

Research Article

Nasal and Oral Inspiration During Natural Speech Breathing

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Purpose: The purpose of this study was to determine the typical pattern for inspiration during speech breathing in healthy adults, as well as the factors that might influence it.

Method: Ten healthy adults, 18–45 years of age, performed a variety of speaking tasks while nasal ram pressure, audio, and video recordings were obtained. Inspirations were categorized as nasal-only, oral-only, simultaneous nasal and oral, or alternating nasal and oral inspiration. The method was validated using nasal airflow, oral airflow, audio, and video recordings for 2 participants.

Results: The predominant pattern was simultaneous nasal and oral inspirations for all speaking tasks. This pattern was not affected either by the nature of the speaking task or by the

phonetic context surrounding the inspiration. The validation procedure confirmed that nearly all inspirations during counting and paragraph reading were simultaneous nasal and oral inspirations, whereas for sentence reading, the predominant pattern was alternating nasal and oral inspirations across the 3 phonetic contexts.

Conclusions: Healthy adults inspire through both the nose and mouth during natural speech breathing. This pattern of inspiration is likely beneficial in reducing pathway resistance while preserving some of the benefits of nasal breathing.

Key Words: speech, nasal pressure, oral and nasal airflow

Most inspirations are routed through the nose, rather than the mouth, for good reasons. Nasal inspiration converts the incoming air to body temperature; increases the humidity of the incoming air; and extracts dust, bacteria, and other contaminants from it (Cole, 1963; Ingelstedt & Ivstam, 1951; Proctor, Anderson, & Lundqvist, 1973). The use of nasal rather than oral inspiration has also been found to be beneficial for voice production. For example, Sivasankar and Fisher (2002) found that participants who breathed continuously through the mouth for 15 min had significantly higher phonation threshold pressures (i.e., the minimum tracheal air pressure needed to produce voice) after oral breathing than before, and six of their 10 participants reported greater vocal effort after oral breathing than before. In contrast, participants who breathed continuously through the nose for 15 min had significantly lower phonation threshold pressures after nasal breathing than before, and seven of the 10 participants reported lower vocal effort after the nasal breathing than before. The researchers concluded that prolonged oral breathing likely results in depletion of the *sol layer* of the vocal folds, a layer

of water that overlays the outer layer of vocal fold tissue. The *sol layer* maintains superficial hydration of the vocal folds and has been found to affect the vibration of the vocal folds (Finkelhor, Titze, & Durham, 1988; Jiang, Verdolini, Aquino, Ng, & Hanson, 2000).

Sivasankar and Fisher (2003) conducted a follow-up study with speakers who had reported a history of vocal attrition (i.e., a decrement of vocal function with voice use characterized by fatigue, discomfort, and throat dryness). Prolonged oral breathing resulted in significantly increased phonation threshold pressure and increased perceived vocal effort in participants with vocal attrition and in normal controls. However, phonation threshold pressure was significantly greater in participants with vocal attrition compared with normal controls after prolonged oral breathing. Interestingly, prolonged nasal breathing significantly decreased phonation threshold pressure in the normal control group, but not in the vocal attrition group. These results indicated that some disordered populations may be more affected by oral breathing than other populations and that breathing patterns can be altered to improve some aspects of voice production for some individuals.

Based on the reported benefits of nasal breathing, it is not surprising that nasal resting tidal breathing is the norm in about 90% of healthy adults (Warren, Hairfield, Seaton, Morr, & Smith, 1988). However, there are situations in which it is desirable to switch from nasal to oral inspiration.

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For example, when nasal pathway resistance (i.e., opposition to airflow through the nose) increases from its usual low magnitude to approximately 4.5 cm H₂O/LPS or higher, most people switch from nasal inspiration to a combined nasal-oral inspiration (Warren et al., 1988; Watson, Warren, & Fischer, 1968). An increase in nasal pathway resistance can be caused by a narrowing of the nasal pathway, as with nasal congestion, or by an increase in airflow, as with more rapid inspiration (Warren, Duany, & Fischer, 1969; Warren, Lehman, & Hinton, 1984).

During speech breathing, peak inspiratory airflow is typically at least 2 times greater (Horii & Cooke, 1978) and average inspiratory airflow is 4 times greater (Bailey & Hoit, 2002; Horii & Cooke, 1978) than during resting tidal breathing. Thus, inspirations routed through the nose would encounter a high nasal pathway resistance. It seems reasonable to predict, therefore, that inspirations during speech breathing would be routed through the mouth rather than the nose. However, there is no research documenting this. It is important to understand the typical pattern of nasal versus oral inspiration during natural speech breathing to identify individuals who deviate from this pattern and to develop breathing modifications that might be used to address voice-related problems such as abnormally high phonation threshold pressure or perception of higher than normal vocal effort.

