

Elisabeth Shoup Pieper
Student Number: 2246691
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Component 1

1. Title:

Goal action coupling for the singer: Sensory Prediction, Feedback, and Attentional Locus. A Rapid Review

2. Rationale:

For the past 20 years, an overwhelming body of motor learning research has shown that seemingly small alterations in instructions and feedback can have a significant impact on a performers' ability to learn and refine complex skills. These alterations affect cognitive load, expectancies of success, and feelings of self-efficacy, all of which can have a significant impact on learners' motivation to continue the activity (Wulf, Höß and Prinz, 1998; Wulf, McNevin and Shea, 2001; Wulf, 2002; McNevin, Shea and Wulf, 2003; Wulf and McNevin, 2003; Zachry *et al.*, 2005; Vance *et al.*, 2010; Wulf, Chiviacowsky and Drews, 2015; Wulf and Lewthwaite, 2016). Understanding the likely effects of instructions and feedback is therefore important both in rehabilitation and habilitation settings, where continuation and practice are strong indicators of goal accomplishment (Cienfuegos *et al.*, 2024). According to Gabrielle Wulf, an instruction will be most effective if it elicits goal action coupling: the instruction draws attention to, and therefore triggers, the intended result, as opposed to a process towards the result (Wulf & Lewthwaite, 2016). In Wulf's motor learning research, this is described as attentional locus, with an external locus of attention being associated with goal action coupling, and an internal locus of attention associated with process-based actions. Wulf and Lewthwaite (2016) explain their results by suggesting that the sensory prediction system in the brain is largely responsible for the success of goal action coupling.

Previous work from the researcher (Shoup Pieper, 2025) has shown significant definitional inconsistencies in published research on attentional locus and the voice. Through examination of these inconsistencies, it was speculated that the nervous system would likely cue a physical external locus target differently than an acoustic external locus target. It was further speculated that if goal action coupling is the true purpose of external locus targets, then a specific sound heard in the head or a vibration felt in the body may meet the definition of external locus, even though these results refer directly back to the body.

More detail, therefore, is needed to transition from speculation to testable theory. While little direct research exists regarding how these processes can affect learning in singers, published work on sensory prediction and feedback in motor learning generally and in the spoken voice specifically sheds light on the mechanisms behind goal action coupling's apparent effectiveness. It is hoped that this line of inquiry will lead to a deeper understanding of how motor learning can be affected in all levels of student singers.

3. Positionality and Insider Research:

Positionality, or “where the researcher is coming from, (Holmes, 2020, p. 1),” has driven this researcher's choice of subject and approach to (Poirier *et al.*, 2023). The researcher personally experienced as a student, and engaged in as a teacher, interventions that, while initially helpful, sometimes became interested in maintaining a certain teaching philosophy or physical rule over even if the student was clearly negatively impacted by the instruction. For example, one teacher who only taught with acoustic targets ignored a students' shaking jaw or poor vowel clarity. Another physically held his students' larynxes down, insisting that this would improve physical coordination over time. Both interventions have a philosophical and physiological basis; however, adherence to them in the face of student failure, even if it is failure of a minority of students, possibly demonstrates a pedagogy that is not student centered, and because of this is more interested in maintaining its philosophical roots than it is in helping the student at hand.

It is experiences like this that have led this author to adopt a pragmatic paradigm. Pragmatism crosses traditional epistemological and ontological boundaries in its insistence that actions be effective (Ormerod, 2021). A doctor practicing under a pragmatic paradigm would consider both a medical intervention and the patient's ability and resources to undergo or carry out such an intervention (Ormerod, 2021). This considers both empirical facts of the patient's health needs and the patient's subjective, lived experience, with the rationale being that the intervention is useless if the human cannot carry it out. In voice pedagogy, the researcher speculates that this translates to giving instructions and technical goals that the student can understand and execute and avoiding ones that, whether empirically or psychologically, the student is unable to perform.

Clearly, the researcher, as both a student and teacher of singing, is far from a neutral observer of anything involving learning mechanisms and the voice. In this sense, she is an insider researcher: one that is part of the community being researched, or as in this case, a part of the community that could be affected by the research (Holmes, 2020; Yip, 2023). As stated above, this insider status inspired the entire line of inquiry of this work; the researcher has been both positively and negatively affected by vocal education models that differentially accounted for understandings of sensory prediction, attention, and feedback. Further, both insider/outsider research literature (Yip, 2023) and pragmatic methodological literature (Juhl, 2014; Foster, 2024) admonish the researcher to acknowledge their inevitable effects on the resulting data whether that comes from choice of questions and article selection, or from direct interaction with participants of a study, as will likely be the case in future work on this topic.

The researcher is, however, very much an outsider in this choice of subject because her scientific background is not formal: she is self-taught on the required subjects of this area of study, including physics, anatomy, and neurology. While the necessity of learning concepts as they directly relate to a subject or goal can result in deep learning (Zhang and Ma, 2023; Schweder, Grahl and Raufelder, 2025) and also result in

improved creativity and self-efficacy (Qian *et al.*, 2023); formal curriculums can result in a comparatively complete overview of the topic (Schweder *et al.*, 2025) that is lacking in the researcher's background. This outsider status perhaps further subjects the work to confirmation bias, in which the researcher could unintentionally weigh conclusions and interpretations heavily if they aligned with her previously held beliefs (Palminteri *et al.*, 2017). The researcher hopes to mitigate this in two ways: by making transparent all methodological choices contained in this work, and by continually reflecting on and questioning conclusions, as illustrated in Juhl (2014) and Ormerod (2021).

4. Goals:

The overarching goal of this work is to more deeply understand the related neurological underpinnings of goals-action coupling and its effects on motor learning for the human voice. Like previous work by the author (Shoup Pieper, 2025), it is hoped that this will serve to inform voice teachers about the vocal and cognitive consequences of instructions for their students. It should be noted that this is in no way intended to be prescriptive of a certain technique or approach but rather is intended to help teachers understand students' cognitive states to predict approaches, incorporate and interpret student feedback, and effect outcomes. The work is intended as part of a larger, mixed methods project, in which professional singers will be interviewed and asked about their phenomenological experiences singing and learning to sing. It is hoped that deepening understanding of empirical, neurological information will lay a groundwork and justification for a future study that is more phenomenologically based. This concept of these two studies is loosely based on justifications in the field of neurophenomenology, in which neurological data is compared to similarly time-locked first-person experiences (Northoff & Ventura, 2025). While no time-locked comparisons will be made in these situations, it is hoped that some insight will be gained by comparing empirical knowledge about vocal learning with how singers experience it in their daily lives.

