Research Article

Respiratory–Swallow Training Methods: Accuracy of Automated Detection of Swallow Onset, Respiratory Phase, Lung Volume at Swallow Onset, and Real-Time Performance Feedback Tested in Healthy Adults

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Background: Preliminary studies have shown that respiratory–swallow training (RST) is a successful treatment for oropharyngeal head and neck cancer patients with refractory dysphagia. Refining the RST protocol with automated analysis software to provide real-time performance feedback has the potential to improve accessibility, reproducibility, and translation to diverse clinical settings.

Method: An automated software program for data acquisition and analysis developed to detect swallows, determine respiratory phase, calculate lung volume at the onset of the swallow, and provide real-time performance feedback was tested for feasibility in a small cohort of healthy adults.

Outcome Measures: Percent difference in swallow detection and accuracy of real-time performance feedback of respiratory phase and lung volume at swallowing onset between the

automated software and the manual gold standard method were determined.

Results: The automated software program accurately detected the onset of the swallow on 91% of the swallows completed during the training trials. Feedback of respiratory phase and lung volume was accurate on 94% of the trials in which the swallow was accurately detected.

Conclusions: This novel, automated, and real-time RST software successfully detected the onset of the swallow, respiratory phase, and lung volume at swallow onset and provided appropriate real-time performance feedback with a high degree of accuracy in healthy adults. The software has the potential to improve the accessibility, efficiency, and translation of RST to diverse patient populations.

Breathing and swallowing must be coordinated to ensure safe respiratory gas exchange and prevent tracheal aspiration of foods and liquids (Charbonneau et al., 2005; Hiss et al., 2001; Hopkins-Rossabi et al., 2019; Martin et al., 1994; Martin-Harris et al., 2005, 2003; McFarland & Lund, 1995; Nilsson et al., 1997; Nishino

et al., 1985; Palmer & Hiemae, 2003; Paydarfar et al., 1995; Perlman et al., 2005; Preiksaitis et al., 1992; Preiksaitis & Mills, 1996; Selley et al., 1989; Smith et al., 1989). A predominant pattern of swallowing during expiration (77%) has been established for single sips of liquids in healthy adults (Hopkins-Rossabi et al., 2019). In addition, McFarland et al. (2016) found that, in healthy adults, swallow onset typically occurred at a restricted range of lung volume. Therefore, the optimal pattern of swallowing during expiration at mid-to-low lung volume, relative to resting expiratory level, is the most typical pattern in healthy adults and has been shown to have important mechanical advantages such as facilitating movements required for laryngeal

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elevation to ensure airway protection and pharyngeal clearance (Charbonneau et al., 2005; Martin et al., 1994; Martin-Harris, 2008; Martin-Harris et al., 2005; McFarland et al., 2016). Dysphagic patient populations, such as patients with oropharyngeal head and neck cancer, with respiratory–swallow discoordination have an increased risk of aspiration and physiological swallow impairment (Brodsky et al., 2010). Targeting this cross-system discoordination directly through respiratory–swallow training (RST), an intervention that retrains the use of this optimal pattern, was shown to both decrease the risk of airway penetration and improve key components of swallowing impairment (Martin-Harris et al., 2015).

Refinements of the RST Methods

RST is an innovative treatment program developed and tested by Martin-Harris and McFarland to train respiratory–swallow coordination, specifically to initiate swallowing during the expiratory phase of respiration at mid-to-low lung volume relative to resting expiratory level (Martin-Harris et al., 2015). Respiratory phase, lung volume, and swallow onset are recorded using respiratory inductance plethysmography and a nasal cannula connected to a pressure transducer (Martin-Harris et al., 2015). A graphic display of the patient's own respiration is provided as the patient is trained to initiate swallowing during expiration at the target mid-to-low lung volume. Chest and abdominal kinematic data (using inductance bands) combined with nasal pressure data (using pressure sensors) are acquired to record respiratory phase and lung volume. Accuracy of swallow detection is analyzed both manually during training and then offline to confirm swallowing at the trained target. The current investigation proposes to improve the RST method by automating the analysis of the patient's performance with the long-term goal of eliminating the manual analysis, improving the accuracy of swallow detection, and improving the accuracy of correct identification of respiratory phase and estimated lung volume at swallow onset.

