' four phases of design-based research (Reeves, 2006, cited in Plomp, 2009, p. 14, original Figure 1).

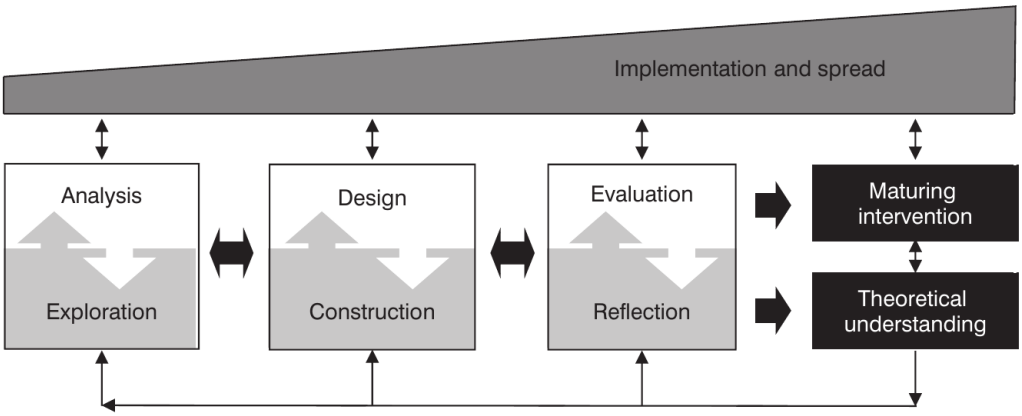


Figure 8b. Generic model for conducting design research in education (McKenney and Reeves, 2012, p. 77, original Figure 3.3).

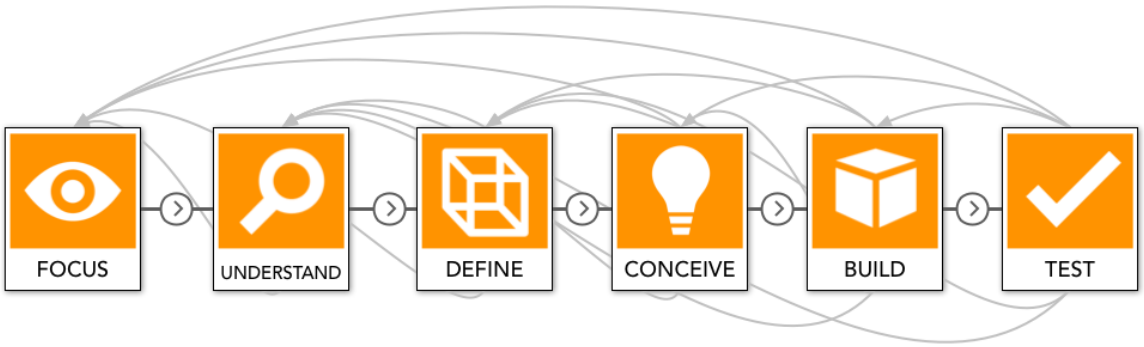


Figure 9. The six-phase design process (Easterday, Rees Lewis and Gerber, 2014, original Figure 1).

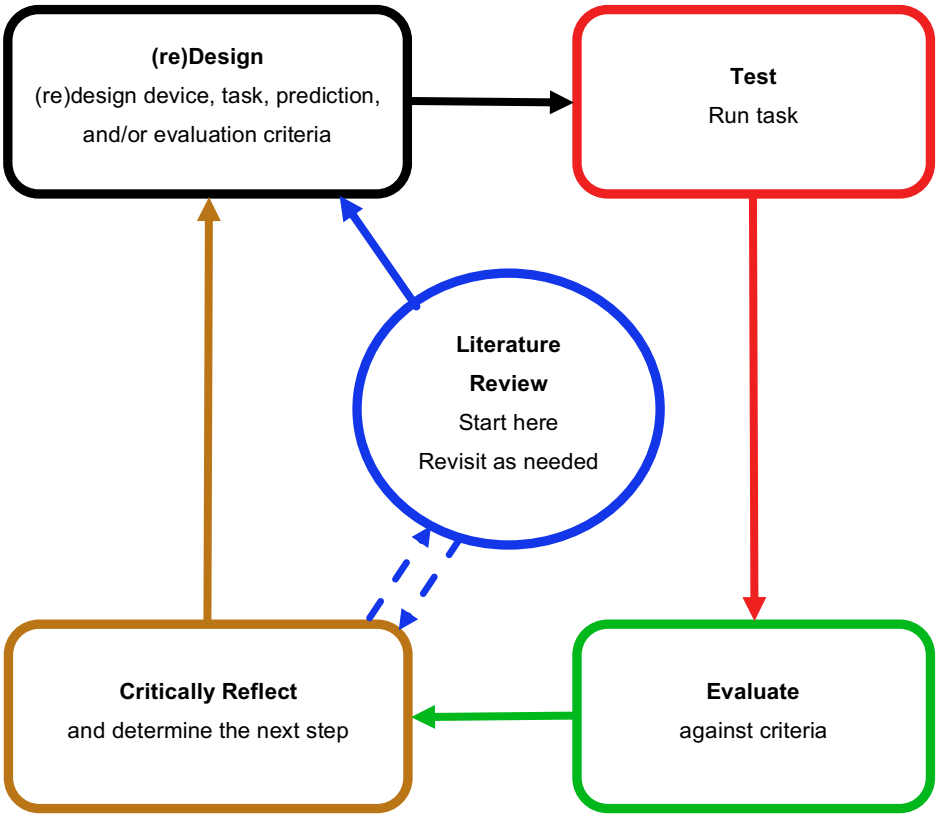


Figure 10. The NTAD development cycle (adapted from Easterday, Rees Lewis and Gerber, 2014).

Evaluation Criteria

Caren, Michon and Wright (2020) identified limitations of existing electronic wind instruments and evaluated the KeyWI against those limitations. I used a similar approach, drawing on the reviewed literature to develop NTAD criteria. I refined these criteria during development and used them to guide component selection and evaluate iterations. Table 3 groups the criteria by how each was assessed throughout the design process.

Table 3. Prototype evaluation criteria.

Criterion	Requirement	Rationale and sources
Assessed on the final build only (Iteration 2.1)		
1 Cost and accessibility	Be affordable and accessible.	Commercial aerodynamic systems are costly (Cler et al., 2016; MicroTronics Corp., 2016).
Assessed through the tasks: qualitative		
2 Practical usability, comfort, and ethics	Be comfortable and non-invasive.	Nasal emission measuring devices can be invasive and interfere with singing (Birch et al., 2002; Tanner et al., 2005; Echternach et al., 2021; Martell, Lastowiecka and Bae, 2025).
Assessed through the tasks: quantitative		
3 Sensitivity	Distinguish low-pressure signals from baseline variability.	Nasal flow during singing can be low and overlap with closure artifacts (Gill et al., 2020; Hoit et al., 1994; Zajac, 2000).
4 Responsiveness	Follow brief changes during singing.	Brief changes in nasal emission and vocal onset require a responsive signal to provide real-time feedback (Caren, Michon and Wright, 2020; Martell, Lastowiecka and Bae, 2025).
5 Graded rather than binary output	Distinguish the intended None, Slight and Much conditions.	The benefits of a VPO may depend on its degree of opening (Bunton and Story, 2012; Bunton, 2015; Gill et al., 2020).
6 Reliability	Give reasonably consistent readings under comparable conditions across takes and sessions.	Device performance should not degrade over long tasks.
Established during sensor and platform selection		
7 Evidence-based	Ground the measurement method and its interpretation in the literature.	Nasal pressure has been used to detect nasal emission during phonation (Thom et al., 2006; Bunton and Hoit, 2018), and nasal airflow measurements are used extensively in singing literature (Birch et al., 2002; Gill et al., 2020; Echternach et al., 2021).
8 Open hardware and software	Use open hardware and software to support experimentation and troubleshooting.	Low-cost, adaptable platform to support troubleshooting and further development (Caren, Michon and Wright, 2020; Dewhurst et al., 2025; Wang, L. et al., 2026).
9 Potential for future development	Allow customization and report physical units to support later calibration.	Device should be produced in such a way that future iterations are possible.

Prototype Testing

Informal Testing

I conducted most development cycles informally, testing, evaluating, and redesigning the device throughout each cycle (Figure 10), keeping notes and observations without quantitative measurements. I continually designed new tasks through hands-on testing and subsequent literature reviews, discarding ineffective tasks as I moved each iteration through the NTAD development cycle (Figure 10). I then selected a final iteration to measure quantitatively based on its performance relative to the evaluation criteria outlined above (Table 3). Figure 12 documents the entire development process.

Hardware and Software

The hardware used in the measured session for Iteration 2.1 included a Shure SM7B microphone, a Focusrite Scarlett 4i4 (3rd Gen), and my personal PC.

For software, I set out to use free, open-source tools wherever possible to support the project's low-cost, accessibility goal. These included Arduino to read the sensor and provide real-time pressure readings, Python to receive and log data, OBS Studio (OBS Project, 2026) to record my PC and webcam, Whisper (Radford et al., 2023) for transcription, and Praat (Boersma, Weenink and Shchupak, 2026) to conduct spectral analysis.

I adapted Sensirion's open-source example sketch (Sensirion AG, 2021) to read 100 times per second instead of the default once per second and automatically "zero out" between takes. I set the live-view graph to a pressure range useful for real-time feedback. I used Claude Opus 5.5 (Anthropic, 2026) to code and monitor the Arduino during testing to ensure the NTAD's sensor was optimized to provide real-time feedback during singing tasks and ensure testing data was logged and backed up. I also used Opus to run Whisper on my measured testing session and to extract still frames of the live-view graph from my OBS recording for Figures 18, 19, 20, 21, 22 and 24. I used AI to run my recorded audio through Praat, which I then exported for analysis of my singer's formant in Figures 23a, 23b and 23c, and of the pinch and release task in Figures 25a, 25b and 25c.

Together, OBS and Praat performed similarly to VoceVista Video Pro for my use case. I trialed VoceVista for testing purposes, and it would otherwise have cost $399, with optional paid renewals for further updates (VoceVista, no date). I could have avoided AI in this use case by using VoceVista, which I found to have a more user-friendly interface, but I chose not to, specifically to address the problem outlined in my introduction of providing a low-cost, accessible alternative for singers. My AI disclaimer above outlines how I used AI to operate and troubleshoot unfamiliar software.

The only paid software I used was Ableton Live 10 Suite (Ableton AG, 2018), which I used to record a backup audio track because I had already purchased it, was familiar with it, and did not want to risk losing data if any software crashed. OBS also records audio for free.

Measured Testing

The following tests were performed during the measured testing of Iteration 2.1. “Device performance” testing measured device specifications such as drift and resting noise floor. “Exploring Studio Applications” is a practical test of potential applications of the NTAD in singing studio environments.

Note: Pressure and flow are used interchangeably regarding the NTAD (described in findings). However, the NTAD measured only relative pressure. A simple formula (square root of pressure) can convert this reading into relative flow, a process commonly used in sleep studies (Berry et al., 2012) but not validated in singing studies. So when I refer to an airflow or pressure reading from the NTAD, the quantity actually measured is relative pressure.

Table 4. Test groups and what each test checks.

Test	What it checks
Device Performance	
Resting noise	Reading with no airflow
Baseline drift	Change in the zero-pressure reading over time
Device delay estimate	Lag between the live-view trace display and device input
Closed-port baseline	Sustained notes with closed port to examine artifact range during vowel production
Task 1: Artifact Test	Effect of a sharp plosive oral sung so the vowel is likely oral, on the reading with the port closed
Task 2: Degree Task	Separation of None, Slight and Much (Gill et al., 2020)
Task 3: Ramp Task	Responsiveness and sensitivity
Task 4: Low-Flow Task	Closed port versus small opening, sensitivity
Task 5: Straight-tone Comparison	Effect of vibrato on the trace
Exploring Studio Applications	
Task 6: Singer’s Formant Task	Harmonic changes near 2.5 to 3 kHz
Task 7: Pinch and Release Task	Harmonic changes near 2.5 to 3 kHz, sensitivity, responsiveness

Device Performance

Task 1: Artifact Test. This test checks for nasal artifacts, meaning signal changes to nasal pressure emissions that are not caused by airflow through a VPO. I used sharp /p/ onsets because the port is typically closed during /p/ (Zajac, 2000), encouraging oral flow exclusively. Any change in nasal pressure during this test is considered an artifact and a limitation of the device.

Task 2: Degree Task. Gill et al. (2020) had singers produce a series of phonations under three VPO conditions: “None,” “Slight,” and “Much,” while measuring nasal airflow (Figure 11). I used this task not to determine VPO or make claims as to the state of my VPO, but to test whether the NTAD distinguished graded changes measured in relative nasal airflow, which I converted from pressure using a simple formula outlined in Findings.