The purpose of this study was to determine the normal pattern for inspiration during speech breathing in healthy adults as well as the factors that might influence inspiratory behavior during speech breathing. Three questions were addressed: (a) Do healthy adults inspire through the mouth more often than through the nose during natural speech breathing? (b) Do healthy adults inspire through the mouth more frequently when producing continuous speech with minimal pausing (e.g., during continuous counting aloud) than when producing speech with more frequent pauses (e.g., during conversation)? and (c) Do healthy adults inspire through the mouth more often when the inspiration is preceded or followed by speech sounds that require an open mouth (e.g., a low vowel) compared with sounds that require a closed mouth (e.g., a bilabial consonant)? It was hypothesized that inspirations would be more frequently routed through the mouth than through the nose during speech breathing due to the high inspiratory flows demanded during speaking. This inspiratory pattern was expected to be more frequently observed during speaking tasks with minimal pausing and in contexts wherein the preceding and following speech sounds required an open mouth.

Method

Participants

The participants in this study were 10 healthy adults (seven women and three men) between the ages of 18 and 45 years. An equal number of female and male participants was not sought, as sex-related differences were not expected in the inspiratory patterns of interest. All participants reported that they were native speakers of English and denied a

history of oropharyngeal-nasal disorders, respiratory disorders, neurological disorders, or smoking more frequently than one time per month within the past 5 years. All participants in this study passed a nasal pathway resistance screening, as described below. This study was approved by the University of Arizona Institutional Review Board (UA IRB).

Procedure

Prior to data collection, the consenting process was conducted according to UA IRB guidelines. Participants were informed that the purpose of the study was to determine how people breathe and talk using measurements of air through the nose, video observations of mouth opening, and audio recordings of speech during different tasks. Participants were naïve to further details regarding the specific aims of this study.

Nasal pathway resistance screening. Prior to initiating data collection, nasal pathway resistance was calculated for each participant to ensure that the resistance was below the value at which individuals typically switch from nasal to oral inspiration (i.e., 4.5 cm H₂O/LPS; Warren et al., 1988; Watson et al., 1968). This screening was conducted by recording oral air pressure and nasal airflow using the Glottal Enterprises Aeroview system. Oral air pressure was sensed by placing a small catheter just behind the lips, the other end of which was attached to a Glottal Enterprises oral pressure adapter and pressure transducer. Nasal airflow was sensed by placing a circumferentially vented pneumotachometer mask, connected to a differential pressure transducer, over the participant's face. The participant was instructed as follows: "Take a deep breath, close your lips tightly around the tube, place the mask over your face, and release the air out your nose." Oral air pressure and nasal airflow signals from the transducers were routed to the Glottal Enterprises MS-110 analog data computer interface and stored on a Dell Precision T3500 desktop computer with Aeroview software version 1.4.4. Custom-written MATLAB (Mathworks) functions were used to determine nasal pathway resistance. This calculation was made by dividing the oral pressure by the nasal airflow at a flow of 250 cc/s, the flow used in a previous study of nasal pathway resistance (Allison & Leeper, 1990). A second nasal pathway resistance measure was made following data collection to ensure that it remained below 4.5 cm H₂O/LPS. All participants' nasal pathway resistance measurements were less than 4.0 cm H₂O/LPS immediately prior to and following data collection.

Data collection. Nasal ram pressure, audio, and video recordings were obtained. Nasal ram pressure was detected by having the participant wear a nasal cannula with the 7-foot-long tubing attached to a pressure transducer (Validyne MP45 with a ± 2 cm H₂O diaphragm). The detected pressure changes reflected the local average pressure in the nasal cannula probe tubes in the anterior nares. Nasal ram pressure is related to local airflow, but not necessarily to the mass nasal airflow due to the air escape around the probe tubes (Bunton, Hoit, & Gallagher, 2011; Thom, Hoit, Hixon, & Smith, 2006). The nasal ram pressure signal was amplified

(Valdyne CD 15) and routed to a desktop computer. The speech audio signal was sensed with an omnidirectional condenser microphone attached to the participant's lapel, amplified (Rane MS1), and routed to the desktop computer. Video recordings were made using a Logitech HD 720p video camera that was focused on the participant's face, neck, and shoulders to document mouth status (i.e., opened or closed) and movement of the upper rib cage during inspiration. The video signal was routed directly to the desktop computer. The nasal ram pressure, audio, and video signals were displayed using LabChart 7 software (ADInstruments) for online data monitoring and recording.