5. Learning Outcomes:

Simply reading the literature in this instance involved learning to understand a novel type of literature for the author. To that end, the author hopes to deepen understanding of neuroanatomy generally, but also to understand different ways in which brain activity is studied in relation to the voice. Central to many of the covered studies on attention, for example, are Event Related Potentials, or ERP's (Luck, Woodman, Geoffrey E and Vogel, Edward K, 2000) These are Electroencephalography (EEG) measurements taken by placing electrodes on the scalp that record electronic impulses close to the surface in the brain in response to a stimulus (Luck, Woodman, Geoffrey E and Vogel, Edward K, 2000). The location and timing of ERP's, measured in milliseconds, are theorized to be correlated with various types of attention, prediction, and error detection (Kim, Lee and Shim, 2021). For this work, most of the ERP studies measured the brain's response to Altered Auditory Feedback, or when the subject's vocal sound was fed back through headphones with some aspect of it altered, usually a vowel formant or fundamental frequency (Weerathunge, Tomassi and Stepp, 2022) The resulting brain activity and vocal behaviors are the data for these studies.

The author additionally hopes to refine research skills started in Module 3. In particular, she hopes to develop her ability to code inductively; in Module 3 coding was performed deductively. She plans to use the Thematic Analysis method proposed by Braun and Clarke (2006). This is projected to be a major aide to the Module 6 project, in which interviews will be conducted and coded.

Finally, it is hoped that the author will gain insight that can be applied directly to teaching. The ERP/AAF studies mentioned above are rich in information about how the brain and voice respond to differences between expected and realized outcomes and may even challenge some of the conclusions reached in previous work by the author.

6. Document Methodology and Highlight Limitations:

This work adopts a pragmatic paradigm, which prioritizes effectiveness over strict adherence to a particular ontology and (Kaushik & Walsh, 2019; Foster, 2024).

According to Juhl (2014, p. 253), “A pragmatic approach to inquiry means that the research approach helps to achieve the ‘what’ and the ‘why’ defined in research.” As suggested above, the pragmatic researcher is therefore free to choose quantitative, qualitative or mixed methods research depending on which of these is most effectively able to address their research question (Foster, 2024).

The approach in this circumstance is qualitative. While the research being reviewed is primarily empirical and quantitative, the analysis is thematic, an approach most often associated with qualitative research (Braun & Clarke, 2006; Clarke & Braun, 2016). As an educator who works individually with students, it is important for the researcher to understand “what works, why, and in what circumstances, (Grant & Booth, 2009, p. 98). “What works” applies to quantitative research; the thematic analysis of this paper will seek to explore the second part of the quote, “why, and in what circumstances” so that technical interventions and wording can be chosen to fit the individual situation. Mining articles inductively for codes and themes allows insights across differently conducted studies to be compared (Braun & Clarke, 2006; Clarke & Braun, 2016) and therefore allows for pedagogical approaches to arise from the searched body of literature. Following the cycles outlined in Juhl (2014), these approaches will be tested and evaluated for effectiveness in future work.

A serious potential limitation of pragmatism is how effectiveness is defined, and whom it is defined by, leaving it open to researcher bias Juhl (2014). The researcher feels that this is of import in the field of voice pedagogy, where taste and personal preference may color a teacher’s or listener’s ideas about effectiveness. In this piece of research, these ideas could be particularly relevant: the themes that arise for this researcher may be reflective of both experiential bias and lack of background with the material, and any pedagogical conclusions could further exacerbate this. As Foster (2024) states, however, these problems are not limited to pragmatism. Juhl’s (2014) emphasis on the need for continual reflection on conclusions and consideration of alternative explanations is perhaps more practical in a field where a myriad of variables- learning

styles, voice type, vocal styles, personality, age, teacher preferences- can affect outcomes.

7. Research Question

It is crucial in this type of review to have a clear research question (Grant and Booth, 2009; Juhl, 2014). Much of Wulf's research on goal action coupling in the body is explained neurologically by sensory prediction (Wulf and Lewthwaite, 2016), and the researcher wanted to know how these concepts might be similar or different in the voice, in the hopes that it would shed more light on issues raised in previous work. Thus, the research question is: "What is currently known about how goal-action coupling is realized in vocal development?"

8. Search Strategy and Inclusion/Exclusion Criteria

While transparency in article selection is crucial in all literature reviews, the pragmatic methodology, mixed methods and insider researcher nature of this work makes it particularly important here (Grant & Booth, 2009; Ormerod, 2021; Yip, 2023). This is a state-of-the-evidence review (Benzies et al., 2006) where current understandings of sensory prediction are reviewed. Because of this, and because of many recent advancements in the field (Petersen & Posner, 2012) only work published after 2010 was included in the search. This was also adhered to with supporting literature: the only instances of pre 2010 literature appear in the portfolio section of this work. Further, due to the 'state-of-the-evidence' nature of this review, Grey Literature (Adamset al., 2016) was eliminated in the main articles and only used sparingly in the supporting literature.

The search was carried out via Google Scholar.

"Sensory prediction" AND music AND feedback AND voice AND singing AND attention turned up 381 results.

To reduce the number of articles and keep the focus on the voice, the following eliminations were made:

- schizophrenia -autism -rhythm -computation -hallucinations -virtual -piano

After these eliminations, the article count fell to 30. These articles were then manually searched for relevance, and the remaining articles fell to 13. Grant and Booth (2009) state that Rapid Reviews require a “time limited formal quality assessment (p.95),” and Mixed Methods Reviews require a generic appraisal instrument. To satisfy both needs, the CRAAP Test (Blakeslee, 2004) was applied to all articles.