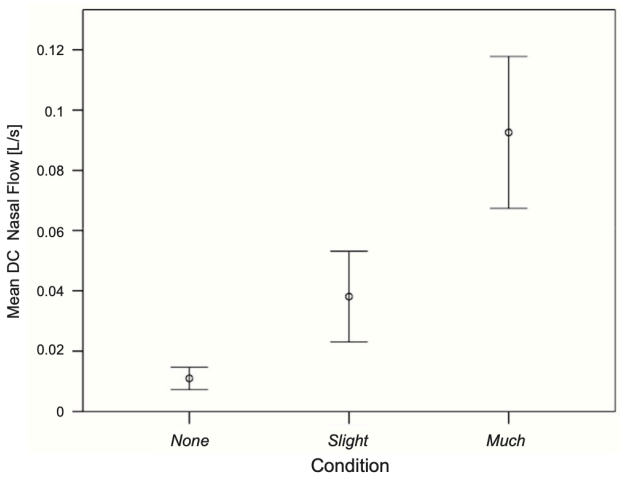


FIGURE 3. Average amplitude of the nasal DC flow in the indicated conditions. The circles represent the mean and the bars the standard deviation.

Figure 11. Nasal flow in the none, slight and much conditions (Gill et al., 2020, p. 348, original Figure 3).

Task 3: Ramp Task. I slowly increased my intended nasal pressure rate over several seconds to see whether the trace followed. This task is designed to help to determine device responsiveness and sensitivity.

Task 4: Low-Flow Task. I sang two notes twice, once with the port closed and once with a small opening, to see whether the device could measure the difference. Gill et al. (2020, pp. 346–347) made a similar comparison, measuring nasal flow with no VPO and with a slight VPO.

Task 5: Straight-tone Comparison. Compared two notes with slight nasal pressure readings: one with vibrato, one without. This was done to determine vibrato's effect on pressure readings.

Exploring Studio Applications

The following vocal tasks were performed by me. Findings of these tasks are not intended to produce meaningful pedagogical implications. The purpose of these tasks is to limit test the NTAD's potential use case both in the teaching studio and as a research tool. To determine if "real world" use cases could provide measurable and usable data. Any claims made as to the validity or pedagogical value of these tasks are to be taken with the utmost discretion.

Task 6: Singer's Formant Task. I sang two sequential notes, one with nasal flow and one without. This was done to observe if the singer's formant (around 2.5 to 3 kHz) increased with the presence of a slight VPO, as has been described in the literature (Gill et al., 2020, p. 346). Gill et al. (2020, p. 346) made a similar comparison, measuring the highest spectral peak between 2 and 4 kHz with and without a VPO.

Task 7: Pinch and Release Task. A nose pinch is a common check in the singing studio (McCoy, 2008, p. 581) to assess nasal flow. I wanted to see whether a pinch test effectively detects nasal flow at the low rates the device should also detect and to investigate the acoustic and flow consequences of the test. I sang a sustained /i/, pinched my nose, and then let go. I evaluated changes in my sensation and listened for changes in sound during the pinch test. I measured the overall recording level and the highest peak in the singer's formant region, as well as the higher harmonic region associated with "vocal roughness" in chest voice.

Take Selection

Takes affected by coughs, unstable onsets, poor vocal performance, poor microphone placement, cannula displacement, improper cannula position, condensate, or logging interruptions were discarded unless no better take was available. My VPO control was limited, so I retained a take only if I completed the task properly, in sequence, in a reasonable amount of time. I made only minor efforts to curb selection bias, which I address in the task analyses and Device and Session Limitations. Because only Iteration 2.1 has logged traces, comparisons with informal testing remain limited.

Prototype Development Process

I built and tested the NTAD in my home teaching studio. I did not monitor temperature, humidity, or other environmental conditions. Development proceeded through the five development cycles shown below in Figure 12. While McKenney and Reeves (2012) cycle was also followed and utilized in the development of the NTAD, I limited my discussion in

this project to primarily Reeves (2006, cited in Plomp, 2009) for the sake of maintaining clarity.

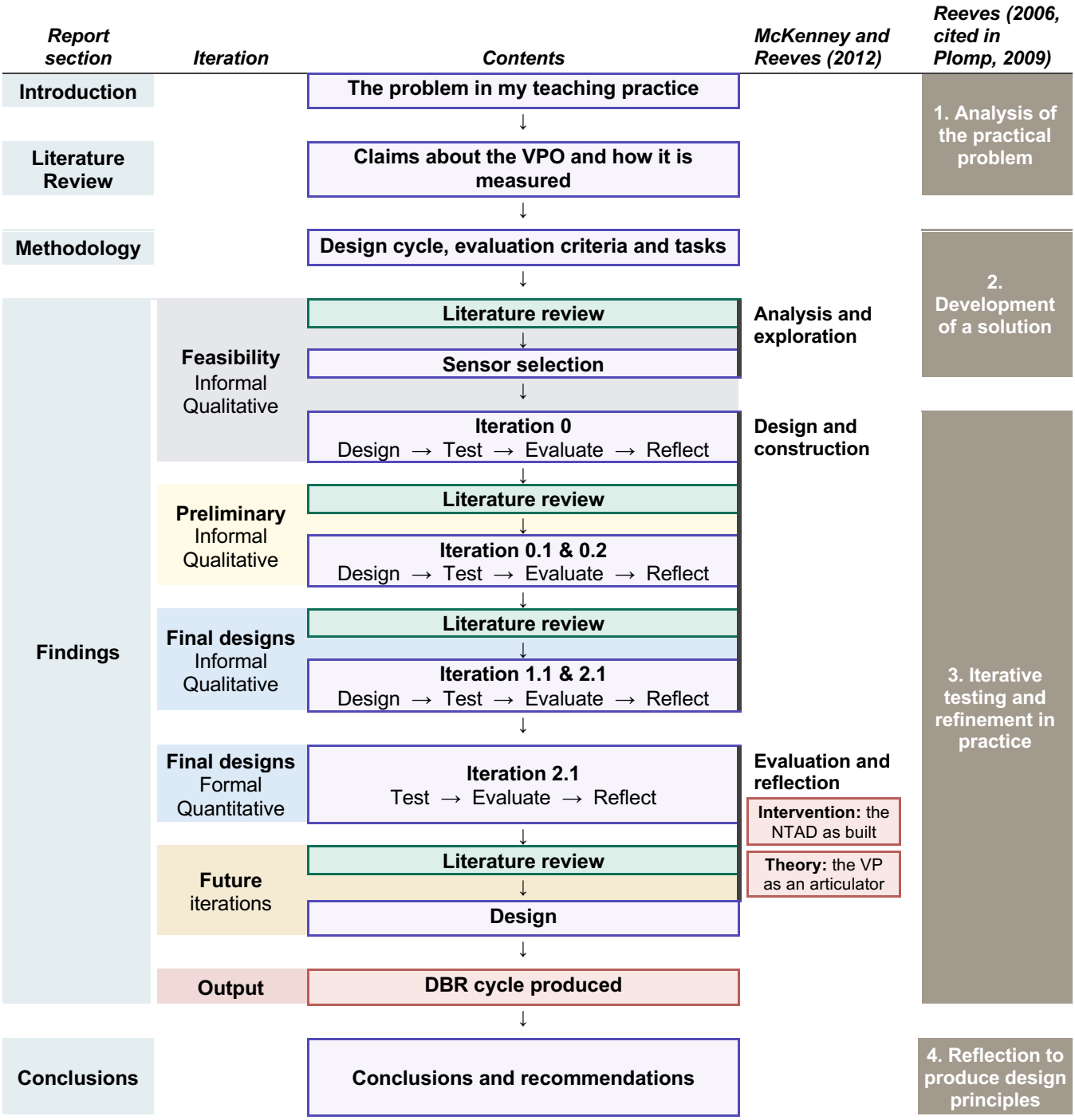


Figure 12. Outline of the DBR cycles

Part 2: The Design Research Cycle

Findings

Iteration 0 tested whether the NTAD's most basic, untested design could detect nasal emission. Limitations informed changes to later prototypes. This section was broadly part of Reeves' DBR phase of testing and refinement (Reeves, 2006, cited in Plomp, 2009, p. 14; Figure 12). This phase examines how the proposed solution performs in practice and uses the findings to refine it. It helps establish which design decisions work as intended and which need revision before further development

Iteration 0: Sensor and Platform Selection

I bought an Arduino microcontroller before selecting the sensor, as whatever sensor I decided to use needed to be Arduino compatible. Arduino is affordable, open-source hardware and free software (D'Ausilio, 2012; Pearce, 2012). This accessibility is important not only for meeting the DBR problem of creating something low-cost and accessible, but for a device that might require multiple rebuilds. The open-source nature and popularity of Arduino make troubleshooting easier, as there is a wide range of user-submitted resources. I then evaluated thermal, acoustic, and aerodynamic sensing options to determine the best fit for my project. These sensor types were picked due to their usage in the literature and their affordability.

Thermal sensors are incredibly affordable at just a few cents for a thermistor. They are also, unfortunately, strongly non-linear, very position-sensitive, slow to respond, difficult to calibrate, and depend on the temperature difference between inhaled and exhaled air (Farré et al., 1998; Hernández et al., 2001). None of the singing studies reviewed here use one (Table 2). Thermal sensors, therefore, in theory, failed the exclusion criteria outlined above for reasons just outlined and were not selected for testing.

Acoustic sensors have solid evidence supporting their use as low-cost nasalance devices (Kılıç et al., 2021; Dewhurst et al., 2025; Wang, L. et al., 2026). However, transpalatal signal transfer and the lack of ability to perform comparative analysis are significant concerns (Bundy and Zajac, 2006; Jayakumar et al., 2024). Acoustic sensors, in theory, also failed the exclusion criteria and were not selected for testing.

Aerodynamic sensors are the field's most established method of nasal emissions testing (see Table 2; Rothenberg, 2014), and for good reason. Aerodynamic sensors give reliable readings, are relatively easy to calibrate, and are sensitive and responsive (Hernández et al., 2001; Rothenberg, 2014). A differential pressure sensor was ultimately chosen because of

its high cost-to-performance ratio (Bunton, Hoit and Gallagher, 2011, p. 69). Differential pressure sensors are regularly used in singing literature to measure nasal flow and pressure. However, singing voice literature relies exclusively on commercial aerodynamic systems which cost considerably more (Cler et al., 2016; MicroTronics Corp., 2016).

The Sensirion SDP810-125Pa sensor (Figure 13) was selected for its low cost ($30.86 before tariffs) and its ability to detect the small, low flows that matter in singing (Gill et al., 2020). It offers high repeatability and no offset drift (Sensirion AG, 2019, p. 1). In my design, one sensor port connects to the nostrils and the other vents to ambient air, measuring relative pressure difference in pascals which can be converted into relative flow (Bunton, Hoit and Gallagher, 2011; Sensirion AG, 2019). Paired with Arduino (Figure 14), the SDP810 can estimate respiratory flow (Fujii, 2025), supported by an Arduino library (Sensirion AG, 2024a, p. 4). It has also been used in a portable respiratory monitor validated against reference equipment (Vieira Junior et al., 2025). A similar device was developed by Hixon and Hoit for detecting nasal emissions during infant vocalizations (Bunton, Hoit and Gallagher, 2011, p. 69).

From options available on Digi-Key, the Sensirion SDP810-125Pa was preferred over the NXP MPXV4006DP used in the KeyWI device (Caren, Michon and Wright, 2020) (who I established my evaluation criteria from) because of its higher sensitivity within its range (Sensirion AG, 2019) and its potential to detect the small nasal emissions relevant to the conditions reported by Gill et al. (2020). The specific quantity measured is called nasal ram pressure (N-RamP), defined as "a local pressure sensed at the anterior nares" (Bunton, Hoit and Gallagher, 2011, p. 69). Hixon and Hoit first used this method to study velopharyngeal function during vocalization in infants (Thom et al., 2006). The NTAD measures a similar parameter through the same interface. Hixon and Hoit chose not to calibrate N-RamP (Bunton, Hoit and Gallagher, 2011), whereas the NTAD reports relative nasal pressure in pascals, with the intention of converting to relative flow and leaving the opportunity open for future absolute calibration in line with the evaluation criteria established in Methodology (Table 3).

The Sensirion was also easy to work with for my use case. Assembly required no soldering, and the sensor is connected to the Arduino with jumper wires through a 4-position Molex connector housing ($0.45 before tariffs). Nasal sampling tubing can be inserted over the sensor's port. This made it easy to change the interface without rebuilding the electronics.

Figure 13. The Sensirion SDP810-125Pa differential pressure sensor (Sensirion AG, no date a)

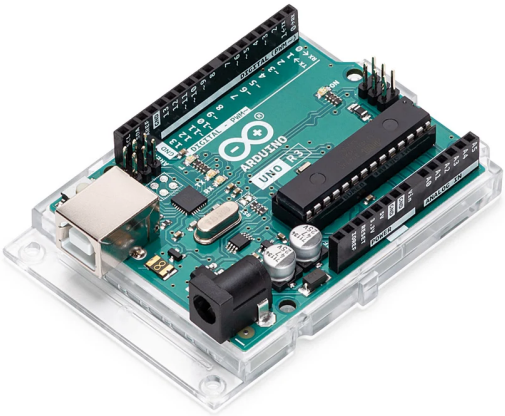


Figure 14. The Arduino Uno Rev3 (Arduino, no date)

Sampling Interface: My initial, and ultimately final, goal of the NTAD was to integrate it with a nasal cannula. A cannula's prongs sit in both nostrils and hold their position without a seal or hand support (Thom et al., 2006). They are cheap (about $2 each or less if bought in bulk; see Build Cost) and disposable, so a new one can be (and was) used for each session for good hygiene.