An automated software program has been developed in our laboratory (Swallowing Cross-System Collaborative, Northwestern University), in conjunction with BIOPAC Systems, Inc., to automatically detect the respiratory phase and estimated lung volume at swallow onset during RST to provide real-time performance feedback to the patient and the clinician. We tested this novel software on young, healthy adults to ensure the software was unambiguously and accurately detecting swallow onset, respiratory phase, and lung volume prior to testing patients with swallowing disorders who are more likely to have aberrant or complex respiratory–swallow patterns.

Method

Institutional Review Board Approval

The Northwestern University Institutional Review Board approved this study by default as “Not Human

Research Determination.” A complete study proposal was submitted and reviewed by the board prior to the enrollment of any participants. All participants gave written informed consent prior to any study trials.

Participants

Healthy adults ($N = 30$, 23 women and seven men; $M_{\text{age}} = 24.9$ years, range: 18–31 years) were recruited from Northwestern University. All participants reported no history of dysphagia or respiratory disease. Individual forced vital capacity (FVC) testing was performed by spirometry using the Pentax Medical Phonatory Aerodynamic System (Model 6600). The standard method was completed using three maneuvers and taking the best effort to acquire the first second of forced expiration/FVC ratio (Miller et al., 2005). All participants had first second of forced expiration/FVC greater than 70% indicative of no obstructive disorder (van Loghum, 2011).

Thirty participants were tested to determine the most reliable and accurate criteria for swallow detection in the software program. The swallow detection criteria for the first group of participants, Group 1 ($n = 10$), were based on pilot data in five healthy adults. The swallow detection criteria for Group 2 ($n = 20$), the next 20 participants, were based on analysis of the software program's performance with Group 1 participants.

Equipment

Respiratory inductive plethysmography, via an Inductotrace system (Ambulatory Monitoring, Inc.), was used to measure respiratory movements. Inductance bands, sized to the participant, were placed around the rib cage (RC) at the midsternal level and abdomen (AB) at the level of the umbilicus and below the lowest rib to record displacement detected by a change in the voltage of the transducers at RC and AB, known to represent changes in lung volume during respiration (Banzett et al., 1995). Nasal pressure, a surrogate for airflow (Heitman et al., 2002), was monitored using a standard, 7-ft nasal cannula (Comfort Soft Plus, Westmed) connected to a pressure transducer (Model TSD160A, differential pressure = 2.5 cm H₂O) and a differential amplifier (DA100C, BIOPAC Systems, Inc.; see Figure 1). All signals were acquired at 2000 Hz and processed with AcqKnowledge software (BIOPAC Systems, Inc.). The output of each inductance band was low-pass filtered (15-Hz cutoff) and smoothed with a moving average (30 samples). All participants were visually recorded during the training trials with the onboard laptop camera (Lenovo Thinkpad). All data were time-synchronized in AcqKnowledge software (BIOPAC Systems, Inc.).

Software Calibration and RST Templates

The software program was designed to facilitate data collection with three task templates. The first template, “lung volume calibration,” recorded RC and AB movements in volts while a participant breathed in and out (five

Figure 1. Participant with inductance bands, nasal cannula. Participants wore thin shirts during actual data acquisition.

to six full breaths) from the mouth into a Spirobag, a sealed bag with a standardized (800-ml) volume (AMI). The second template, “tidal volume,” recorded RC and AB movements during three to five quiet resting breathing measured in volts. The two signals (RC and AB) were then combined using the standard ratio of 2 (RC):1 (AB) to weight the signals (originally recorded at an equal gain) based on validated methods developed by Banzett et al. (1995). Using the lung volume calibration data collected from the Spirobag and tidal volume trials, the software calculated the range of resting tidal lung volume and the midpoint (50%) of the resting tidal lung volume range in milliliters. Finally, the third template, “training,” displayed the real-time estimated lung volume signal of the participant’s respiration overlaid with a visual cue (a blue line) bisecting the respiratory signal at midpoint of the participant’s resting tidal volume (see Figure 2). This midpoint (50%) of the participant’s rest breathing provided a visual cue for the participant to swallow at or below the midpoint to target swallow onset at the optimal mid-to-low resting tidal lung volume range.