Data were recorded while each participant performed several tasks. To begin, the participant was instructed to "sit quietly while I get everything set up." This allowed for documentation of the participant's normal resting tidal breathing to ensure that resting tidal inspirations were routed through the nose. The participant then performed five speaking tasks. Four of the speaking tasks were included to elicit different pausing behaviors: Counting, paragraph reading, and spontaneous speaking were designed to elicit the least number of pauses, and participating in a conversation was designed to elicit a substantially greater number of pauses.

1. **Counting:** The participant was instructed to "count from 1 to 50 in your normal speaking voice and with your normal speaking rate." If the participant used an atypical speaking rate, intonation, or breathing pattern (e.g., taking an inspiration after each word), she or he was provided with a model and was asked to repeat the task.
2. **Paragraph reading:** The participant was provided with the California Passage (Hoit & Hixon, 1986). She or he was instructed to "read the passage aloud."
3. **Spontaneous speaking:** The participant was told, "I need to have you talk for a full minute about your favorite vacation. I will not say anything until I tell you that you can stop."
4. **Conversation:** Prior to each participant's study session, she or he was asked to be prepared to have a phone conversation with a friend or family member during the session. The participant was told, "I need you to call a friend or family member and have a conversation with him/her for a few minutes. Tell him or her a little bit about this study and your day, and then you can just go back and forth."

The fifth speaking task consisted of reading sentences that were designed to manipulate the probability that a participant would inspire through the nose or mouth.

5. **Sentence reading:** The participant was asked to read aloud 28 pairs of sentences. If the participant did not inspire after the first sentence in each pair, she or he was provided with further instruction to "take a breath after each sentence" and was asked to reread the pairs of sentences that she or he had already produced. These sentences included seven different phonetic contexts surrounding inspirations designed to elicit production

of different combinations of a low vowel with lips abducted (/a/), bilabial stop consonant with lips adducted and velopharynx closed (/b/), and bilabial nasal consonant with lips adducted and velopharynx opened (/m/):

- a. /a/ preceding the inspiration and /a/ following the inspiration ("The daughter thought that the job would surely be given to her pa. Oddly, the job was offered to another applicant instead.").
- b. /b/ preceding the inspiration and /a/ following the inspiration ("The applicant thought he would get the job. Oddly, it was offered to someone else.").
- c. /a/ preceding the inspiration and /b/ following the inspiration ("The daughter thought that the winner would be pa. But, the other candidate won.").
- d. /b/ preceding the inspiration and /b/ following the inspiration ("The applicant thought that he would get the job. But, it was offered to someone else.").
- e. /a/ preceding the inspiration and /m/ following the inspiration ("The daughter thought that the job would surely be given to her pa. Many of the other applicants were not as qualified for the job.").
- f. /m/ preceding the inspiration and /a/ following the inspiration ("The man thought that his interview had gone very smoothly with the manager Tom. Oddly, he heard that Tom offered the job to someone else instead.").
- g. /m/ preceding the inspiration and /m/ following the inspiration ("He thought the interview went well with Tom. Many others thought that theirs went well too.").

Each of the seven sentence pairs was produced four times. Sentences with /m/ contexts were not produced by the first two participants because these contexts were not yet part of the protocol.

Two participants returned for a second session on a different day so that stability of performance across sessions could be determined.

Data Analysis

The initial plan for data analysis was to categorize nasal versus oral inspirations. However, as data analysis progressed, it became clear that participants used a variety of inspiratory patterns. Therefore, data analysis consisted of categorizing inspirations into one of four categories: nasal only, oral only, simultaneous nasal and oral, or alternating nasal and oral. This was determined by visually examining the recordings of nasal pressure, video, and audio data displayed on three separate channels in LabChart and listening to the audio recordings over a speaker (Cakewalk by Roland MA-7A). Auditory-perceptual methods, rather than acoustic methods, were used for detecting inspirations, as these have been found to be more reliable (Wang et al., 2012). An inspiration was judged to be (a) nasal only if the mouth was closed (lips adducted) and the nasal pressure was negative, (b) oral only if the mouth was opened (lips abducted) and the nasal pressure was zero, (c) simultaneous nasal and oral if the

mouth was opened (lips abducted) and the nasal pressure was negative, and (d) alternating nasal and oral if both (a) and (b) were observed during the same inspiration. The categorization scheme for inspirations is summarized in Table 1.

All inspirations were categorized for the counting, paragraph reading, and sentence reading tasks. The first 10 inspirations were categorized for the spontaneous speaking and conversation tasks. An inspiration was not analyzed if it (a) was accompanied by audible mouth obstructions (e.g., tongue clicks) or visible mouth obstructions (e.g., tongue elevated to alveolar ridge during inspiration), (b) was preceded or followed by laughing or swallowing (swallowing was identified by a pause in speaking accompanied by laryngeal elevation and a rapid positive and negative fluctuation in nasal ram pressure around zero), (c) preceded the first breath group of a speaking task (e.g., the inspiration before the first breath group of the paragraph reading), or (d) followed the last breath group of a speaking task. Using these criteria, the total number of nasal, oral, simultaneous nasal and oral, and alternating nasal and oral inspirations were tabulated for each participant for each speaking task.