Safety: Connecting a nasal cannula to a differential pressure sensor is an established, noninvasive method in medicine and science. With ethics approval and without any reported filter, it has been used to study vocalization in infants (Thom et al., 2006; Bunton and Hoit, 2018), velopharyngeal function in trombone players (Bennett and Hoit, 2013), and sleep-disordered breathing in infants and children (Trang, Leske and Gaultier, 2002; Jurado et al., 2022). A cannula connected to a pressure transducer is recommended for a multitude of uses in sleep studies (Berry et al., 2012; Norman et al., 1997; Hernández et al., 2001). Patients can even apply it themselves for unattended studies (Norman et al., 1997). (Berry et al., 2012), including home sleep testing (SleepSense, 2025, p. 27) Nasal pressure sensors are used in home sleep testing (SleepSense, 2025, p. 27).

Sensirion lists medical use among the SDP8xx's applications (Sensirion AG, 2024a, p. 3) and recommends the SDP8xx for tube-connected CPAP devices (Sensirion AG, 2024b). The SDP810 is the successor to Sensirion's SDP610 (Sensirion AG, no date b), which has been connected to a nasal cannula to monitor breathing (Massaroni et al., 2019). Sensirion differential pressure sensors have been used, with and without a reported filter (my use was without a filter), in breathing devices with human patients and volunteers (Vieira Junior et al., 2025; Mander et al., 2025; Wang, S. et al., 2026). The NTAD drew 5 V from my computer's USB port, far below the 50 V at which US workplace rules require exposed live parts to be guarded (Occupational Safety and Health Administration, no date).

First Design Stage: Feasibility Design

Iteration 0 tested whether the basic design could detect nasal emission at all. Its limitations guided changes to the later prototypes. This put McKenney and Reeves' design and construction phase into practice. Each version helped me decide what to build and test next (Figure 12). This feasibility test represents the first NTAD development cycle (Figure 10).

Iteration 0 (Long Open Tubing)

Redesign: Tested feasibility. A single 4 mm tube about 2 feet in length (unmeasured), connected to one port of the Sensirion SDP810-125Pa (Figure 15a). The tube was held below one nostril during phonation, with the other nostril open.

Figure 15a. Iteration 0

Prediction: It might detect nasal emissions, though I was unsure how it would perform since nasal emissions are such low flow.

Results: The device seemed to register nasal emissions somewhat well. However, low-pressure output was unreadable, and performance varied across trials.

Critical Analysis & Literature Review

Iteration 0 was a promising feasibility test, but the NTAD needed to be far more sensitive and reliable to pass the evaluation criteria. Since I already had tubing in place, I decided to test an open tube against a standard cannula. I based the open-tube design for Iteration 0.1 on Tanner et al. (2005), who secured a foam cork occlusion in one nostril and measured nasal flow through the other. My version was simpler and far less invasive.

Second Design Stage: Preliminary Designs

The design, testing, and evaluation of Iteration 0.1 and Iteration 0.2 represent the addition of two NTAD development cycles (Figure 10).

Iteration 0.1 (Shortened Open Tubing)

Redesign: To improve reliability and sensitivity, I reduced tube length (unmeasured) to decrease airflow travel distance (Figure 15b) and occluded one nostril by gently pressing it closed with my finger. I tried to reduce tube movement during the session by putting my nostril over the tubing instead of holding it. I did not do any flow physics research in establishing this design, so citation as to why I did this is not available.

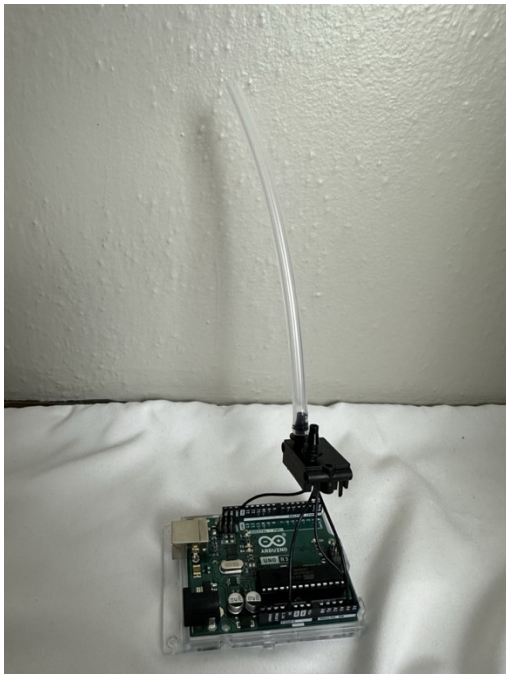


Figure 15b. Iteration 0.1

Prediction: That one nostril occlusion in addition to shortened tubing would make low-pressure events more readable, that the Degree task would become possible, and that intranasal placement would be both more sensitive and more reliable.

Results: Sensitivity did increase, and the degree task performed reasonably well, although low-pressure events were still unreliable or poorly detected. Holding the nostril closed was uncomfortable to maintain (my arm tired and my nose began to run) and may have negatively affected my singing.

Iteration 0.2 (Standard Cannula)

Redesign: The standard oxygen cannula seemed to restrict flow when I blew into it, so I cut it from its housing and fitted it inside Iteration 0.1's 4 mm tubing, hoping to remove the restriction (Figure 15d). My justification for removing the cannula from its housing in this manner has no basis in the literature and represents a lack of adequate literature analysis before this cycle. This was likely a mistake, probably restricting airflow even more due to distortions in the tubing and an imprecise connection. However, the NTAD development cycle and DBR broadly allow for this type of experimentation.

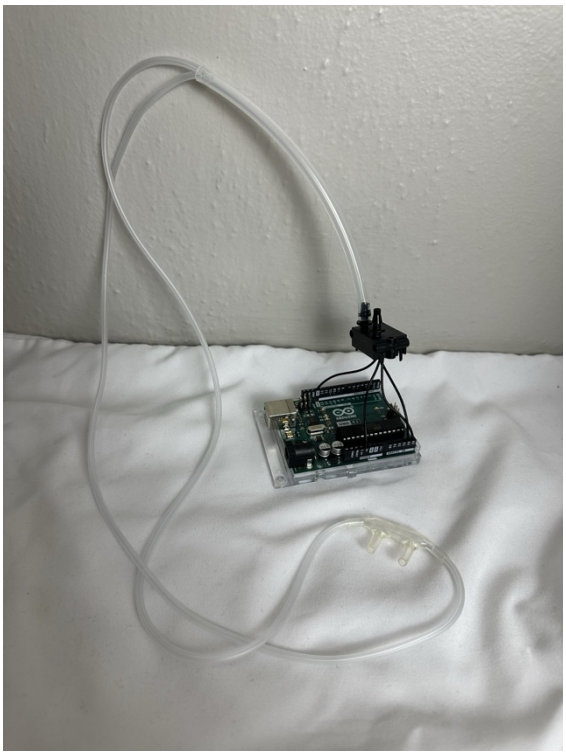


Figure 15c. Iteration 0.2

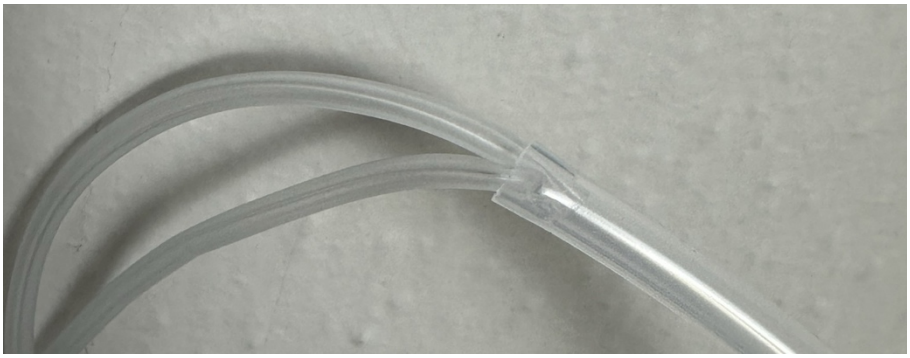


Figure 15d. Iteration 0.2, the cannula housing in the tube.

Prediction: Iteration 0.2 would perform better than Iteration 0.1.

Results: This was by far the most comfortable and reliable design, as it held its position far better than loose tubing. However, sensitivity to low flow events was generally worse than Iteration 0.1. I ended the session early when the prongs briefly fogged, to avoid risking damage to the device.

Critical Analysis & Literature Review

I was disappointed with the performance of the cannula broadly. I had hoped the two-prong sampling method would have significantly improved the device from iteration 0.1. A return to the literature was needed in compliance with the NTAD development cycle (Figure 10) to determine if I could improve the next iteration. Neither iteration passed the evaluation criteria, as performance across tasks was both unreliable and insensitive to low flow events.

High Flow Cannulas

I was surprised at how effective the cannula was despite such a flawed tubing design. High-flow nasal cannulas deliver up to 60 L/min through wide-bore tubing and prongs, whereas a standard cannula, the one I used in iteration 0.2, carries only about 4 to 6 L/min (Sharma et al., 2023). Although my use was the reverse of what it was designed for, sampling exhaled air rather than delivering oxygen, the same mechanics should at least improve my existing design, since a wider tube should resist flow less in both directions (Sensirion AG, 2024a, p. 15).

Moisture

Exhaled air carries moisture that condenses on cooler surfaces, so condensate reaching the sensor might fall outside its rated operating conditions (Sensirion AG, 2019, p. 2; Lewis and Chambers, 2023). The solution to this problem would be to install a simple moisture filter. However, I did not want to risk further reducing tube flow rates and could not find research on the effects of cannula filters on flow. As discussed under Safety in Sensor and Platform

Selection, nasal cannulas connected to pressure sensors are used extensively in medical settings without any reported moisture filter or moisture concerns (Norman et al., 1997; Berry et al., 2012). Still, out of an abundance of caution, I would remove the cannula between tasks in the next, final NTAD Iteration 2.1 utilizing a high-flow cannula.

Third Design Stage: Final Designs

The design, testing, and evaluation of Iteration 1.1 and Iteration 2.1 represent two additional NTAD development cycles (Figure 10). Bringing the total to five complete cycles.

Iteration 1.1 (Y-Adapter): Comfort Trial Only

Redesign: To increase sensitivity, I designed a Y-shaped interface adapter. This adapter connected to two small lines of tubing, each with an earbud tip at the end. The intention was to, essentially, build a custom semi-sealed high-flow cannula with wide tubing. It would also eliminate the need to occlude a nostril, as both nares would be sampled.

Figure 15e. Iteration 1.1, the Y-adapter.

Prediction: That Y-adapter would outperform the high flow, since I had such poor results from the standard cannula. I believed that nasal cannulas were not designed for low-flow singing events; I would need to design a cannula for singing myself for the NTAD to pass the evaluation criteria.

Preliminary results: Before connecting the Y adapter to the sensor, I checked comfort by resting the adapter's earbud tips gently against my nose as I tried a random phonation task. This brief task (1 or 2 seconds) caused very mild discomfort due to airflow resistance, indicating that a partial or full seal over longer use would not pass the evaluation criteria. In line with the ethics approval, I stopped there and rejected the adapter for final testing.

Iteration 2.1 (Cannula): High Flow Cannula

Redesign: Iteration 2.1 was intended to address the problems with Iteration 0.2. I replaced the standard cannula with a high-flow cannula and connected it directly to the sensor rather

than fitting it into the old tubing (Figure 16). I cut about 22.5 in (57 cm) from the 2 ft cannula tube to reduce the required airflow distance, hopefully improving low-flow sensitivity. I intentionally selected a model with 1 cm prongs, which I fully inserted.

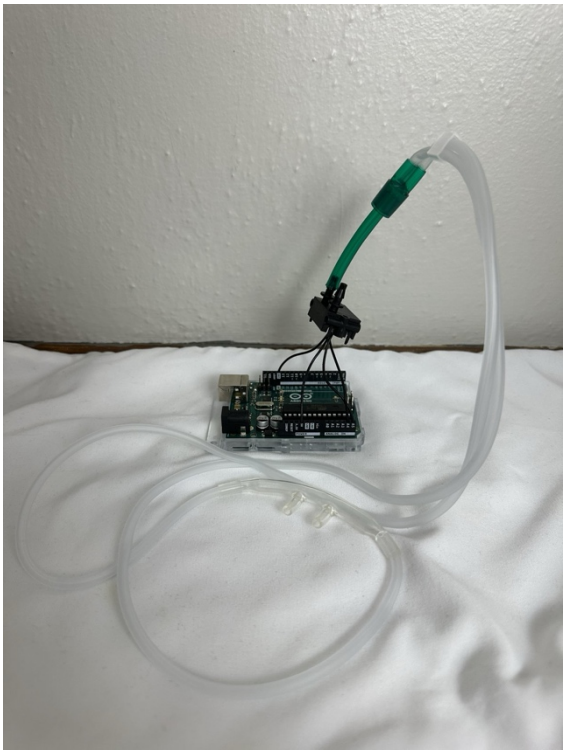


Figure 16. Iteration 2.1

Prediction: I expected the high-flow design and direct connection to the Sensirion to increase airflow delivered to the sensor compared with iteration 0.2 by a moderate amount.