Author(s)	Title	Year	Type of Research	Aspects Discussed
Alemi, Razieh; Lehmann, Alexandre; Deroche, Mickael LD;	Adaptation to pitch-altered feedback is independent of one's own voice pitch sensitivity	2020	Study, Quantitative	Just Noticeable Difference (JND) determined for each participant in AAF study to study if this could account for discrepancies in other literature
Behroozmand, Roozbeh; Sangtian, Stacey;	Neural bases of sensorimotor adaptation in the vocal motor system	2018	Study, Quantitative	AAF study where fundamental was altered. Adaptation remained after intervention was removed.
Darainy, Mohammad; Vahdat, Shahabeddin; Ostry, David J;	Neural basis of sensorimotor plasticity in speech motor adaptation	2019	Study, Quantitative	Cross adaptation in brain between direct motor training and auditory training.
Franken, Matthias K; Acheson, Daniel J; McQueen, James M; Hagoort, Peter; Eisner, Frank;	Consistency influences altered auditory feedback processing	2019	Study, Quantitative	Adaptation vs. Compensation and how to affect them
Franken, Matthias K; Eisner, Frank; Acheson, Daniel J; McQueen, James M; Hagoort, Peter; Schoffelen, Jan-Mathijs;	Self-monitoring in the cerebral cortex: Neural responses to small pitch shifts in auditory feedback during speech production	2018	Study, Quantitative	Adaptation to auditory feedback without consciousness
Lametti, Daniel R; Krol, Sonia A; Shiller, Douglas M; Ostry, David J;	Brief periods of auditory perceptual training can determine the sensory targets of speech motor learning	2014	Study, Quantitative	Explicit training and its effect on new skills vs. old habits

Scheerer, NE; Jacobson, DS; Jones, JA;	Sensorimotor learning in children and adults: Exposure to frequency-altered auditory feedback during speech production	2016	Study, Quantitative	Different groups hypothesized to rely differently on feed forward and feedback
Schirmer, Annett; Fox, P Mickle; Grandjean, Didier;	On the spatial organization of sound processing in the human temporal lobe: a meta-analysis	2012	Review, Quantitative	Looked for lateralization, or lack thereof, of sound, in temporal lobe
Tivadar, Ruxandra I; Knight, Robert T; Tzovara, Athina;	Automatic sensory predictions: a review of predictive mechanisms in the brain and their link to conscious processing	2021	Review, Quantitative	Consciousness and whether it affects the existence and amplitude of prediction error detection
Tumber, Anupreet K; Scheerer, Nichole E; Jones, Jeffery A;	Attentional demands influence vocal compensations to pitch errors heard in auditory feedback	2014	Study, Quantitative	Increased attentional load and its effects on auditory processing and resultant behavior
van Vugt, Floris T; Ostry, David J;	Early stages of sensorimotor map acquisition: learning with free exploration, without active movement or global structure	2019	Study, Quantitative	Differing learning conditions and their effects on mapping
Zamorano, AM; Zatorre, RJ; Vuust, Peter; Friberg, Anders; Birbaumer, Niels; Kleber, Boris;	Enhanced insular connectivity with speech sensorimotor regions in trained singers—a resting-state fMRI study	2019	Study, Quantitative	Insular cortex of singers compared to nonsingers
Zhang, Yilun; Sarmukadam, Kimaya; Nejati, Vahid; Behroozmand, Roozbeh;	Functional Neural Oscillatory Activities Reveal the Impact of Attentional Instructions on Speech Auditory Feedback Control	2025	Study, Quantitative	Measured vocal compensation responses to Auditory Feedback with and without attentional instructions

9. Reflection:

Juhl (2014) presents a pragmatic reflective cycle that emphasizes usefulness of knowledge gained. As discussed previously, I am new to the neuroscience concepts discussed in this paper, which leaves my work more vulnerable to my own interpretive

biases than if I had studied formally. This cycle's emphasis both on real-world usefulness and on validity from self reflectiveness and self critique allows me to explore deeply my initial understandings and interpretations while remaining open to other, possibly contradictory ones that I may encounter in research and lived experience. The cycle has four main components: the decision to "Do something (Juhl, 2014, p. 251)", which involves discovering connections and asking a research question; the Experiment, carrying out the research that addresses the question; Experience, or "seeing the connections between 'doing' and consequence of doing' (Juhl, 2014, p. 252)"; Reflection and Analysis, which hopefully leads back to the next "Do something."

1. **Decision to "do something** (Juhl, 2014, p. 251)"

The immediate decision to "do something" in this work was instigated by my Module 4 paper. While I outlined important definitional inconsistencies in the published literature on attentional locus, I did not have the background or information to do much more than speculate philosophically and logically. While this clearly has value (citation), I felt that my critiques of the literature were incomplete without forming a clearer idea of what current neurological literature says about the voice. This in itself is the aspect of Juhl's cycle in which the researcher is encouraged to question conclusions. To that end, a large part of my goal with this paper was to heed my own call to make future attentional work in line with current neurological understandings, but first I needed to learn what those were. Since attentional locus is intimately connected with sensorimotor prediction (Wulf & Lewthwaite, 2016) and likely helps form sensorimotor prediction (Wulf & Lewthwaite, 2016), I chose these for my search criteria.

Step 2: Experiment

In this literature review, the action taken was finding and understanding the published literature from my search. Of my work so far, the literature in this was the most challenging to understand. As discussed in the previous section, I do not have a formal scientific background, so the bulk of my energy went into simply trying to understand the concepts that I was reading about at a level where I felt I could start to write about them.

This was reflected in my first draft, which was rich in information but poor in interpretation and pedagogical usage. Having spent this energy, I still do not feel that I have the expertise to critique or praise the designs of the studies, but I do feel that I gained a grounding in certain aspects of vocal neurology and particularly in how it can be studied. This removes a significant barrier from my future work: I was previously hesitant to explore ‘hard scientific literature’ and now can understand and interpret many types of studies with some efficiency. In my teaching practice, I have noticed that deepening my understanding and background of neurological literature has helped me to interpret challenges that my students have. For example, a testosterone voiced student whose voice recently dropped due to puberty has struggled with pitch in a way that he didn’t when he was a treble voice. Researching sensorimotor adaptation helped me to realize that his newly changed physical anatomy was forcing his sensorimotor predictive system to adapt: his body could no longer execute the targets he had developed. This has helped me to empathize with a voice change that I will never personally experience, which in turn has helped me to ‘reflect-in-action’ (Schön, 1983) and give him more in lesson time to repeat and practice.