Intrarater reliability was determined by having the first author reanalyze two randomly selected participants' data in the same manner described above. Interrater reliability was determined by having the second author analyze the same two randomly selected participants' data. This was completed using the same method described above, except the speech context and time of inspirations for the 10 inspirations that occurred during the spontaneous speaking and conversation tasks were provided to the second author. This ensured that the two raters categorized the same inspirations.

Validation Procedure

To confirm that an opened mouth was accompanied by airflow through the mouth, two participants were asked to complete a validation protocol immediately following the protocol described above. In addition to the information that was provided to the other eight participants, these participants were informed that the purpose of the study was to determine how people breathe and talk using measurements of air through both the nose and mouth. Participants were again naïve to further details of the specific aims of this study.

Table 1. Categorization scheme for nasal only, oral only, simultaneous nasal and oral, and alternating nasal and oral inspirations based on mouth status and nasal pressure.

Category	Mouth status	Nasal pressure
Nasal only	Closed	Negative ^a
Oral only	Opened	Zero ^b
Simultaneous nasal and oral	Opened	Negative
Alternating nasal and oral	Closed then opened, or opened then closed	Negative and zero

^aNegative nasal pressure indicates inspiratory nasal airflow. ^bZero nasal pressure indicates no nasal airflow.

For the validation protocol, nasal airflow, oral airflow, audio, and video recordings were obtained using the Glottal Enterprises Transducer and Analog Data Computer Interface Model MS-110, a dual-chamber OroNasal mask, and a microphone. The mask covered the nose and mouth, was circumferentially vented, and had a partition separating the nasal and oral regions. Each region of the mask was connected to a separate pressure transducer, and the signals were routed to the ADInstruments Powerlab 16/30, which was attached to the desktop computer with LabChart software (ADInstruments). Audio recordings were made with an omnidirectional condenser microphone attached to the participant's lapel. Video recordings were made using the same video camera described above, but with the camera focused on the mouth, as viewed through one of the mask vents. The participant was instructed to place the face mask gently over the mouth and nose so as to avoid compressing the outer nose. It was considered acceptable to allow air to leak around the sides of the mask because only the presence and direction of airflow was of interest in this study. Thus, airflow was not calibrated. With the face mask in place, the participant was asked to perform the resting tidal breathing and three of the speaking tasks described above: counting, paragraph reading, and sentence reading.

Data analysis consisted of categorizing inspirations as nasal only, oral only, simultaneous nasal and oral, or alternating nasal and oral, as above. This was determined by visually examining the recordings of nasal airflow, oral airflow, video, and audio data on three separate channels in LabChart while simultaneously listening to the audio recordings over a speaker. The audio recordings were used to detect inspirations and to determine the speech context surrounding each inspiration. Using the video images, mouth status during inspiration was characterized as opened (lips abducted), closed (lips adducted), or a combination of opened/closed or closed/opened if the mouth status changed during the inspiration. Nasal airflow and oral airflow were characterized as being zero (no flow) or negative (inspiratory flow). The categorization scheme is summarized in Table 2.

All inspirations were categorized except those that (a) were preceded or followed by laughing or swallowing (swallowing was identified by a pause in speaking accompanied by a rapid positive and negative fluctuation in nasal airflow around zero), (b) preceded the first breath group of a speaking task (e.g., the inspiration before the first breath group of the paragraph reading), or (c) followed the last breath group of a speaking task. The total number of nasal, oral, simultaneous nasal and oral, and alternating nasal and oral inspirations were tabulated for each task.

Reliability

Intrarater reliability was 98%; specifically, 135/138 inspirations were identified and assigned to the same categories for the first and second analyses by the first author. Interrater reliability was 95%; that is, 131/138 inspirations were identified and assigned to the same categories by the first and second authors. Interrater reliability was lower than

Table 2. Categorization scheme for nasal only, oral only, simultaneous nasal and oral, and alternating nasal and oral based on mouth status, nasal airflow, and oral airflow for the validation protocol.

Category	Mouth status	Nasal airflow	Oral airflow
Nasal only	Opened or closed	Negative ^a	Zero ^b
Oral only	Opened	Zero	Negative
Simultaneous nasal and oral	Opened	Negative	Negative
Alternating nasal and oral	Closed then opened, or opened then closed	Negative and zero	Negative and zero

^aNegative indicates inspiratory airflow. ^bZero indicates no airflow.

intrarater reliability because one author characterized a greater number of inspirations during the counting and paragraph reading tasks.