Results: The high-flow cannula worked well in informal use. It was reliable and appeared highly sensitive to low-flow events. This interface was selected for final testing.

Iteration 2.1 Measured Testing Session

The Iteration 2.1 measured testing session was conducted in continued accordance with Reeves' DBR phase of testing and refinement (Reeves, 2006, cited in Plomp, 2009, p. 14; Figure 12). I used pressure logs, audio, personal sensations of comfort, and general observations to evaluate Iteration 2.1. As stated in the methodology, pedagogical claims are not intended to test, validate, or invalidate any theories. Limitations in this section relate to the task and to my execution. Broader technical limitations with the overall design of the study and the NTAD are discussed later under Device and Session Limitations.

It is important to acknowledge that, although significant effort was invested in verifying numerical assertions, a substantial portion of the data below was collected and calculated with the assistance of AI. For instance, I conducted spectrographic analysis using Praat with AI support, as it was one of my first times using the software and I needed assistance. Errors may have been introduced at various stages during this process due to my lack of expertise. Therefore, I emphasize once more that the objective of these findings is not to derive scientific conclusions or make assertions beyond confirming that this constitutes an initial prototype test stage of a low-cost, relative pressure-sensing device intended for use by singers. Further, more detailed work remains to be completed.

This measured session took place on 28 September 2026, with logged data spanning 19:57 to 23:15 (about 3 h 18 min).

Device Performance

Iteration 2.1 Build Cost

Table 5. Parts and prices for the final build.

Part	Supplier	Price (USD)	US tariff at purchase (USD)
Sensirion SDP810-125Pa differential pressure sensor	DigiKey	$30.86	$4.79
Arduino Uno R3 (A000066)	Amazon	$27.60	Included in listed price
Molex 4-position 2.00 mm connector housing (502351-0400)	DigiKey	$0.45	$0.13
ResOne high-flow adult nasal cannula, 2 ft, pack of five	Amazon	$9.99	Included in listed price
USB 2.0 A-to-B cable	Already owned	Not included (about $5 new)	
Total		**$68.90**	**$4.92**

Prediction: Iteration 2.1 will likely pass the measured task when weighed against the evaluation criteria. It will be a moderate but significant improvement over previous iterations. Sensitivity will increase slightly. Reliability will improve.

Table 6. NTAD specification test results.

Spec	NTAD
Sensor range	±125 Pa
Sampling Rate	100 Hz (10 ms)
Resting noise	0.00 Pa mean, 0.01 Pa SD
Baseline drift	0.02 Pa over 3 h 17 min
Artifact (/p/ onset)	−0.49 to +0.12 Pa
Closed-port sustained note pressure variation	−0.19 to +0.11 Pa
Rise time (time to rise after a tap on the cannula)	10 ms for firm taps
Estimated display delay (delay between phonation and reading appearing on screen)	0–35 msa
Estimated audio alignment	within about 0.05s

Task 1: Artifact Test

I produced five sharp /p/ onsets, each followed by a vowel, to determine whether any artifact was present. That is, to ensure no nasal emission leakage from soft-palate vibration displacing air out of the nose, even when the VP is closed.

Results: The five /p/ releases (Figure 17) produced a small negative dip, with readings ranging from −0.49 to +0.12 Pa.

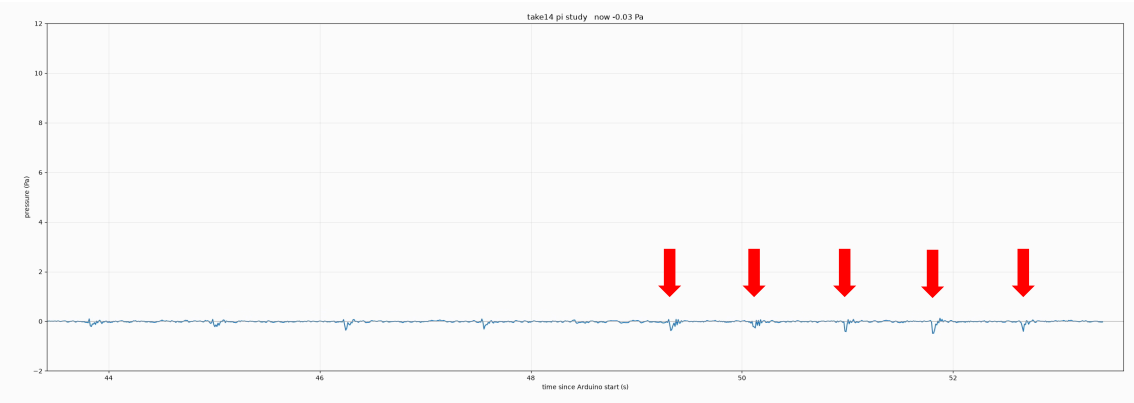


Figure 17. Artifact test pressure reading
(OBS screen recording export with AI assistance)

Critical Analysis: Because I am not very familiar with the literature, I was surprised to see negative pressure here, since most of what I remember reading in the initial literature review suggested artifacts were responsible for positive pressure. However, small positive or negative nasal readings can occur with the port closed, because soft palate movement displaces small volumes of air (Thompson and Hixon, 1979, cited in Zajac, 2000, p. 473).

Limitations: This task exclusively assesses a strong plosive. Thus, this test does not give me much information about artifacts produced during sustained phonation.

Task 2: Degree Task

I sang a sequence with None, Slight, and Much nasal flow, aiming to keep the volume similar across the three conditions, similar to Gill et al. (2020, p. 347).

Results: In the second pass of take 13 (Figure 18), median pressure was −0.02 Pa for None, 0.81 Pa for Slight, and 4.29 Pa for Much, with loudness between takes varying within about 2.3 dB. The Much note started near 10 Pa and settled near 3.5 Pa. Converted to relative flow, the three conditions followed a pattern similar to Gill et al. (2020) (Figure 18b).

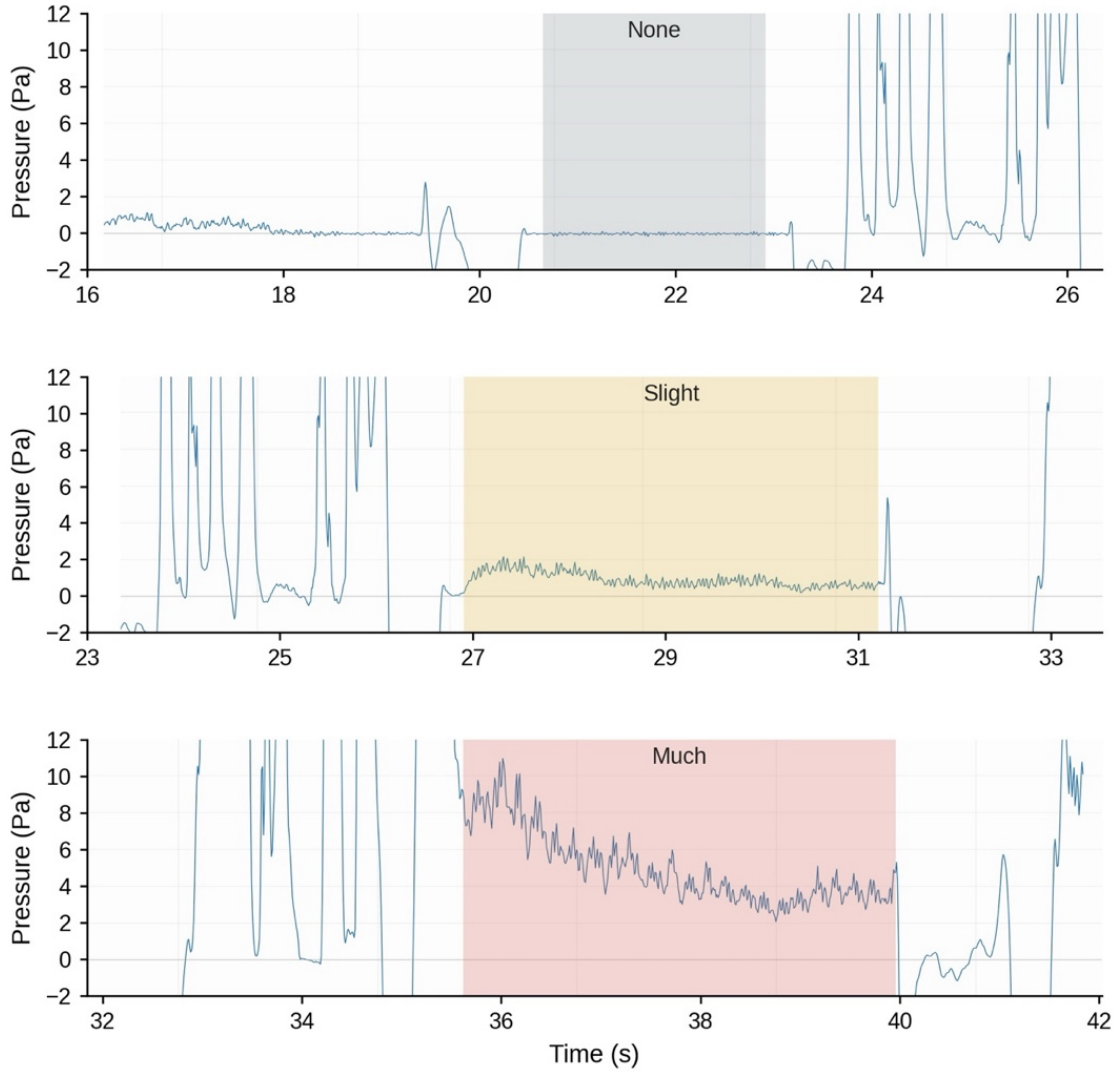
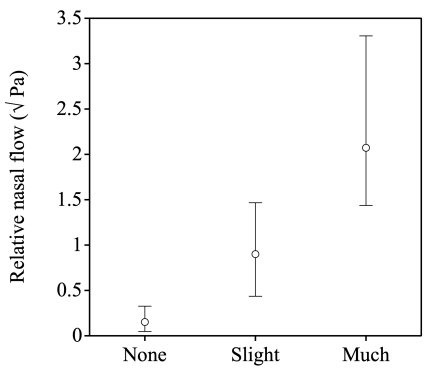


Figure 18. Degree task
(OBS screen recording export with AI assistance)



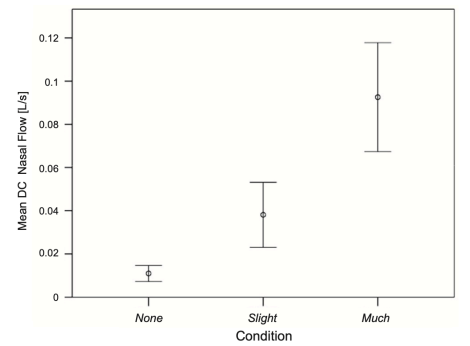


FIGURE 3. Average amplitude of the nasal DC flow in the indicated conditions. The circles represent the mean and the bars the standard deviation.

Figure 18b. Degree task relative flow beside Gill et al. (2020, p. 348, original Figure 3)
(Left: created in Praat with AI assistance)

Critical Analysis: This test is a first step toward demonstrating that the NTAD has potential use both in the teaching studio and as a research tool. I did many takes of this task, and all

of them felt responsive and sensitive. However, most previous iterations could also measure a Gill-style task with reasonable success.

Limitations: The NTAD is uncalibrated and reads relative pressure at the naris. That pressure gives a relative degree of nasal flow. So, the comparison to Gill et al. (2020) is fundamentally flawed because it cannot directly compare the two tasks. Additionally, Gill et al. (2020) claimed that their nasal flow measurement was related to singers' expected VPO. Nasal flow, however, is only one factor in determining VPO and the NTAD only measures relative nasal pressure. I make no claims that the NTAD alone can determine VPO area, size, shape, etc.

Task 3: Ramp Task

I slowly increased my intended nasal flow degree over several seconds to see whether the trace followed.

Results: The trace rose somewhat steadily from about 0 Pa to about 10 Pa over about 4s.