Step 3: Experience

From a research standpoint, I am able to understand neurological and learning literature in a way that will allow me to provide more solid evidential literature support for future direct research. From a teaching standpoint, I have reframed my teaching goals: I want my students to have an updated feedforward systems that reflects vocal efficiency. I have felt humbled to learn the extent to which acoustic sensory processes are by definition below anyone’s, including trained singers,’ conscious control, and moreover, the extent to which lasting vocal learning can occur without awareness that it is happening. In support of the ‘consistency’ argument, (Van Vugt & Ostry, 2019) showed that many modes of learning can yield similar amounts of sensorimotor learning so long as the spatial conditions remain constant. In this way I feel reduced pressure to discover an optimal way for singers to learn. Some clearly respond well to acoustic targets and progress quickly when asked to imitate qualities; others, who for a variety of reasons, struggle with targets, need to rely on a more physical focus for the consistency

necessary for learning. From Dairany et al (2019), I have further learned that physical manipulation is reflected in the part of the brain responsible for acoustic targets. This increases my confidence that, for example, attending to or even sometimes manipulating the jaw and tongue can eventually help a student develop or refine their targets.

Step 4: Reflection and analysis.

Emphasizing updates to the feed forward system has led me to adopt greater usage of recordings for certain students and to encourage them to sing along with the recordings. I know from literature and from direct observation that the auditory system will tend to self-correct a mismatch. Like many of the authors I have cited, I do not know why students tend to match recordings rather than correct in the opposite direction as subjects in the AAF studies, though I suspect it is because it is clear to their auditory systems that my piano or my voice are not them, so the mismatch is not with the voice's own prediction of itself but rather a mismatch with one that has been imposed from the outside. In a similar fashion to my experience with the adolescent singer discussed prev, simply thinking like this helps me to reflect-in-action (Schon, 1983) and make better choices about when the student needs an explicit instruction or simply to sing along with me, a piano, or a recording. For adult amateurs, these reflective decisions have led to faster, more accurate melodic learning in certain circumstances, and faster sound learning in others. While I do not feel that this fits the definition of skill development as outlined in Stanley and Krakauer (2013), it is clearly a necessary step towards the most important goal of updating their feedforward systems. Further, from the literature, I have learned that, while attentional overload will have negative impacts on vocal output (Zhang, 2025), consistency will tend to have positive impacts on learning and retention (Franken, 2019; van Vugt & Ostry, 2019). This has helped me to restrain my tendency to give too much information in lessons. Even choices like whether to play a song accompaniment on the piano are affected by this. It is auditory input that the singer cannot ignore. In one circumstance, for example, I chose to make sure the student was able to sing technically and musically competently a cappella before adding the distraction of the accompaniment. The feedforward framing therefore helps guide

pedagogical choices primarily from a combination of cognitive load and repeatability. This does not mean avoiding conscious skill building as discussed in Stanley and Krakauer (2013); it does, however, mean attempting to understand what students can perceive and what they cannot perceive and working with them at all stages of this process. If they cannot perceive whether they are in tune, but automatically match to a recording or other singer, it will likely be far better to simply have them sing along with a recording to develop auditory targets than to instruct them to correct in a certain direction.

An important aspect of the Juhl (2014) cycle is seeking validity by challenging ones' own conclusions. I wanted to find a justification for using physical cues alongside acoustic ones and I found one (Dairainy et al, 2019) paper that did this in this search. It is possible that I over-weighted it in my conclusions because it is a point of view that I feel is dismissed in much literature (Moss Ericsson, 2023; Titze, 2021). However, I am aware that this may be an instance of my lived experience as a singer coloring how I weight the literature I read. This is a topic that I would like to explore extensively in future research.

Component 2

I. Intro

Background and definition of terms

Important theories about the neural nature of vocal learning and adaptation have developed through the studies described below. The most prevalent model of vocal learning, named Directions into Velocities of Articulators (DIVA), describes a process in which, through childhood, acoustic, physical action, and finally, somatosensory targets are developed (Tourville & Guenther, 2011). These targets and their accompanying actions are known as the feedforward system (Zuk, Loui and Guenther, 2022). When the feedforward system is activated, the brain simultaneously predicts acoustic, motor, and somatosensory outcomes. Much research, therefore, details how the brain reacts when some aspect of the expected target is not matched with the produced phonation. Research indicates two major categories of responses to the mismatch: compensation,

or momentary reaction to the mismatch, and adaptation, which is an update to the feedforward system (Zuk et al., 2022). Different models speculate degrees with which these systems are connected (Franken et al., 2018; Franken et al., 2019). Experimental conditions can be manipulated by altering various factors, such as degree of deviance (Franken et al., 2018; Franken et al., 2019), attentional instructions (Zhang *et al.*, 2025), degree of distraction (Tumber, Scheerer and Jones, 2014), training (Lametti *et al.*, 2014), feedback consistency (Franken *et al.*, 2019) and articulator manipulation (Darainy, Vahdat and Ostry, 2019). Teaching voice definitionally involves enabling students to change their vocal usage, updating their feedforward systems, so incorporating current understandings of the conditions in which this takes place is an important part of evidence-based vocal pedagogy.

These deviances from expectation are often studied using Altered Auditory Feedback (AAF). In AAF studies, the subject phonates into a microphone. The sound that the subjects emit is then fed back to them through headphones and altered (Tang, 2024). In several of the discussed studies (Lametti *et al.*, 2014; Franken *et al.*, 2018; Alemi, Lehmann and Deroche, 2020), the fundamental frequency (f_0) of the sound is shifted; in others (Behroozmand and Sangtian, 2018; Franken *et al.*, 2019; Zhang *et al.*, 2025), component frequencies of the sound, formants, are altered, feeding back a slightly different vowel than the one originally emitted by the subject. This creates a mismatch between the predicted pitch or quality, and the one that is heard through the headphones. This is a different condition than what students encounter in voice lessons, as the auditory feedback students receive is a combination of what is perceived through the body and what is reflected from the room back to the ears, but they are still processing matches and gaps between their expectations and perceived outputs. In studies, how subjects react to mismatches is of high interest, and potentially relevant to voice lessons, particularly for beginning students singing in a novel range, students undergoing a vocal change, and students singing in an acoustically novel space (Zuk et al., 2022). While most study subjects will correct in the opposite direction of the AAF, they occasionally correct in the same direction, and it is not yet known why or under what conditions this happens (Alemi, Lehmann and Deroche, 2020), though it

is speculated that it is part of the brain's continual calculations about whether it is adjusting to deviance from its own predictions or to an external stimulus (Alemi et al, 2020). The studies usually begin with a certain number of baseline trials without AAF, a certain number with AAF, and then a 'washout' set of trials without AAF. Behaviorally, compensation and adaptation to the AAF are primarily determined by the extent to which vocal adjustment remains in the washout trials (Zuk et al., 2022). Two major downsides of the examined AAF studies, however, are the limited speech ranges used and the absence of melody or even prosody in the studies, both significant differences between spoken and sung vocal usage. Still, these studies yield important insights into the behavioral tendencies of the human voice.