Session-to-session stability was 93%; specifically, 100/107 inspirations were identified and assigned to the same categories across two sessions for two participants. This variability was partly related to differences in the number of inspirations across the two sessions for one participant.

Statistical Analyses

The data were analyzed using a two-factor within-subjects analysis of variance (ANOVA) with the factors of speaking task (i.e., counting, paragraph reading, spontaneous speaking, and conversation) and inspiration category (i.e., oral only, nasal only, simultaneous nasal and oral, and alternating nasal and oral). Because the data violated the assumptions of independence of observations and homogeneity of variance, all data were converted to proportions, and a logit transformation was applied to the proportions prior to the analyses described below. Note that because some proportions were zero, a constant (0.5) was added to all counts before converting to proportions. The formula used for the logit transformations was $\text{logit}(p) = \log(p/(1 - p))$, where “p” is the proportion. Post hoc comparisons were conducted using Tukey’s honestly significant difference (HSD) test to analyze the effect of inspiration category and a paired two-tailed *t* test to analyze the effect of speaking task. The frequency of combined nasal and oral inspirations during sentence production was analyzed using a one-factor within-subjects ANOVA, with phonetic context as the factor with three levels (i.e., /a+/a/, /b+/b/, /m+/m/). Partial eta squared was calculated to determine effect size. All statistical analyses were conducted using SPSS Version 20 (IBM Corp.).

Results

During resting tidal breathing, all participants kept their mouths closed and inspired through the nose. In contrast, inspirations during the speaking tasks were characterized by a variety of inspiratory patterns. As shown in Figure 1, the predominant inspiratory pattern was simultaneous nasal and oral inspirations for counting, paragraph reading,

spontaneous speaking, and conversation, with group averages ranging from 100% for counting to 84% for participating in a conversation. This pattern was essentially the same for female and male participants. Note that the total number of inspirations differed across participants for the counting, paragraph reading, and spontaneous speaking tasks. For counting and paragraph reading, this was due to individual differences in breath group length (i.e., amount of speech per expiration). During spontaneous speaking, Participant 7 produced only eight inspirations that could be analyzed; the remainder of inspirations contained tongue clicks and were therefore excluded from analyses. For all other participants, 10 inspirations were categorized during conversation.

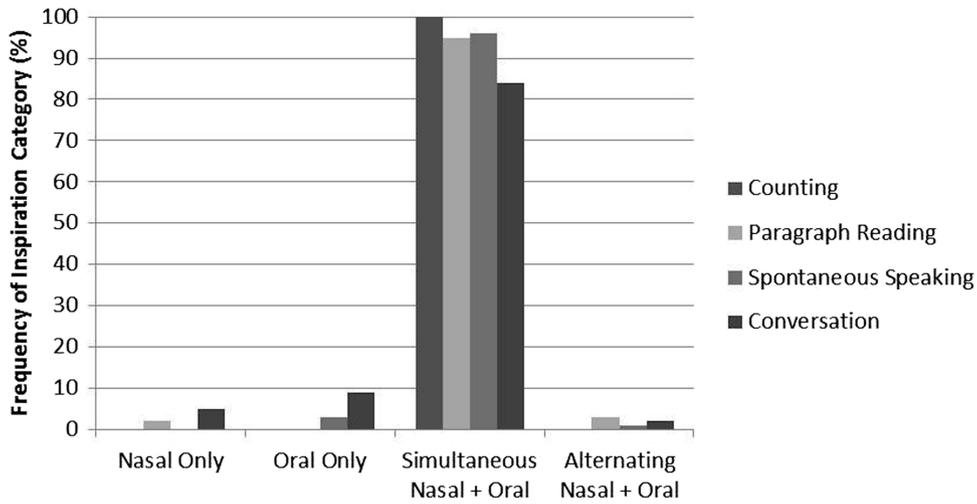
The within-subjects ANOVA, with the factors of speaking task (i.e., counting, paragraph reading, spontaneous speaking, conversation) and inspiration category (i.e., oral only, nasal only, simultaneous nasal and oral, and alternating nasal and oral) revealed that there were significant main effects of speaking task, $F(3, 27) = 7.041, p < .005$, partial $\eta^2 = 0.439$, and inspiration category, $F(3, 27) = 468.248, p < .001$, partial $\eta^2 = 0.981$. When a Greenhouse–Geisser correction was applied due to violation of the assumption of sphericity, as indicated by a significant result of Mauchley’s test of sphericity ($p < .001$), there was no significant interaction of speaking task and inspiration category, $F(3.447, 31.026) = 2.579, p = .064$, partial $\eta^2 = 0.223$.