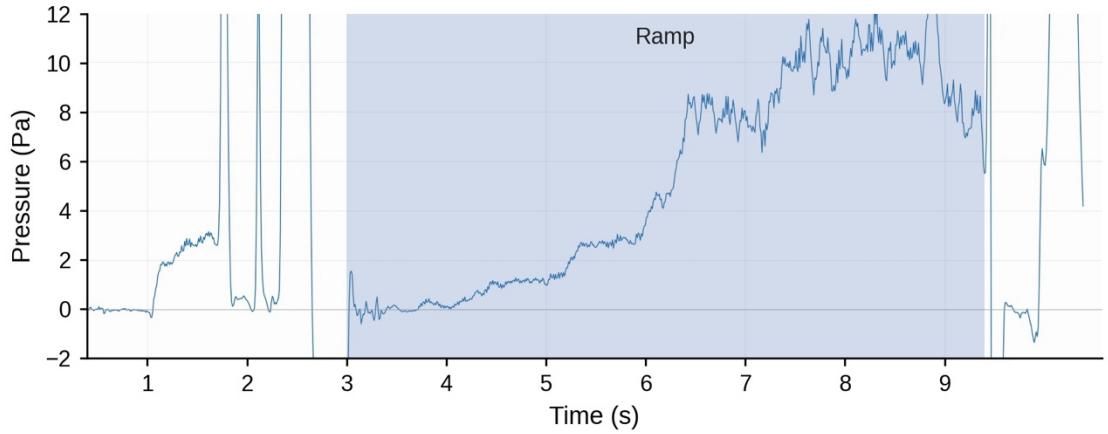


Figure 19. Ramp task pressure reading
(OBS screen recording export with AI assistance)

Critical Analysis: In earlier iterations, similar tasks caused readings to jump from zero to a slight condition, so a gradual ramp like this wasn't possible. This indicates that the NTAD is quite a bit more responsive and sensitive to low flow events.

Task 4: Low-Flow Task

I sang the same note and vowel twice, attempting a low flow on the second task.

Results: Median pressure was −0.03 Pa with the port closed and 0.54 Pa with it open (Figure 20). The lowest point recorded in the low flow condition was 0.14 Pa.

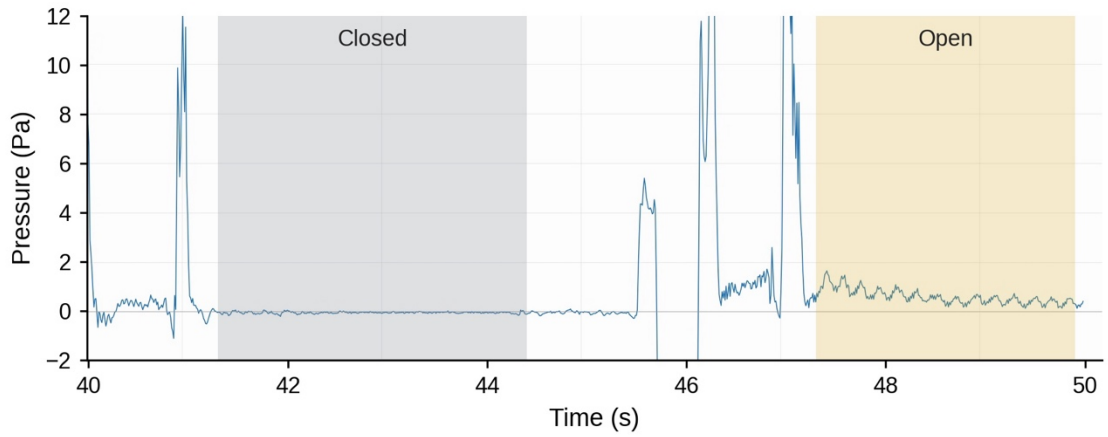


Figure 20. Pitch, volume, vowel
(OBS screen recording export with AI assistance)

Critical Analysis: This task indicates that the NTAD is sensitive enough to detect low-flow phonation events. Previous iterations were not sensitive enough to reliably trace low-flow events to effectively produce a ramp in this manner during informal testing. Iteration 2.1 is a significant improvement.

Task 5: Straight-tone Comparison

I repeated the Degree task without vibrato, as all my prior takes had been with vibrato. I wanted to see if the pressure trace would appear more stable without vibrato. Figure 21 compares a Slight note without vibrato to the previous Slight note sampled.

Results: The straight-tone trace was steadier.

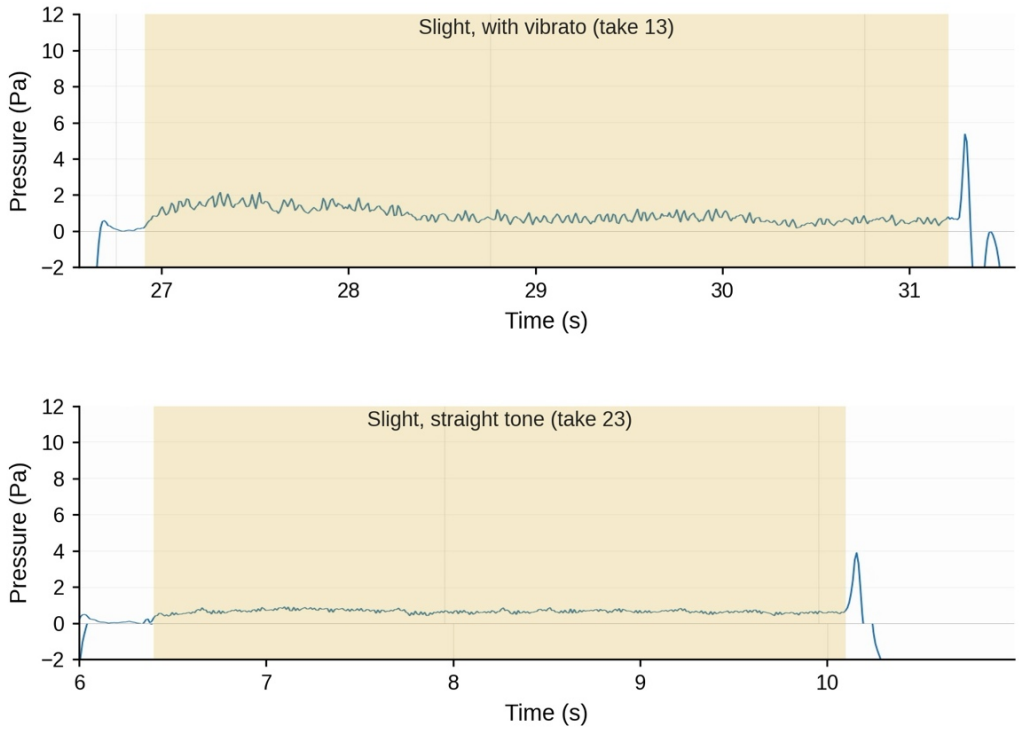


Figure 21. Slight note with and without vibrato
(OBS screen recording export with AI assistance)

Critical Analysis: There may be a relationship between vibrato and VPO. Or I need to learn to adjust my technique to maintain a steadier VPO during vibrato.

Limitations: This was a quick, last-minute, exploratory comparison, not a controlled test of vibrato. These two takes were taken potentially hours apart (VERIFY).

Exploring Studio Applications

Task 6: Singer's Formant Task

I sang a few notes with and without nasal flow and compared one pair on the same vowel (/i/), using the highest spectral peaks between 2.5 and 3 kHz as the points of comparison. I picked a pair from the same take with the greatest difference and the most similar vowel.

The notes chosen were sang sequentially, 14 seconds apart, and tried to keep the volume the same.

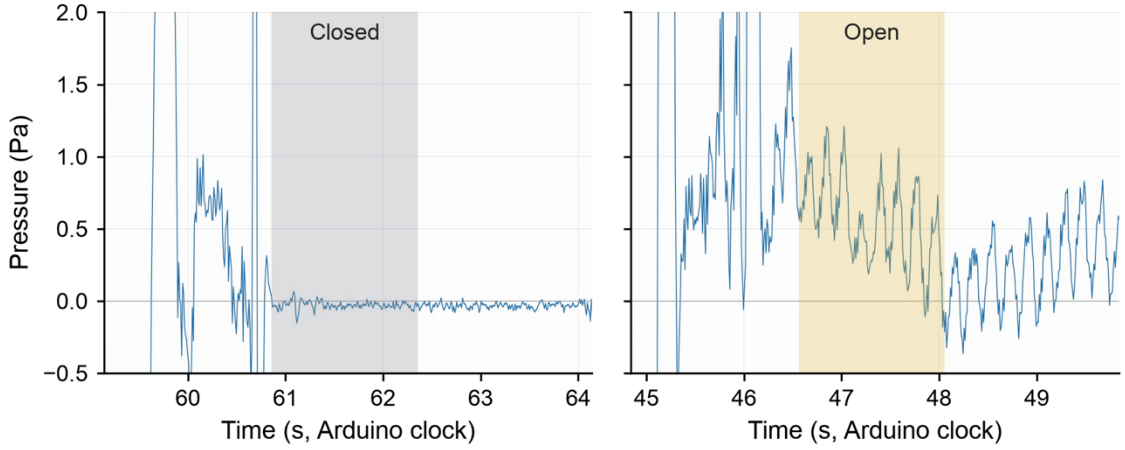


Figure 22. Singer's formant task pressure reading (OBS screen recording export with AI assistance)

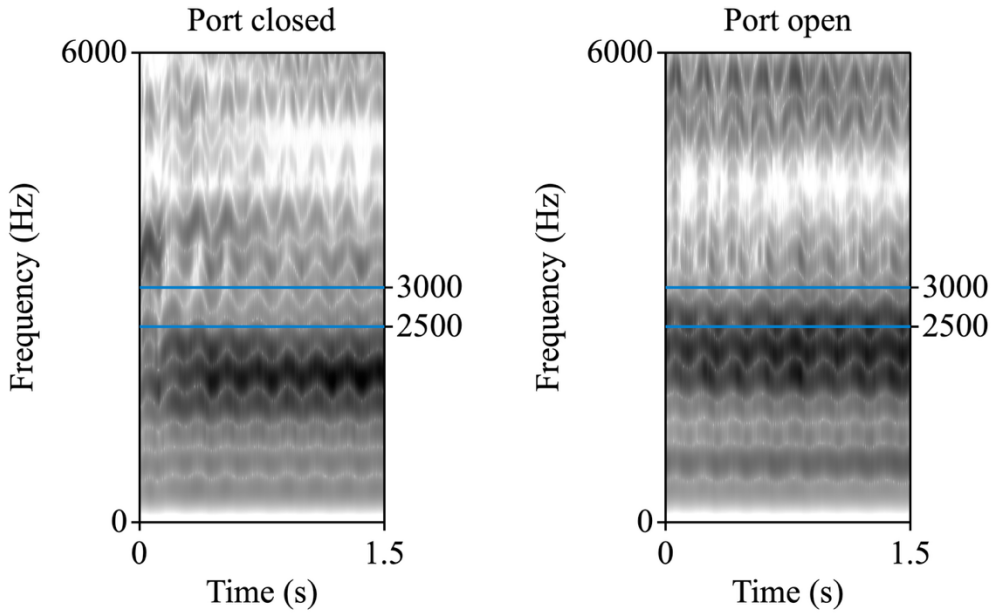


Figure 23a. Spectrographic analysis of singer's formant task VPO vs non-VPO (Created in Praat with AI assistance)

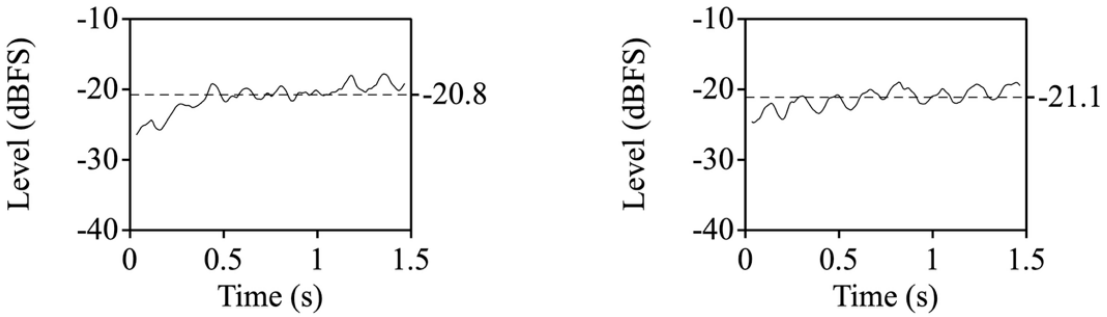


Figure 23b. Loudness in the singer's formant task. (Created in Praat with AI assistance)

Results: The note with a VPO's highest peak between 2.5 and 3 kHz, measured in Praat, was about 15 dB higher at the same overall loudness. The second peak in that range was also higher with a VPO, 27.2 dB against 21.3 dB closed. The audio level of each note, in dBFS, was about −21.1 open and −20.8 closed. The median pressure was 0.55 Pa with the port open and −0.03 Pa closed (Figure 22). The open note also had more energy between 4 and 6 kHz, with an average level of 17 dB open and 6 dB closed.