Several studies (Tumber, Scheerer and Jones, 2014; Behroozmand and Sangtian, 2018; Franken *et al.*, 2018) add information to AAF studies by including electroencephalography, or EEG. EEGs record continuous neuronal voltage changes through electrodes placed on the scalp (Kappenman and Luck, 2012) when neurons fire at the same time and in the same direction (Kappenman and Luck, 2012). That EEG is noninvasive (Kim, Lee and Shim, 2021) is an asset: it can easily be performed on many participants; however, it only is able to record voltage changes that occur relatively close to the surface of the brain and cannot detect events that occur deep in the brain (Kappenman and Luck, 2012; Singh, 2014) and the signals can be distorted by fluid and bone (Kappenman and Luck, 2012). In the work cited below, EEG is used to detect two major categories of brain activity. The first is general neurological oscillation frequencies, known as Alpha, Beta, Gamma, Theta, and Delta waves, which are associated with levels of alertness and learning states (Zhang *et al.*, 2023). Another EEG use averages signals and allows detection of both time and location associated neural responses to "measure the response of the brain to a time- locked event (Kim et al., 2021, p. 93)." This is known as an Event Related Potential (ERP). The subject is provided with a stimulus- in the case of the studies below, it is auditory and the timing and location of the brain's average electrical response allows researchers to make inferences about how and why the brain is reacting to the stimulus (Kappenman and Luck, 2012; Kim, Lee and Shim, 2021). Beyond behavior, these studies yield insights

about how a singer's brain may be reacting when, for example, an expected musical cue does not occur.

Less frequently used but still important to the discussion below is Functional Magnetic Resonance Imaging (fMRI). This is used in Darainy et al (2019) and Zamorano et al (2019). Generally, fMRI scans detect differences in the magnetic charges of oxygenated and deoxygenated blood that flow through capillaries in the brain (Lv *et al.*, 2018). Since “neurons do not contain any internal reserves of energy, either in the form of glucose or oxygen (Lv et al., 2018, p. 1390),” they are dependent on blood flow from their surrounding capillaries. fMRI, being Blood Oxygen Level Dependent (BOLD), is therefore able to give researchers a relatively accurate picture of what parts of the brain are being activated (Lv et al., 2018). The magnetic nature of the MRI allows for much deeper brain imaging than the scalp-based EEG scans (Lee, Smyser and Shimony, 2013). There are, importantly, two major types of fMRI scans: task based (tfMRI) and resting state (rsfMRI) (Zhang *et al.*, 2016). Similarly to the ERP experiments discussed above, tfMRI detects brain activity in direct response to an event or stimulus. rsfMRI, in contrast, shows activation of often disparate brain regions (Lee, Smyser and Shimony, 2013; Zhang *et al.*, 2016). Importantly, while it doesn't depict events in real time, it can be used to detect fluctuations in blood oxygen levels that occur because of a recently performed task and further, that it “captures the history of repeated task dependent synchronized activation between brain regions (Guerra-Carillo et al., 2014, cited in Zamorano et al., 2019, p. 2). Because it can depict multiple brain regions, particularly deep ones, it allows researchers to strengthen their understanding of the many connected neurological components that underly various systems in the body (Lee et al., 2013; Zhang et al., 2016). This provides insight into the multiple systems that the brain must organize to properly execute singing tasks.

II. Discussion

a. Attention:

Synthesizing Wulf's athlete-focused theory in a voice-specific context requires that the effect of attention on vocal performance be addressed. In this spirit, it is imperative to first find a working definition of attention. "Attention," according to Tsotsos (2019, p. 127), "has the goal of matching current task to processing resources by manipulating the brain's processing machinery to preferentially process expected stimuli while ignoring the irrelevant, yet monitoring all stimuli in order to deal with the unexpected." According to Lindsay (2020), p. 1, "it is the important ability to flexibly control limited computational resources." Lindsay (2020) laments the lack of a consistent definition across research; however, two themes arise from these three definitions: all assume a mechanism by which the brain can choose which stimuli, be they self-generated or external, to which it devotes its resources. Further, the fact of this choice implies flexibility. Past these two points, the definitions differ: Tsotsos (2019) depicts a brain that can monitor constantly while simultaneously filtering what information rises to the conscious level. It should be noted also that Tsotsos' 'matching of the current task to processing resources' is most closely in line with Gabriele Wulf's 'goal action coupling.' Lindsay focuses on the conscious aspect of attention by focusing on the brain's limited resources. An important difference between limb and the vocal tract is the extent to which the components can be controlled separately. While limbs have been shown to coordinate more efficiently and with lower cognitive load when the attention is placed on the action goal rather than on the individual components (Vance et al, 2010; Wulf & Lewthwaite, 2016), physical athletes are still capable of moving limbs and even skeletal muscles independently (Wulf & Lewthwaite, 2016). Voice users, in contrast, simply do not have such a choice (CITATION), as many of the component muscles are enervated in a way that only works in coordination with a goal that in some capacity, will be acoustic (CITATION). Thus, the voice user's version of "matching current task to processing resources (Tsotsos, 2019, p. 127) will always include an auditory component, and this must be included in any motor learning model of the voice.

Attentional Instruction: Of the research included in this review, Zhang et al (2025), an AAF study, most directly tested both Tsotsos' definition and applied aspects of Wulf's research to the voice. Subjects were given instructions to "produce a steady

vocalization of the speech vowel sound /a/ for approximately 2-3 seconds, maintaining their normal pitch and loudness levels during each trial (Zhang et al, 2025, p.3).” The experimental group was further instructed to focus on the sound they perceived through the headphones and to indicate detection of a change in the feedback. They found evidence that the attentional instructions altered both the waves detected by the EEG signal, and the behavioral output of the subjects. Specifically, the Gamma wave, which is connected to “sensorimotor integration and error correction during speech (Zhang et al, 2025, p. 6),” significantly increased in power as the instruction group was making corrections. Behaviorally, these subjects demonstrated reduced compensation to AAF in comparison to subjects without instructions, which is speculated to be a result of superior feedback filtering because of attention: the auditory system was better able to detect to what extent it needed to correct itself. Zhang et al (2025), however, also speculate that the increased cognitive load of the instruction could have dampened responses. While a similar study with a greater range of vowels and pitches would be of use, the main finding is potentially significant for singers: attention to auditory feedback may result in more subtle vocal changes when the singer is in an unfamiliar space and may help them to process new feedback more accurately.