Post hoc comparisons were conducted to verify that the basis for the main effect of inspiration category was the observed difference between the frequency of simultaneous nasal and oral inspirations and the frequency of nasal-only, oral-only, and alternating nasal and oral inspirations. Tukey’s HSD test indicated that there was a significant difference between the means for the simultaneous nasal and oral inspiration and the nasal-only inspirations (mean difference = 4.404, $SE = 0.144$), oral-only inspirations (mean difference = 4.367, $SE = 0.144$), and alternating nasal and oral inspirations (mean difference = 4.410, $SE = 0.144$). No other pairwise comparisons were significant.

Post hoc comparisons were also conducted to analyze the main effect of speaking task. A *t* test was used because the only comparison of interest was between the three continuous speaking tasks (counting, paragraph reading, spontaneous speaking) and the noncontinuous speaking task (conversation) to answer the question: “Do healthy adults inspire through the mouth more frequently when producing continuous speech with minimal pausing than when producing speech with more frequent pauses?” The *t* test revealed that there was no significant difference between the frequency of combination nasal and oral inspirations during the continuous speaking tasks ($M = 1.652, SD = 0.204$) and conversation ($M = 1.172, SD = 0.805$), $t(9) = 1.822, p = .102$, partial $\eta^2 = 0.168$.

Results for the sentence reading task are shown in Figure 2. The /a+/a/ and /b+/b/ sentence analyses do not include the data for Participant 7 because this participant reported that she was purposefully inspiring through the nose throughout the sentence reading task. Therefore, the /a+/a/ and /b+/b/ data are from nine participants only. Participant 7’s data were also excluded from the /m+/m/ sentence

Figure 1. Percentage of inspirations categorized as nasal only, oral only, simultaneous nasal and oral, and alternating nasal and oral for the 10 participants for four of the speaking tasks (i.e., counting, paragraph reading, spontaneous speaking, and conversation). Total number of inspirations for counting 2–11, paragraph reading 7–21, spontaneous speaking 8–10.



analyses, as were the data from Participant 10 because this participant produced audible mouth obstructions (i.e., tongue clicking) throughout the /m/+m/ task. Participant 1 and Participant 2 did not produce the /m/+m/ sentences because these were not part of the protocol at the time of their participation. Therefore, the /m/+m/ data are from six participants. As can be seen in Figure 2, simultaneous nasal and oral breathing was the predominant pattern for the /a/+a/, /b/+b/, and /m/+m/ sentence pairs. The within-subjects ANOVA revealed that there was no significant effect of phonetic context, $F(2, 10) = 1.010, p = .399, \text{partial } \eta^2 = 0.168,$

on the frequency of simultaneous nasal and oral inspiration. The other inspiratory categories (i.e., oral only, nasal only, alternating nasal and oral inspiration) were not analyzed because of the infrequent occurrence of these patterns during the sentence reading task (i.e., range of 0–15% of trials for eight participants and 60% for one participant). The other phonetic pairs (/a/+b/, /b/+a/, /a/+m/, /m/+a/) were not analyzed due to a lack of effect of phonetic context on the inspiratory pattern evidenced by these initial analyses.

Results of the validation procedure, which involved recording oral and nasal airflow in two participants, are

Figure 2. Percentage of inspirations categorized as nasal only, oral only, simultaneous nasal and oral, and alternating nasal and oral for nine participants for the /a/+a/ and /b/+b/ sentence productions and for six participants for the /m/+m/ sentence productions.

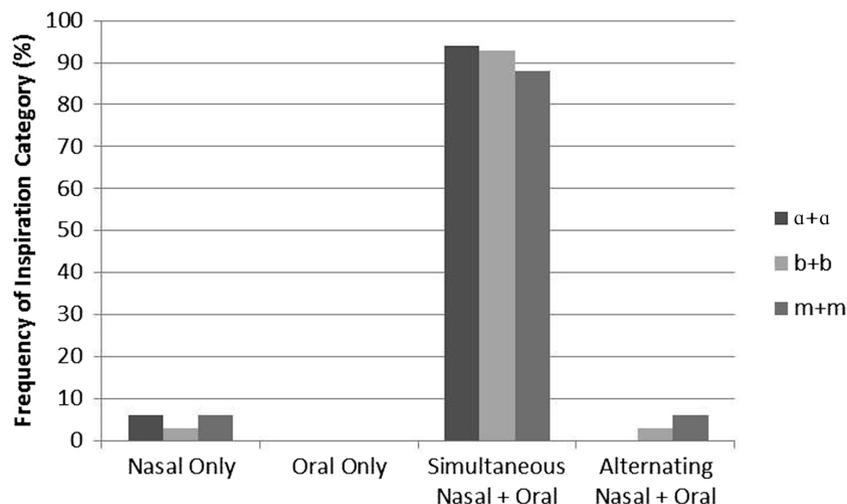


Table 3. Percentage of inspirations categorized as nasal only, oral only, simultaneous nasal and oral, and alternating nasal and oral for the nasal pressure method and the validation protocol using the nasal and oral airflow method for three tasks for the two participants.