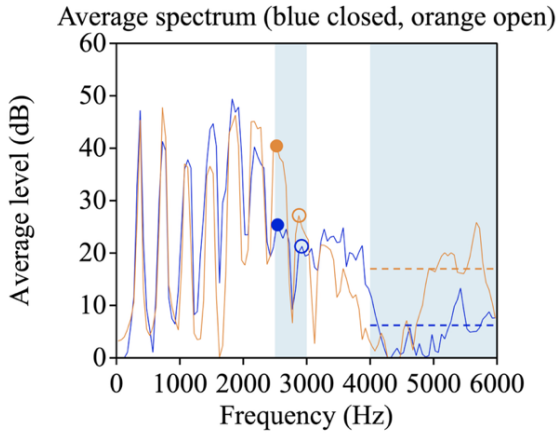


Figure 23c. Average spectrum of singer's formant task VPO vs non-VPO (Created in Praat with AI assistance)

Critical Analysis: I am not a classical singer (professional or otherwise) nor an expert in classical singing acoustics. I cannot claim any degree of expertise in producing or analyzing a singer's formant. Therefore, I am uncertain whether my change in nasal flow caused the observed difference or whether the change in the formant region itself was significant. My initial literature review may have introduced a bias, subtly shaping my singing to achieve a result described in the literature (increased singer's formant in VPO condition). Nevertheless, I find the outcome interesting and largely consistent with my expectations and the literature review above. The unexpected elevation in the high-frequency "auditory roughness" range associated with more intense singing was also particularly noteworthy, at about the same overall dB level. (Howell, 2016, p. 39)

Limitations: I am not a classical singer and have no idea how to produce a singer's formant or how to listen for one. I have never conducted any serious spectrographic analysis of my voice before; I was assisted by AI in inputting my datasets to create figures in Praat. Additionally, listening back to my samples as a CVT-trained teacher, I hear more than a change in VPO. Going from open to closed, I hear factors such as a lowered larynx, reduced twang, and a lifted velum. In my experience, these types of adjustments can lead to a darker vocal tone, which I assume may also affect the singer's formant. I have no reason to believe my VPO specifically caused the change beyond my existing bias and familiarity with the VPO's theoretical effects on the singer's formant, which may have subconsciously influenced my vocal production.

Task 7: Pinch and Release Task

I sang one continuous note and pinched my nose with my fingers mid-task, then released before the end of the task. This created three acoustically significant conditions: pre-pinched, pinched, and released.

Results: Pinching my nostrils while singing /i/ slightly muted the sound. I did not, however, feel a significant change in my singing sensation beyond the occlusion itself. In the pre-pinch sample with a slight leak, the median pressure reading was +0.13 Pa, peaking briefly over 1 Pa just after the note began. In the pinched sample, pressure fell to about −0.02 Pa (Figure 24) and the overall dB level rose by about 1.2 dB. During the pinch, the highest peak between 2.5 and 3 kHz fell about 6 dB from about 33 to 27 dB (Figures 25a and 25c). This peak returned in the release sample, and the overall level rose another 1.4 dB, while pressure remained close to zero.

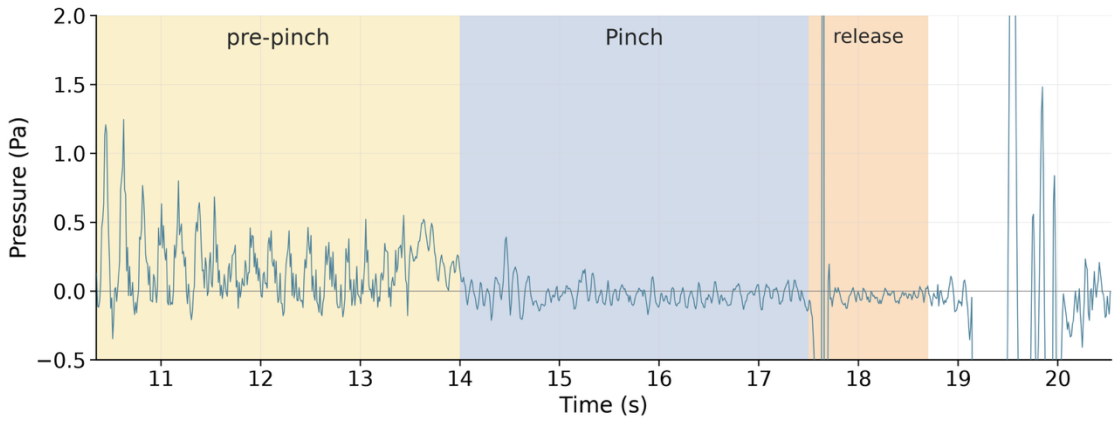


Figure 24. Pinch test pressure reading
(OBS screen recording export with AI assistance)

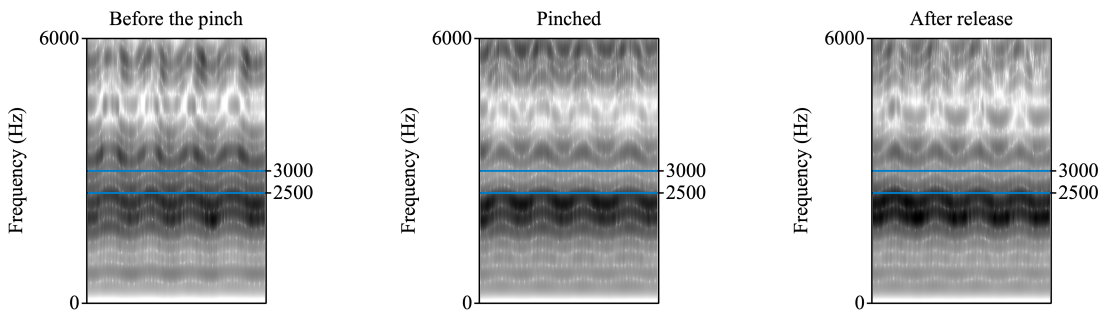


Figure 25a. Spectrographic analysis of pinch and release task
(Created in Praat with AI assistance)

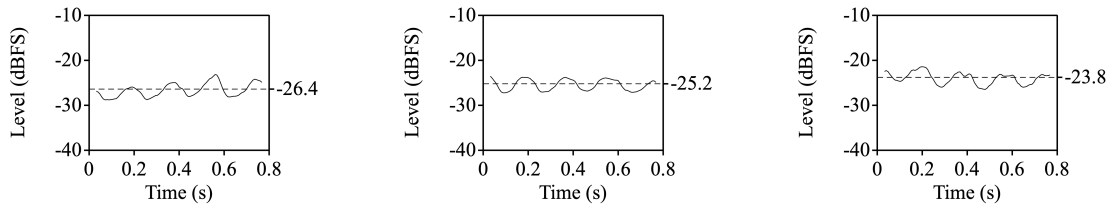


Figure 25b. Loudness in the pinch and release task. (Created in Praat with AI assistance)

Critical Analysis: In my view, this suggests that changes in vocal production during the pinch task may not always reflect a change in VPO but may instead reflect a singer's response to the task's more invasive nature. Although there was no flow in the after condition, the first peak (solid circle in Figure 25c) recovered after the pinch, whereas the second peak in the region (unfilled circle) did not. Upper harmonics after the pinch also rose above both prior samples. The singer's formant was affected, but in a clear linear manner.

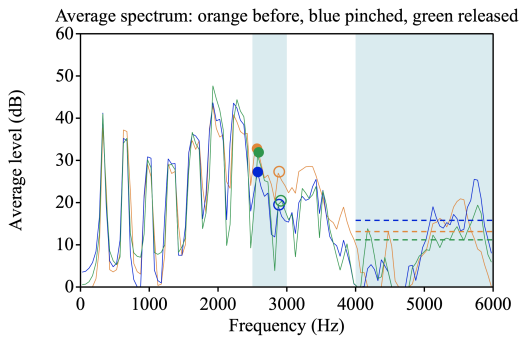


Figure 25c. Average spectrum of pinch and release task (Created in Praat with AI assistance)

Limitations: The pinch task was unblinded, and I was both the singer and the listener. I knew when I would pinch and release. I may have anticipated these conditions and adjusted my singing to compensate. AI assistance was used in the production of the Praat figures.

General Device and Session Limitations

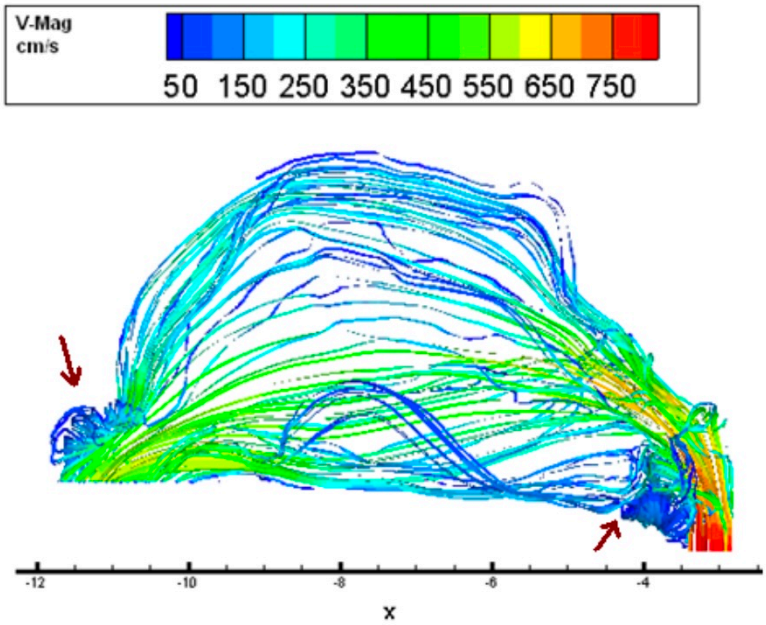
The following limitations apply to Iteration 2.1 and its measured testing session.

Moisture: Because of the length of this testing session, condensate accumulated in the sampling line again (Figure 26). Most of the load came from breathing through the interface by mistake. This condensation may have affected device performance, but I did not notice any of it travel down the tubing.

Figure 26. Condensation in the cannula tube.

Prong Positioning: Air accelerates through the nasal valve and diffuses once it leaves the naris. The nasal valve sits roughly 1 to 1.5 cm inside the naris (Nigro et al., 2009). The prongs on my high-flow cannula were roughly 1 cm long, so even small changes in their position might change the reading. It's also possible the prongs were not long enough to reach peak flow events in the naris since they do not reach an insertion depth of 1 cm.

Unfortunately, I had to reposition the prongs frequently to avoid moisture buildup in the cannula and was frequently careless with repositioning. I tried to control for this by picking takes via the OBS recording, in which I could observe myself (via webcam recording) and the cannula placed properly. Unfortunately, no data seems to exist on ideal prong length and positioning during singing.



(b)

Figure 27. Modelled expiratory airflow (Nayebossadri et al., 2018, original Figure 5b).

Sensor connection: I did not press the cannula tubing down fully on the Sensirion's port because it felt a bit rigid and difficult to press down. I didn't want to break the device before testing, so the cannula may not have had a full seal. A partly seated connection could leak or shift, which may have affected my data.

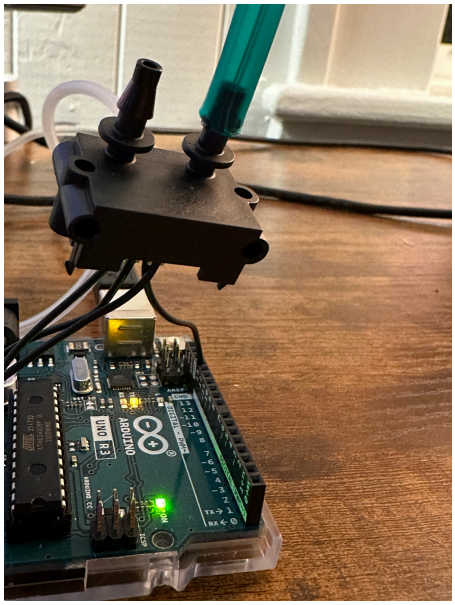


Figure 28. The sensor connection.

Fragile device: The connectors between the Sensirion and Arduino are incredibly delicate. It's possible that the upright position of the Sensirion is causing stress on these cables which might impact results.

Tube length: I cut the cannula tube short on purpose to limit the pressure signal's travel time to the sensor to increase device sensitivity. Because the tube was too short, it began to fall off the table during testing. About halfway into the design, I decided to hold it in my hand during tasks to prevent it from falling and breaking. This could have added handling noise to the traces.

No reference instrument: I do not have any sort of reference instrument by which I can determine if the NTAD's readings are accurate or not.

Subject VPO Control: I don't have the greatest control of my VP. It's challenging for me and takes a lot of attention that could otherwise go toward the tasks. Because of this, I was forced to watch the live graphical pressure display during sung tasks for feedback. This was great for my practice and learning, but not ideal for task execution. As a result, many tasks were unused due to improper execution. It's not possible to know if changes in the pinch-and-release task, for example, would be different if I had greater control of my VPO.

SM7B Presence Boost: I accidentally left the presence boost on my Shure SM7B during the measured testing session. This caused a bump in the upper midrange, covering much of the same region as the singer's formant (Shure Incorporated, 2023). While this change was applied across all takes, it did not boost one take more than another. However, I cannot claim it had no impact, particularly when analyzing the singer's formant region and comparing between takes.