Attentional Load and Distraction: Tumber et al (2014) found that increasing attentional load did not alter subjects’ reaction to sound but did alter their behavioral output. It is speculated therefore that increased attentional load affects articulator and vocal coordination but does not affect the sensory impact of the AAF. This is important in that it demonstrates that the brain’s ability to detect differences may not be as costly to Lindsay’s (2020) ‘limited computational resources;’ what does appear to be costly, however, is the ability for the body to adjust based on the deviance detection, and to integrate these adjustments into future actions. Important also is the way that Tumber et al ‘increased attentional load.’ Subjects were given a visual task that was irrelevant to their vocalizations, pulling attention towards a different task and distracting them. This is in line with speculation from Scheerer et al (2016). Also an AAF study, it compared the abilities of children and adults to respond to perturbations in auditory feedback. While their brains’ reactions were similar, the children produced greater variety in behavioral

responses than the adults, and authors speculated that this was partly due to the children having been distracted during the experiment. By the definitions listed above, they were using their computational resources for something other than the task at hand, a possible definition for distraction. These studies suggest that in voice teaching, resonance, breath, and posture may each individually be loci that demand full attention, and students attempting to focus on more than one of these simultaneously may have vocal outputs negatively impacted from instructions that overload their attentional resources.

b. Sensation, Perception and Learning

A sensation, according to Albright (2015), is “the immediate neurobiological consequence of stimulating sensory transducers, such as photoreceptors, mechanoreceptors, and chemoreceptors (Albright, 2015, p.1).” It is purely biological in nature and occurring below conscious awareness, sometimes referred to as ‘bottom up.’ A sensation can only be perceived through “probabilistic inference about the cause of sensation (Albright, 2015, p. 3).” Schirmer et al (2012) strengthen this definition in their review on auditory pathways, concluding that different ones have different purposes and the reason for this was associating a sound with an action that had created it, exactly fitting Albright’s definition of how a sensation becomes perception through “inference about the cause.” For example, auditory pathways that detected noise seemed to extend to visual areas because they were associated with an action, such as a door closing. Interestingly, they found no observable difference in pathways between sounds and musical tones, though this does not override the major conclusion that pathways exist to elevate sensations to perceptions. Exactly what criteria the brain relies on to make this elevation is the subject of much of the research discussed in this section; while research has not reached definite conclusions, it is clear that evolution has been very protective of Lindsay’s (2020) “limited computational resources.” Multiple studies reveal that prediction and learning seem to be occurring at the level of sensation, before it can be consciously perceived. This adds nuance to the discussion in Shoup Pieper (2025) about a boundary between implicit and explicit learning.

In their review, Tivadar et al (2021) demonstrate that some amount of pattern detection happens even when subjects are unconscious. They review studies of patients in varying levels of mental arousal, from actively attending to anesthetized. All showed evidence of Mismatch Negativity (MMN). However, it is important to note that attention seems amplify deviations from patterns and lack of consciousness ‘down weights’ deviations (Heilbron and Chait, 2018 cited in Tivadar, 2021). Franken et al. (2018 & 2019) showed that fully alert subjects adapted to AAF that altered their pitch (Franken *et al.*, 2018) or formant (Franken *et al.*, 2019) at intervals too small to have been detected consciously. While on the surface contradictory to Zhang et al’s (2025) results, they may support them; as was demonstrated in Tumbare et al, Deviance Detection, studied here, and behavioral output, part of Zhang’s study, are not necessarily indicative of each other. Zhang was studying the effect of attentional instructions versus general attentiveness and alertness and found that the instructions made the brain more selective about which inputs it attended to and incorporated into behavior; Tivadar compares amounts of deviance detection varying degrees of alertness. It should be noted, however, that Tivadar was studying deviation from an established auditory pattern without AAF, so there is no possibility that the brain was engaging in self-correction of an emitted sound, an important difference that has not been entirely resolved in the research. Still, while attention can amplify detection of deviation from an established pattern, it is clearly happening whether humans are actively conscious of it or not. As discussed above, instructions appear to add granularity to already alert states when the deviation or emitted error is at a level that it can be detected consciously. This presents both opportunities and challenges for pedagogues as they seek to facilitate student development. A student who is not yet capable of consciously perceiving their deviations from a melody, for example, may learn it simply from singing along to a recording of a piano or another singer and relying on automatic pitch adjustments that are unconscious. However, it also may mean that any demonstration errors, be they musical or technical, on the part of the teacher, could be incorporated unconsciously into the student’s feedforward system.

Lametti et al (2014) and Dairany et al (2019) study vocal motor learning by explicitly training perception. Lametti justifies this by referencing literature that links perceptual and motor updates in the voice. Both studied vowel perception, though Lametti's data were exclusively behavioral where Dairany's were both behavioral and neurological. Lametti et al (2014) divided the subjects into two groups. One group spoke the word 'head,' and the AAF delivered a word through the headphones that was closer to the word 'had;' the frequency of the first formant had been shifted slightly higher. The reverse was done with the other group. Subjects were instructed not to make errors in their speech. Following this, subjects heard the words through headphones and were told to select which word was heard. They were then given explicit 'CORRECT/INCORRECT' feedback based on the direction of the AAF that they had received. All demonstrated perceptual and motor learning during the washout phase, despite having been given an instruction during the AAF to speak 'correctly,' which suggests that the unconscious aspects of vocal learning may override conscious attempts to resist it.