Task	Nasal only		Oral only		Simultaneous nasal and oral		Alternating nasal and oral	
	Pressure	Flow	Pressure	Flow	Pressure	Flow	Pressure	Flow
Counting	0	0	0	0	100	100	0	0
Paragraph reading	0	0	0	0	100	96	0	4
Sentences	a+a	29	0	0	71	0	0	100
	b+b	25	13	0	0	75	25	63
	m+m	25	0	0	0	75	0	100

shown in Table 3. This procedure confirmed that nearly all inspirations during counting and paragraph reading were simultaneous nasal and oral inspirations, whereas for the sentences, the predominant pattern was alternating nasal and oral inspirations across the three phonetic contexts. These validation results were consistent with those obtained using nasal ram pressure in the study proper for counting and paragraph reading. In contrast, they differed from the nasal ram pressure results for the sentences in that the nasal and oral inspirations were seen to alternate rather than occur simultaneously. Further, there were fewer nasal-only inspirations when the flow mask was worn.

Discussion

This study revealed that healthy adults inspired simultaneously through the nose and mouth during speaking. This was true for speaking tasks that were scripted (counting and paragraph reading) and extemporaneous (spontaneous speaking and conversation), continuous (counting, paragraph reading, spontaneous speaking) and noncontinuous (conversation). This was also true for speaking tasks that elicited inspirations bounded by different phonetic contexts (sentence reading). Below are speculations as to why this pattern of inspiration might be used during natural speaking, why this pattern has not been documented in previous research, and why the method used in this study was effective in determining this pattern.

Pattern of Simultaneous Nasal and Oral Inspiration

The current study clearly showed that healthy adults inspire simultaneously through the nose and mouth during speech breathing. This pattern appears to be advantageous for two reasons. First, it likely minimizes upper airway resistance under conditions of high inspiratory airflow by routing the flow through both the nasal and oral pathways. Nasal pathway resistance increases with greater nasal airflow (Warren et al., 1969, 1984), and when nasal pathway resistance exceeds a critical value of approximately 4.5 cm H₂O/LPS, most people switch to mouth breathing (Warren et al., 1988; Watson et al., 1968). It seems reasonable to assume that nasal pathway resistance would exceed this critical value if speech inspirations were routed through the nose, given that inspiratory airflow during speech breathing is substantially greater than during resting tidal breathing (Bailey & Hoit,

2002; Horii & Cooke, 1978). Thus, it is not surprising that speech inspirations are produced with open nasal and oral pathways as a means to reduce the overall airway resistance. A second reason that a simultaneous nasal and oral inspiratory pattern is advantageous is that it likely preserves some of the benefits of nasal breathing. Specifically, the air that passes through the nasal pathways would be filtered, humidified, and warmed, thereby helping to protect the tissues along the airway. For these reasons, the simultaneous nasal and oral pattern of inspiration appears to be the most efficient and healthiest of the possible patterns.

Despite the fact that simultaneous nasal and oral inspiration was the predominant pattern observed in the current study, participants apparently did not perceive this to be their usual pattern. After each study session was completed, participants were informally asked to repeat the paragraph reading task while consciously attempting to inspire through the mouth only, through the nose only, and through both the nose and mouth simultaneously. The majority of participants reported that they found it most natural to inspire through the mouth only and least natural to inspire through both the nose and mouth. When attempting to simultaneously inspire through the nose and mouth, some participants demonstrated difficulty coordinating these inspirations, as indicated by their facial expressions, pause times, and occasional snorting sounds. Most of these participants performed alternating oral and nasal inspirations instead. This suggests that individuals have limited awareness of velopharyngeal status and may lack volitional control of velopharyngeal musculature. As a result, it might be difficult to teach simultaneous nasal and oral inspiration to someone who deviates from this normal pattern. It is possible, however, that this awareness and control might improve with specific education regarding velopharyngeal function and biofeedback.