SM7B Microphone Distance: The SM7B is a cardioid dynamic mic whose response (both in harmonic content and loudness) varies significantly with distance and placement (Shure Incorporated, 2023). While I tried to select tasks in which I maintained the same mic distance, I was far from perfect. Any small movement may have changed dB levels between takes. This is particularly problematic for tasks that compare to one another, such as the singer's formant task. Perhaps the mic's polar rejection pattern, combined with the presence boost, caused more significant issues than I could account for.

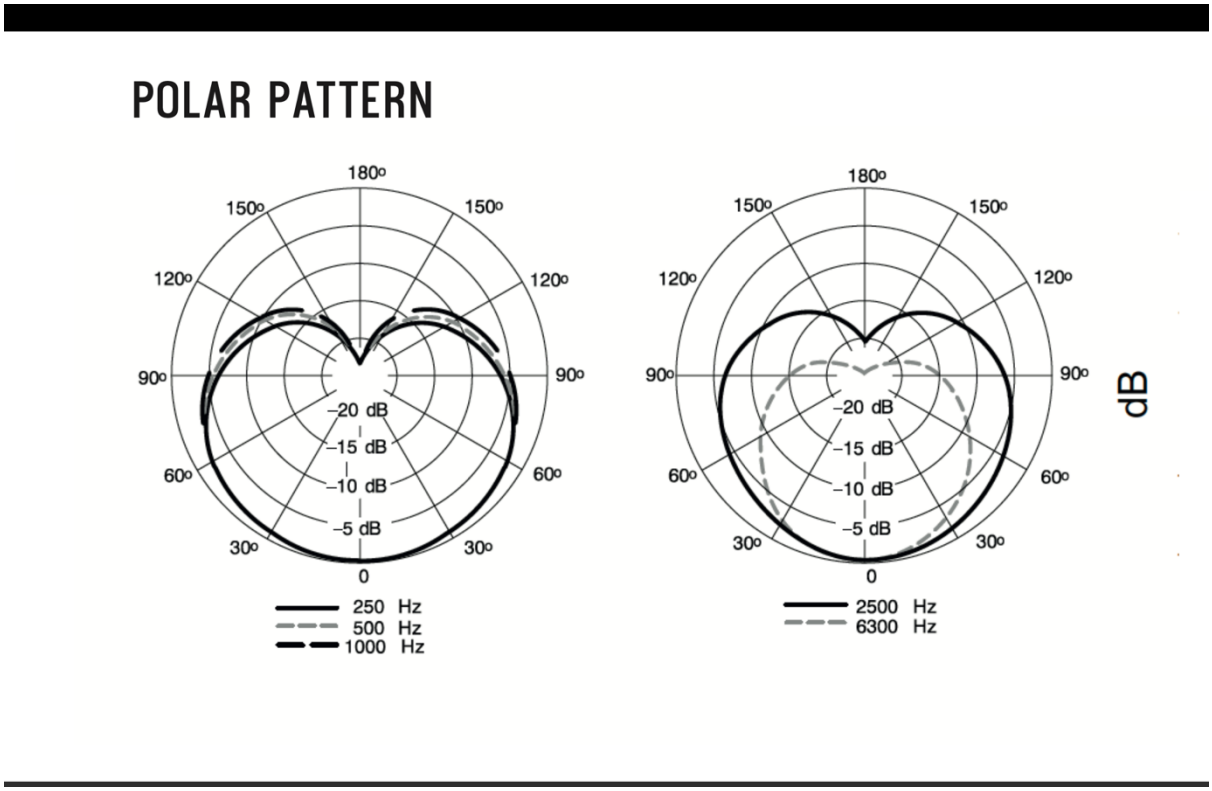


Figure 29. Shure SM7B polar pattern (Shure Incorporated, 2023)

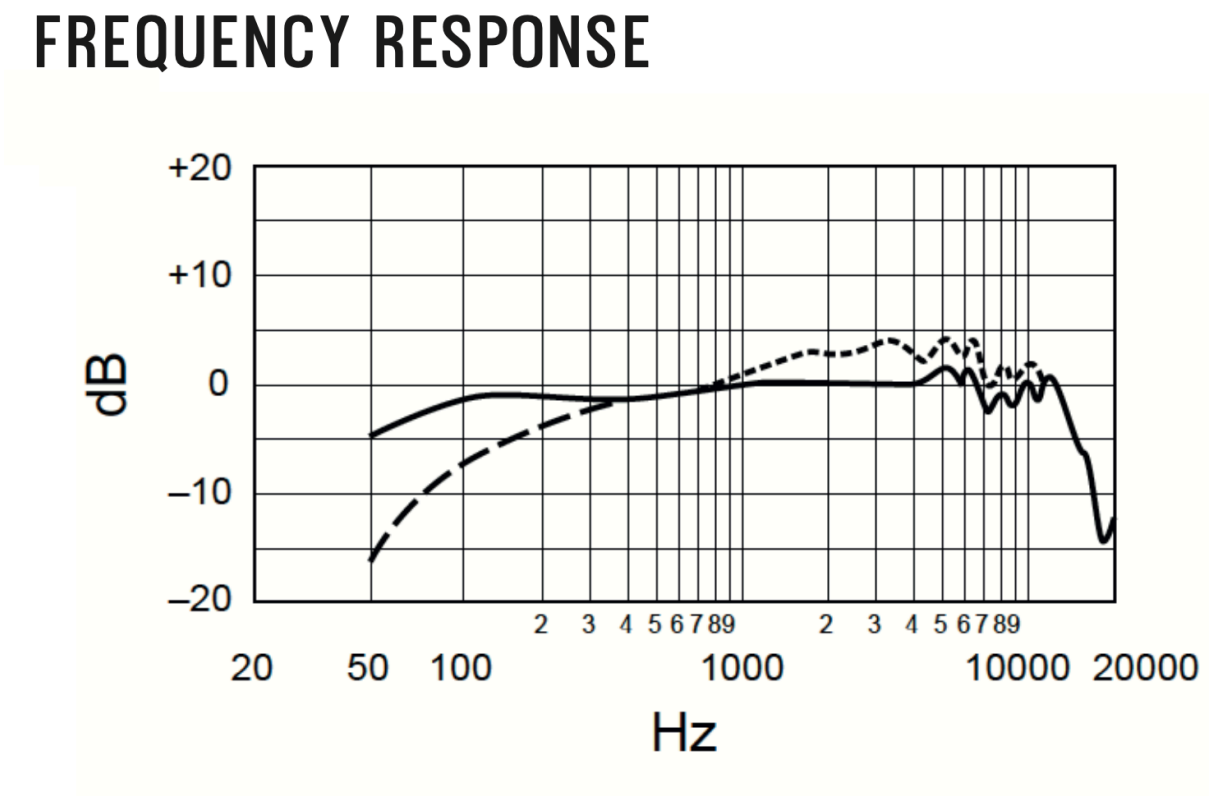


Figure 30. Shure SM7B frequency response (Shure Incorporated, 2023)

Evaluation Against the Criteria

Table 7 returns to the nine evaluation criteria set in Methodology. It brings together the logged results, observations from the formal session, and design choices reported above. I use a simple pass/fail/partial system here. However, a criterion passing doesn't mean the device cannot be improved, nor does it mean the device should be used by singers in its current iteration. I consider this criterion a functional baseline from which future development can continue and reference. Overall, iteration 2.1 exceeded all expectations for a prototype device, and I believe it has strong potential for both studio and research use.

It's important to note that some of these criteria are subjective. For example, what I find comfortable may differ from another singer's experience. My evaluation of unreliability could stem from how I use the device, and familiarity with one configuration could make it seem more reliable than it is.

Table 7. Evaluation against the criteria.

Criterion	Tests / tasks	Pass/Fail/Partial	Assessment
Assessed on the final build only (Iteration 2.1)			
1 Cost and accessibility	Parts-cost check (Table 5)	**Pass**	Device was less than $100 to construct and all relevant software is free.
Assessed through the tasks: qualitative			
2 Practical usability, comfort, and ethics	Session observations	Pass	Comfortable and non-invasive. Removing the cannula between takes is quite annoying over long sessions. Cannula has a plastic smell that became annoying.
Assessed through the tasks: quantitative			
3 Sensitivity	Resting baseline Degree Low-Flow	**Pass**	All low flow tasks tested were detected.
4 Responsiveness	Tap / display timing Ramp	**Pass**	Low delay, fast sample rate.
5 Graded rather than binary output	Degree Ramp	**Pass**	Can detect very low flow to very high flow
6 Reliability	Baseline checks Session observations	Partial	Device in use for three months so far with no issues. However, moisture control needs serious attention. Consistent performance across multiple sessions is yet to be tested.
Established during sensor and platform selection			
7 Evidence-based	Not task-assessed	**Pass**	Nasal pressure and nasal flow sampled via cannula are very well represented in literature across multiple fields. The SDP series is also widely used in medical research.
8 Open hardware and software	Not task-assessed	**Pass**	Arduino compatible, OBS to record sessions, Praat for acoustic analysis
9 Potential for future development	Session observations Design review	**Pass**	Highly customizable, effective, easy to use, compatibility with free software.

Final Literature Review

Design-based research produces the device and the understanding gained from building it (Barab and Squire, 2004; Design-Based Research Collective, 2003). These correspond to McKenney and Reeves' outputs of a maturing intervention and theoretical understanding (2012, p. 77; Figure 12). Iteration 2.1 is the intervention, and this review develops a proposed new theoretical interpretation of the VP as an articulator.

Pedagogical Implications: The VP as an Articulator

Note: I am making broad pedagogical claims here. Keep in mind I am only presenting a possible argument and not intending to generalize based on my incredibly limited project.

In singing voice pedagogy, vowel modification is an accepted solution for avoiding vocal tract instabilities. "Formants need to be avoided, not sought out, in the choice of a vowel" (Titze, 2007b, p. 199), and "there are good vowels and bad vowels for a given pitch" (Titze, 2007b, p. 201). Bozeman (2021) argues that appropriate vowel migration and modification across the range improve phonation efficiency.

As pitch rises, singers in both classical and CCM styles adjust their articulation to maintain their intended timbre, and those adjustments limit the vowels available to them. In belting, Titze (2007a) describes a rising larynx, a lowering jaw, and spreading lips, and notes that a raised larynx "crowds the hyoid bone, the tongue, and the jaw" (p. 558). Classical male voices "must use active vowel modification (opening) on their closest vowels into and above the zona di passaggio" (Bozeman, 2021, p. 51). Complete Vocal Technique similarly describes a narrowing of vowel choices in the high range when maintaining metallic modes (Complete Vocal Institute, 2026, p. 163), and mode-specific vowel restrictions are also described by Leppävuori et al. (2021). In other words, higher pitches can restrict which vowels can be sung (Titze, 2007b, p. 201) and, subsequently, the extent to which articulators can alter the vowel (Titze, 2007a, p. 558).

Nasal involvement in male classical voices tends to increase through and often beyond the passaggio (Birch et al., 2002, pp. 63, 70; Perna, 2008, p. 46; Perna, 2014, p. 406; Echternach et al., 2021; Vampola, Horáček and Laukkanen, 2021, p. 2155). The continued nasal involvement above the passaggio implies that its significance extends beyond merely negotiating the crossing, as suggested in my first literature review. Since articulation tends to become more restricted with pitch, after the hands-on experience of completing a full DBR cycle in the development of the NTAD, I believe the VPO gives singers another way to modify vowels in the high range.

The VP takes multiple shapes in operatic singers (Birch et al., 2002);,clinical assessment treats closure pattern, gap size, and gap shape as separate observations (Kummer et al., 2012), and singers likely use their VPO graded ways (Gill et al., 2020). Opening it changes vowel quality (Fant, 1970, cited in Birch et al., 2002; Bozeman, 2021) and while it can raise the first resonance (Vampola, Horáček and Laukkanen, 2021), this effect is not uniform across vowels (Sundberg et al., 2007; Havel et al., 2023) as the voice is interconnected enough that the effect of the opening (along with its shape and size) depends on the rest of the vocal tract configuration (Sundberg et al., 2007, pp. 129, 134; Havel et al., 2023). Vocal tract configurations differ between singers, styles, anatomy, etc. (Birch et al., 2002; Sundberg et al., 2007; Jelinger et al., 2024). A VPO has also been found to draw F3, F4, and F5 closer together in one model (Vampola, Horáček and Laukkanen, 2021), an effect similar to epilaryngeal narrowing (Vampola et al., 2024). Vampola et al. (2024) modeled epilaryngeal narrowing and an open VP together and found them complementary, with narrowing compensating for the loss of level at the first formant. In this way, the velopharyngeal port musculature behaves more like an articulator as well as similarly to twang. Kummer (2011, p. 152), a leading clinical authority on velopharyngeal dysfunction, states: “What is often forgotten, however, is that the velopharyngeal valve is an articulator, just like the tongue and lips. As such, there is also a learned component to velopharyngeal function.”