Dairany et al (2019) built on Lametti et al (2014) and performed the same AAF study but added two elements: physical manipulation of the jaw and rs-fMRI. The rs-fMRI was carried out separately after the AAF and then again after the jaw manipulation. The only study in this paper to look at neurological and behavioral results of physical manipulation, this portion of the experiment warrants attention. The subjects placed their chins in a device that measured the pressure at which they protruded their jaws to make the required speech sounds. The device then used this information to press the jaw in as the subjects phonated, measuring the pressure at which the jaw resisted. As previously stated, this was followed by rs-fMRI, the results compared with the fMRI from the AAF portion of the experiment. They found that, for the AAF portion, blood flow was highest in the motor parts of the brain, and for the jaw manipulation it was highest in the auditory parts. This supports speculation from Shoup Pieper (2025) stating that attentional locus towards a physical structure perhaps being fundamentally different from auditory attentional locus.

Alemi et al (2020), in another AAF study, attempted to test levels at which subjects could perceive a deviance, known as a just noticeable difference or JND, and compare the behavioral results from this experiment to a previous one where the same subjects received a standard AAF of 100 cents. One of the many purposes of this was to determine if the direction of the AAF compensation (usually, but not always, in the opposite direction of the AAF) could be predicted. They theorized that the distance of the pitch shift from the subject's own JND threshold would both be more consistent in one direction or the other, and result in superior adaptation, or learning, relative to a blanket 100 cent AAF. In all conditions, they additionally tested this on three different vowels: /a/, /e/, and /o/ to determine if there was a vowel to which the body adapted more readily. Interestingly, they did not show evidence of improved adaptation in the JND condition over the baseline condition. They speculate that "long term recalibration of motor plans might be driven by factors other than sensory-error-based adaptation (Alemi et al., 2020, p. 11)." They also, however, speculate that the lack of adaptation may have been partially due to changing vowels, wondering if the attentional load from this interfered with memory consolidation. If future research findings strengthen this speculation, it would address questions posed above about the boundaries between task relevant and task irrelevant information for the voice. It also would lend support to Tumber et al (2014)'s conclusion that attentional load negatively affected the brain's ability to generate output.

A topic discussed at length in previous work by the author (Shoup Pieper, 2025) is the development of a clear definition of implicit and explicit motor learning, particularly one that could be applied to singers and other voice users. It was found that conscious, explicit learning did not need to be synonymous with the ability for either the student or the teacher to verbalize it, thereby expanding the definition of explicit learning to one that was nonverbal and narrowing the definition of implicit learning to one that was truly unconscious. The performer's lack of awareness of every physical element they are coordinating does not make the learning itself unconscious; only a lack of awareness that learning is occurring does this. The above research provides nuance to the discussion, though it does not fundamentally change it. Implicit learning clearly does

occur in the voice and, at least in experimental circumstances, shows robustness over time (Franken et al, 2018). Equally important are findings from Tivadar et al (2021) that the brain detects auditory patterns and deviances even in states of extreme unconsciousness, such as in coma and under anesthesia. Not only does implicit learning happen with regards to the voice in the form of sensory response, it cannot be suppressed. While the author maintains that explicit learning is the main goal of a voice lesson, teachers would be naïve to discount the roles that sensory based pattern recognition and alterations play in vocal learning. The research further adds granularity to a distinction between implicit and explicit learning that is relevant for singers and revolves entirely around perception. A difference that cannot be perceived may be incorporated into the vocal usage implicitly; a difference that can be perceived, or contextualized consciously (Albright, 2015) can be consciously targeted and become an external locus of attention.

c. Consistency

“Consistency,” states Muratori et al. (2013, p. 5) “refers to the repeatability of performance – is the individual able to perform the task consistently over a period of trials conducted over a number of sessions.” While the role that conscious perception plays in vocal learning may show some clear differences from motor learning of the rest of the body, research indicates that the role consistency plays is similar, though with the added element of auditory predictions. Tivadar (2021) summarizes this: “To formulate a prediction, first regularity needs to be established, often through repetition. Repeating a given stimulus, for example, a sound, results in a reduced response at the neural level, commonly referred to as... repetition suppression in human research (Tivadar, 2021, p. 2).” The researcher speculates that this may partially explain the amount of sensory information that does not filter from outside of consciousness ‘up’ to the perceptive level: auditory input that matches what is expected remains unconscious. Consistency of auditory and predictions also plays a role in motor learning and relating an action to a planned sound (Van Vugt and Ostry, 2019)

Van Vugt and Ostry (2019) tested the development of sensorimotor maps in relation to sound creation. They divided a large group of participants ($n=165$) into groups of 20 to 25 and studied learning of a novel sensorimotor task, in which subjects moved a handle at various angles that were associated with specific sounds. With all these groups, they were able to test several different conditions: active with targets, in which subjects were given an auditory target and received a feedback sound; active without targets, or free exploration, in which subjects were given no targets but feedback sounds; alternating between targets and no targets, where the first set of trials were free exploration and the second set was only targets with no feedback; passive, where subjects were connected to an active participant and given targets and feedback; passive without feedback; permuted, where the relationships between movements and sounds were adjusted in a way to make them intuitive acoustically but not physically; scrambled, so that that a movement could not be associated with a particular sound. Surprisingly, similar amounts of learning took place in all these conditions except for the scrambled one. While not directly connected to vocal learning, this study has significant implications for vocal learners. Humans are adaptable to different learning conditions, even passive and unintuitive ones, so long as the relationship between movement and outcome is maintained. This illustrates both challenges and opportunities for singers and voice teachers. In this author's experience, many beginning singers appear to struggle to connect a perceived movement to a consistent outcome, likely both due to their own developing feedforward commands and developing acoustic and physical perception, and, it is speculated, muscular changes both from starting a new physical activity and, depending on the age of the singer, on physical changes that are happening. Once the singer can start to reliably associate an action or thought with an acoustic outcome, they seem to make considerable progress. However, the path to this stage may prove difficult for early -stage singers who are learning sensorimotor targets, and this therefore is an important framing of import for these students. Here, the author suggests that Dairany et al (2019)'s work may be of considerable benefit: knowing that a physical action may be neurologically mapped as an update to an acoustic target may prove an important tool both for developing consistency that the student can practice, and for

associating movement with sound outcomes. It would be important here, though, to choose actions carefully so that the attentional resources were not overloaded.