It is surprising that this apparently prevalent pattern of inspiration has not been reported in prior literature on velopharyngeal function during speaking. This is likely due to the fact that previous research has focused primarily on velopharyngeal function during speech production (expiration) rather than during inspiration. However, review of x-ray videos obtained during sentence production by a healthy adult male revealed that the velum was lowered and the lips were abducted during inspirations (Munhall, Vatikiotis-Bateson, & Tohkura, 1995). More recently obtained real-time

magnetic resonance images and audio recordings also demonstrated this same pattern (Narayanan, Nayak, Lee, Sethy, & Byrd, 2004). These physiologic observations support the current finding that speakers inspire through both the nose and mouth during speech breathing. Future research is needed to determine the relative airflow through the oral and nasal pathways using calibrated flow measurements. Although it might be expected that there would be greater airflow through the oral cavity, simulations of oral and nasal inspiration have indicated that approximately 75% of the flow is directed through the nasal pathway when nasal pathway resistance is within normal limits (i.e., 2.2 cm H₂O/LPS; Warren et al., 1984).

Critique of the Method

The method used in this study to determine the pattern of inspiration during speech breathing was designed to be as noninvasive and natural as possible. Although it would have been feasible to obtain measurements of oral and nasal airflow with a face mask and pneumotachometer system, application of a face mask can compress the nasal pathways and increase the nasal pathway resistance, as discussed by Hixon, Weismer, and Hoit (2014). Because it seemed likely that a change in nasal pathway resistance would alter the natural pattern of nasal versus oral breathing, a nasal cannula was chosen in favor of a face mask for the current study. It should be noted that, although the method used in this study was the least invasive method available, it is still possible that participants' awareness of breathing assessment could have influenced their inspiratory patterns.

The participants in this study indicated that the nasal cannula was comfortable and that, in fact, they often forgot they were wearing it during the recording session. In contrast, the two individuals who also participated in the validation protocol stated that the face mask was less comfortable and indicated that they had to attend to the mask to hold it in place. When comparing the inspiratory patterns observed using the two techniques, it was clear that application of the face mask decreased the frequency of nasal-only inspirations (during the sentence production task). This was probably a result of the pressure placed on the outer nose by the face mask, despite careful instructions to participants to gently apply the face mask. It was also noted that participants inspired half as many times during the counting task when they were wearing the face mask compared with when they were wearing the cannula. This indicated that, when the timing of inspirations was not constrained by variables such as linguistic structure or punctuation, participants inspired less frequently (and presumably inspired larger volumes) with the face mask compared with the nasal cannula. These findings are inconsistent with the findings of Huber, Stathopoulos, Bormann, and Johnson (1998), who found no significant differences in inspiratory frequency or volume measures with and without a face mask. However, their experimental tasks included only productions of repeated syllables and a familiar nursery rhyme, which dictated the timing of inspirations. A follow-up study by Collyer and Davis (2006)

investigated the effects of variety of face masks on breathing patterns during paragraph reading and singing. Only lung volume and duration of inspiration and expiration were measured; measurements of inspiratory frequency were not reported. Therefore, further research is needed to investigate the influence of a face mask on inspiratory frequency and volume during linguistically unconstrained speech production (such as extemporaneous speaking) and on the frequency of nasal inspirations during speech production.

The only apparent advantage of using the nasal and oral airflow technique over the nasal ram pressure technique was that it was easier to identify alternating nasal and oral inspirations. It proved to be difficult to determine the exact timing of inspiratory events by inferring oral airflow from video recordings of mouth status (recorded at a rate of 30 frames per second) and by comparing the estimated time of mouth opening with the onset of nasal ram pressure changes (which may have been slightly delayed by transduction of pressure changes at the anterior nares through the 7-foot-long nasal cannula tubing to the pressure transducer). The finding that inspirations during the sentence reading tasks were alternating rather than simultaneous nasal and oral inspirations may have been related to the ability to directly measure nasal and oral airflow using the validation procedure. Fortunately, this degree of sensitivity for distinguishing between simultaneous and alternating nasal and oral inspirations was not needed to answer the questions of the current study. But, it is important to consider the precision of information regarding the timing of nasal and oral events needed in future studies.

The tasks in the current study were useful in documenting the inspiratory pattern in different speaking contexts. In particular, the method used for eliciting conversation by having participants talk with familiar partners over the phone (Warner, 2012) was successful in establishing natural and comfortable conversational interaction. Phone calls also appeared to be easy for participants to schedule and did not pose any human subjects challenges because the loudness of the phone was kept low enough to avoid recording the conversational partner's speech.

Conclusions

In conclusion, this study has shown that healthy adults simultaneously breathe in through the nose and mouth when they speak. This pattern appears to be an efficient way to take quick inspirations during speaking and may preserve some of the benefits of nasal breathing. The method used in the current study was effective in determining the pattern of inspiration during speech breathing in healthy adults and did not appear to alter the natural pattern. Future studies should examine if individuals with speech and voice disorders deviate from this pattern, and if so, whether or not modification of their inspiratory patterns might be beneficial.

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