Therefore, I posit that a singer has two options in the high range when reaching points at which articulators and vowels become severely restricted. Either the singer opens the VP and uses it to modify the vowel, or the singer can close the port and resolve the issue with other articulators, such as raising the larynx (Titze, 2007a) and narrowing the epilarynx (Titze & Worley, 2009). Twang and a raised larynx, however, when done in excess, are what listeners often refer to as “sounding nasal” (Perna, 2020; Saldías et al., 2021; Jelinger et al., 2024). That is, closing the port to avoid a “nasal sound” may produce one, whereas opening the port may allow greater freedom of articulation without necessarily creating a perceptible “nasal timbre” (Birch et al., 2002; Perna, 2020, p. 430).

Perna (2014, p. 409) arrives at a similar conclusion, suggesting that “continually asking tenors to raise (lift) the soft palate [partially responsible for a closing of the port] through the transition into full head voice could be counterproductive and lead to laryngeal tension.” However, despite the wide-ranging potential benefits of considering the VPO as a means of vowel modification, teachers have difficulty identifying it (Perna, 2020, p. 430) and have historically favored its closure (Vennard, 1967, pp. 93–94; Bozeman, 2021, p. 46). A low-cost device like the NTAD may help bridge that gap, giving teachers and singers an

accessible, mask-free way to study the role of the port in a comfortable studio or home environment.

Developing the Context With The Device

Teaching inherently relies on perceiving adjustments that are not directly observable. For example, teachers can address a student's tongue position, degree of epilaryngeal narrowing, and soft palate height through listening to the singer's voice and their reported sensations. The VPO, however, is often unaddressed or obscured by instructional misconceptions. Perna (2020, p. 430) articulates a similar perceptual challenge: "There has not been a study that demonstrated whether or not nasalance creates perceptible nasality. Birch et al. attempted to have expert listeners identify which examples demonstrated nasality, but the results were inconclusive" (Perna, 2020, p. 430). This not only tells us that a "nasal sound" and a VPO are not necessarily the same thing; but that many teachers do not know how to detect an open velopharyngeal port.

There is also a lack of clarity about what nasal airflow tells us about the VPO. This is because nasal flow alone, without an oral chamber, cannot tell us whether airflow changes are the result of respiratory changes or the VPO. Adding an oral chamber introduces a degree of invasiveness that this project seeks to avoid. So, improving the device may be more about improving singing teachers' ability to detect the VPO through auditory analysis. Complete Vocal Technique has reported high listener agreement in identifying its vocal modes (Complete Vocal Institute, 2017), and opening the VPO is already part of their method. However, they do limit the function of the VPO to simply coloring the sound, with no mention of its potential acoustic or articulatory benefits. If a teacher can be trained to hear the degree of flow, the device's readings become a check on that judgment. That is the direction I would take for Iteration 2.2.

While my initial goal was to improve the NTAD's data collection after this project by means of adding an oral chamber, mask, or acoustic channels, these additions would point away from what the project is for. Teachers are not going to hook students up to elaborate instrumentation; they are going to do what they already do, which is listen and ask the singer what they felt. The device earns its place by potentially helping to validate that exchange rather than replace it with invasive instrumentation.

Fourth Design Stage: Future Design Proposals

The literature provides a strong foundation for continuing to develop the NTAD, not only for future singer development but also to open the door to more research on the function of the VP. Initially, I intended to do this by adding data channels, such as an oral channel, an

acoustic channel, a thermal channel, or an EGG. However, I believe the NTAD's simplicity is exactly what made it effective for me. Adding more channels only increases complexity, invasiveness, and failure points. Dual-channel acoustic systems suffer from transpalatal bleed, and aerodynamic systems require tight-sealing masks. Neither is ideal, and the trade-offs do not seem worth the limited gain in data, which still cannot determine VPO with any degree of certainty.

Teachers and singers need greater access to tools that build upon open-source material, like I attempted to accomplish with the NTAD, so that more people can investigate singing and singing science as a broader community. For that reason, comfort, ergonomics, device accuracy, and performance are my priorities in future NTAD design proposals. The following proposals attempt to address some identified limitations found after the measured testing session.

Iteration 2.2: Improve Ergonomics

Adding simple plastic housing and a slightly longer cannula to iteration 2.1 would be a significant improvement. It seems sensitive enough not to need such a short-length cannula, and protecting the NTAD would make practicing with it less stressful. The housing would allow it to rest on my desk and be available for practice sessions more readily, whereas now I need to store it in a safe cabinet to prevent damage.

Iteration 2.3: Improve Cannula

Home sleep testing devices have specially designed cannulas which are used for measuring respiration (SleepSense, 2025, p. 27). These cannulas also tend to have filters or filter adapters (SleepSense, 2025, p. 27). I was initially concerned that a filter would reduce flow sensitivity, but that no longer seems to be a concern, considering earlier iterations had worse performance. This may no longer be a concern with 2.1. So, I would love to see if I could eliminate moisture concerns by testing an appropriate moisture filter.

Iteration 2.4 (Cannula): Refine Prong Geometry

With the chosen filter in place, I would vary prong length, bore, and insertion depth, informed by Lorino et al. (2000, 2001) to determine what the best prong design might be for singing-related tasks. This may require some form of controlled flow device for more reliable results. Each design would also be tried against the criteria.

Further Possibilities

I could test a sensor upgrade on the same rig when a suitable alternative becomes available, retaining the cannula, filter, and housing. I could then compare its pressure–flow response and detection limit with those of the existing sensor.

If I were to add an additional channel at some point, likely for research purposes, I would be most interested in adding a channel for EGG, as I currently own one and never ended up using it. Electroglottography could add information about vocal-fold contact (Herbst, 2020), allowing its timing to be compared with nasal-pressure changes. Gill et al. (2020, p. 347) recorded an EGG signal but did not report its analysis, while Echternach et al. (2021, pp. 500.e10–500.e15) analyzed EGG alongside nasal and oral airflow. However, improving overall device ergonomics are a priority.

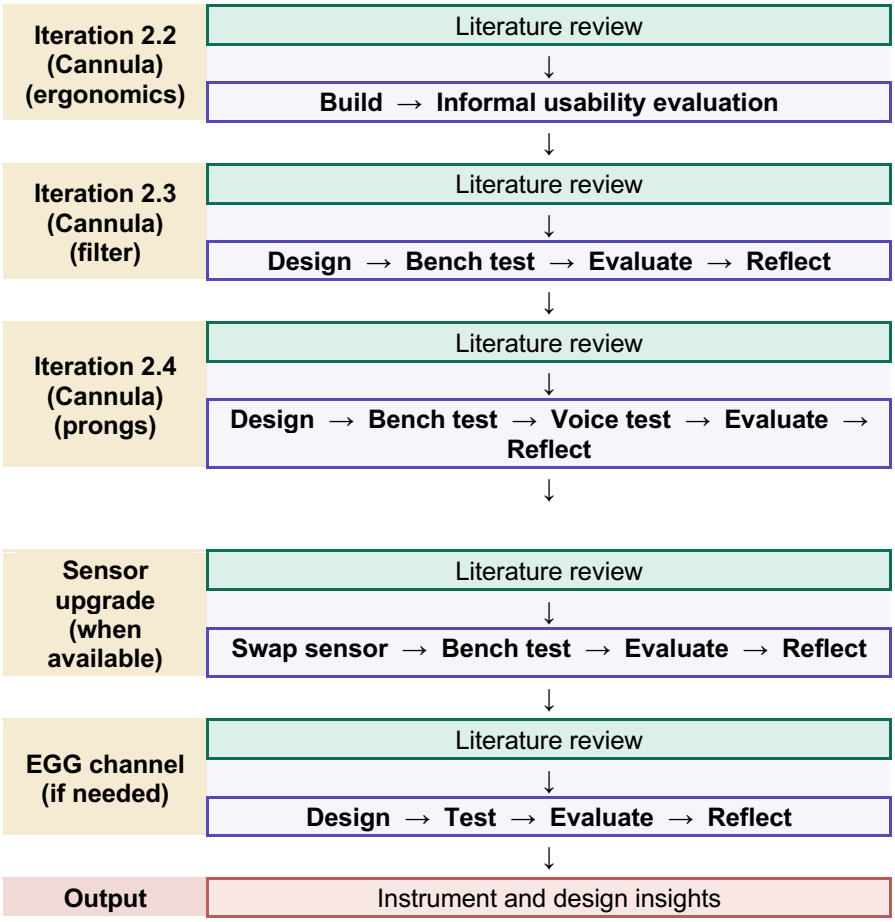


Figure 31. Proposed future iterations.

A Low-Cost Workflow for Practice and Analysis

One of the most exciting outcomes was realizing how much I could do with this setup. I could sing, watch the NTAD respond, record the session, and then go back and investigate what happened. Adjusting the displayed pressure range for singing made small changes easier to

see during practice. OBS let me record the trace alongside audio and webcam video, so I could revisit what I sang and how I was using the device (OBS Project, 2026).

This is a practical output I am eager to keep using. A question that comes up while singing can become something I record, listen back to, and examine more closely. I can then return to practice with something specific to try. That makes the development cycle useful beyond building the device. It gives me a low-cost way to keep exploring the questions that made me want to build it in the first place and potentially creates an effective practice loop for singers who's learning style is well suited to this type of analysis.

NTAD Development Cycle (Figure 10)

In the production of the NTAD, I developed two DBR-related concepts. While they are unlikely to be anything novel to the literature, they were effective for my use case. The NTAD Development Cycle (Figure 10) process involved continual testing, evaluation, and redesign even during the testing process itself. This cycle gave me the freedom to, on the spot, decide to implement a nasal pinch test. And because the software I was using was so well integrated with one another, it was incredibly easy to do. This informal, more experimental process led me to develop new tasks and discard ineffective ones with minimal time loss. It was a quick, structured, flexible process that was able to adjust rapidly and procedurally to new challenges in the iteration process. I also produced evaluation criteria, which I will use in future iterative design cycles.

What design-based research gave me, which I do not think another methodology would have, was permission to treat an unfinished and actively developing artifact as a legitimate research output rather than as an incomplete experiment. The device is not finished. Under DBR, it does not have to be, because the unit of analysis is the design cycle rather than the object at the end of it.

Critical Reflection

I initially thought the small number of iterations weakened the project but now see the early analysis as one of its strengths. I spent probably a bit too much time compiling and reading literature in the production of this project, leaving me with little time toward the end. However, the time I spent feels worth it in that I was able to produce a design that exceeded my expectations in functionality and integration with open-source software. The literature helped me choose the sensor and platform before building, and I returned to the research library I built when problems with placement, tubing, and condensation required design changes. The practical design knowledge generated by the build, including sensor selection, software decisions, the NTAD development cycle (Figure 10), the creation of an evaluation criteria, and calibration challenges, may inform future low-cost device development for singing research (Design-Based Research Collective, 2003; Plomp, 2009). The interface comparisons and recording workflow provide a starting point for another build, while the moisture and calibration limitations identify what still needs testing.

I misjudged the scope early on. I framed this as a project that would produce measurements, and it is a project that produced an instrument. Those need different write-ups and recognizing the difference late cost me time and a considerable number of words. The same misjudgment showed up in how I described the subject. I wrote about nasal airflow for months before accepting that the subject is the velopharyngeal port and airflow is only the most accessible way to point at it.

Conclusions and Recommendations

Conclusion

These conclusions address Reeves' fourth phase, reflection to produce design principles, by drawing together what the NTAD achieved and what should guide further development (Reeves, 2006, cited in Plomp, 2009, p. 14; Figure 12). I investigated whether nasal emissions could be detected during singing using low-cost components. Iteration 2.1 cost only $68.90 in parts before tariffs, runs on entirely free, easily customizable software, and does not require a tight-sealing mask. It easily distinguished between low-pressure events and its fairly low resting noise floor. The NTAD is safe, has minimal latency, and a sampling rate more than adequate for sung tasks.

The only other type of device in its league would be a low-cost acoustic nasalance device. These devices, however, are incredibly unreliable and produce large amounts of artifacts. By contrast, the NTAD measured no artifact during phonated tasks. It did, however, produce a negative pressure drop during plosives; these may simply reflect the consonant itself rather than a functional error with the device.

The final literature review prompted me to propose that the port may function as an articulator, potentially giving singers an additional way to modify vowels in the upper range. Of course, my experimental tasks cannot confirm this hypothesis. The involvement of one singer, a single recorded session, and my dual role as designer and evaluator limit the generalizability of these findings. However, I now believe I have the tools to begin investigating this idea at least within a limited capacity.

Recommendations

The next iterations should make the device easier to use and test the existing interface properly before adding anything new. A PowerPoint presentation should be constructed both to present for this project and to present to my online community of singers. I will need to compile audio recordings of data and re-verify the accuracy of numerical findings by hand to ensure their accuracy. Again, not to make pedagogical claims, but to be more confident in my data. This process will be incredibly fun, and I look forward to doing so. In future research, testing other singers and training teachers to judge the port by ear and checking those judgments against the readings would show whether the NTAD is useful in a real studio. Both would need further ethical review.

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