Franken et al directly addressed the topic of consistency in a 2019 behavioral AAF study. One of the major goals was to determine whether consistency in AAF would affect consistency and adaptation. Participants vocalized on /e/ in tandem with letters on a screen, for 3 seconds. The AAF shifted the first formant either up or down, though as in Franken et al (2018) the change was too small to be perceived. In the inconsistent condition, the presence or absence of perturbation was random; in the consistent ones, the AAF was present for all trials. While adaptation occurred in both conditions, as shown by F1 changes made close to the onset of the sound, more adaptation occurred in the consistent than inconsistent condition. Statistical analysis showed that compensation and adaptation may be two distinct processes, somewhat contradicting the DIVA model's assertion that adaptation is a build up of compensatory responses.

Zamorano et al's (2019) rs-fMRI study of the insular cortex compared conservatory trained singers to non singers and found morphological differences between the insular cortexes of the two groups. While this is likely not transferable to all singers of all styles, as the training and skills required differ greatly between singer populations, it still yields important insights into neurological changes that can result from consistent vocal practice. The insular cortex, a lobe that is deep to the frontal, parietal, and temporal lobes (Gogolla, 2017) is believed to be responsible for integrating processes in the brain, such as the ones indicated in Schirmer (2012)'s meta-analysis (Gogolla, 2017, Zamorano et al, 2019). Rs-fMRI, it will be recalled, is blood oxygen level dependent, or BOLD. As such, it detects both recently and commonly used areas of the brain where increased blood flow has been required to perform tasks. Additionally, researchers were able to compare results with previous studies on pianists and orchestral musicians (Zamorano et al, 2017) to make inferences about brain activation regions associated with music training in general, and ones that were unique to singing. In this 2019 study on singers, subjects, half of whom were non-singers and half of whom were conservatory trained classical singers, performed a pitch matching task to activate

coordinated vocal centers of the brain, and then given the rs-fMRI scan. Behaviorally, the trained singers were far more accurate than non-singers at the task. The fMRI findings showed clearly that “experienced singers showed a positive correlation between the total amount of accumulated vocal training and increased insula co-activation with the sensorimotor speech network’s core constituents (Zamorano et al, (2019, p.6).” While the granular aspects of consistency discussed in previous works were out of the scope of this particular study, the results of this continually practiced activity produced traceable changes that were both unique to vocal learning and in alignment with learning models.

Pedagogical Implications:

Information from this study has allowed the researcher to fundamentally reframe her approach to teaching, from one that is focused on conscious skill building, to one that primarily seeks to update the student’s feedforward signaling, and only secondarily seeks skill building. To this end, three major themes arose from the literature: attention, perception, and consistency. Attention, the brain’s direction of its computational resources (Lindsay, 2020; Tsotsos, 2019) can either help or hinder vocal output. Attentional Instructions can help the brain to choose where to put its resources (Zhang et al, 2025); however, overloading attention affects vocal output (Tumber et al, 2014). This occurs when the overload comes from a task irrelevant distraction, as in Tumber et al (2014), and it may also occur when the overload results from task relevant information, as in Alemi et al (2020). The most obvious pedagogical conclusion from this is for voice teachers to respect the limited attentional resources of all students and to direct those resources with clear instructions that, per Shoup Pieper (2025), do not necessarily need to be verbal. Feedback from the teacher that is not related to the instruction, task irrelevant information, environmental distractions, and overly complex music and exercises may all overload the student’s attention and degrade performance.

Perception was defined as the brain’s contextualization of sensory information (Albright, 2015). A significant amount of both auditory processing and vocal learning takes place without perception, as shown in Tivadar et al (2021), Franken et al (2018), and Franken

et al (2019). Alemi et al (2020)'s use of the subjects' JND's in the AAF study further did not prove to create a predictable cause and effect outcome for how subjects would respond to AAF. As stated previously, the amount of learning that takes place below the level of subjects' consciousness is an important fact for teachers to acknowledge. While perception can be trained and used to create auditory targets, independence, and a strong feed forward mechanism (Lametti et al, 2014; Tumber et al, 2014), students listening back to themselves or others may engage in truly implicit vocal learning that is clearly a part of our evolved neural-vocal system.

Van Vugt and Ostry (2019) demonstrate flexibility in many aspects of learning conditions but not flexibility in consistency for development of sensorimotor targets. Franken et al (2019) make a similar statement but with auditory feedback. Like attentional load, this research emphasizes the import of consistency of message and feedback. Consistent self-generated auditory feedback may pose as a challenge for beginning students and those whose bodies are changing as with puberty, menopause, students undergoing gender-affirming care, or students whose voices are simply developing due to practice and vocal load. The researcher speculates that in these cases, any consistency that can be found will be helpful for the student. For example, Dairany et al (2019) found that physical alterations appeared to update and refine acoustic predictions. If a student can associate a movement pattern with a sound outcome, even though some authors perhaps correctly, find this to be less than ideal (Moss Erickson, 2023) it may be crucial for some students' early learning to be able to do that one thing consistently.

Limitations:

A serious limitation of this study is that the bulk of the works cited were on speech alterations that exist in a limited pitch and vowel range. None of the studies included the pitch and formant relationships that would occur higher in a vocal range, and none of them included prosody or moving pitches. While important concepts were gleaned from the works studied, future work would ideally delve more deeply into behavioral differences in AAF studies between singers and non-singers, such as several studies cited in Zuk et al (2022). It is hoped that this would allow researchers to draw

comparisons or contrasts between Zamorano et al (2019)'s conclusions and those of behavioral studies. Further, even studies that focused on singers, such as Zamorano et al (2019), studied one group of conservatory trained classical singers, and did not account for the variation of skills required between classical, pop, and jazz singers.

Conclusion:

The above study was undertaken to find deeper granularity in understanding of how Gabrielle Wulf's research on attentional locus could be applied to the voice, and to test speculations in the researcher's previous work. Research on sensory prediction, the system believed to be largely responsible for the effects of attentional instructions on the rest of the body (Wulf & Lewthwaite, 2016) was explored in the context of the vocal research, as were feedback and attention. The articles were then mined inductively for themes; attentional instruction, attentional load, the role, or lack thereof, of perception, and the effects of consistency were deemed to be the most salient and pedagogically useful. While the overall concepts outlined in previous work by the author were upheld, this research added nuance to the discussion of perception and attention: it supported claims of different encoding between physical and acoustic cues, demonstrated that vocal learning does not necessarily require consciousness to occur. Any future research on attentional locus and the voice therefore should include the acknowledgement of physical and acoustic cues and awareness, and the possibly for truly implicit, unconscious learning to occur in the voice in a way that it may not in the rest of the body.

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