Procedure

All participants were seated upright in a chair and encouraged to maintain an erect posture throughout data acquisition. Instructions were to swallow during expiration at approximately the midpoint of their resting tidal lung volume during swallowing trials. Ten training trials each of 5-, 10-, or 20-ml boluses of volumes of water at room temperature were planned for each participant. Premeasured volumes were self-administered from a 236.6-ml (8-oz) plastic cup. Participants were instructed to hold the liquid in their mouth and return their hand and cup to the tabletop

prior to the swallow to limit movement artifacts in the data. Although in the previous investigation of RST patients were not instructed to hold the bolus, we wished to control the timing of the onset of the swallow in this project to ensure unequivocal swallow detection. The onset of each swallow was also manually annotated with an event marker by the investigator for comparison to the automated data analysis.

Software Program Signal Analysis

The primary goal of the software program was to identify the swallow onset, then identify the respiratory phase and lung volume at this onset of each accurately detected swallow, and provide immediate real-time performance feedback about whether or not the swallow occurred during the optimal respiratory phase (expiration) and optimal lung volume range ($\leq 50\%$ of the resting tidal lung volume).

Swallow Onset

The software was programmed to use the respiratory pause (time interval of minimal airflow) in the nasal pressure signal for accurate swallow detection because past experiments have shown this pause to be a consistent and reliable marker of a swallow event (Martin-Harris et al., 2015, 2000; McFarland et al., 2016; Nilsson et al., 1997; Preiksaitis et al., 1992; Selley et al., 1989). Two nasal pressure signal thresholds were used for swallow detection. The threshold for Group 1, based on data from pilot testing in our lab, was a minimal nasal pressure ($< \pm 0.10$ cm H₂O) maintained for a 0.4-s duration. The threshold for Group 2, based on the analysis of Group 1 swallow detection, was a minimal nasal pressure ($< \pm 0.015$ cm H₂O) maintained for a 0.4-s duration. The range of air pressure during the pause in the nasal signal may vary between participants due to individual differences in the participants’ anatomy, breathing patterns, and electronic noise in the signal (see Figure 3).

Respiratory Phase

The software detected the phase of respiration by determining the slope of the estimated lung volume signal at the onset of the swallow in real time during training trials (after 15-Hz low-pass filtering). However, to confirm that the automated software program correctly identified the respiratory phase, the data were manually analyzed after the trials. Manual analysis used two criteria to determine respiratory phase. Nasal pressure greater than ± 0.028 cm H₂O and a lung volume signal slope of ± 30 ml/s were used to confirm inspiratory or expiratory phase (see Figures 4 and 5). The nasal pressures during all of the swallow pauses did not exceed 0.027 cm H₂O in any of the swallows recorded (see Figure 3 and Table 1). As such, the nasal pressure criterion above ± 0.028 cm H₂O was determined to represent unambiguous airflow associated with true respiratory activity (negative values for inspiration and positive values for expiration). Lung volume signal sections that corresponded to unambiguous airflow were extracted and analyzed using MATLAB (MATLAB and Statistics Toolbox 8.1, The

Figure 2. y-axis: estimated lung volume; x-axis: time (s). A visual cue (a blue line) bisecting the respiratory signal at midpoint of the participant's resting breath volume. This midpoint (50%) provides a visual cue for the participant to swallow at or below midpoint of the resting breath volume.

Figure 3. y-axis: estimated lung volume; x-axis: time (s). Individual variability in the range of centimeters of water during the pause in the nasal signal. (a) The pause or cessation of airflow in the nasal signal during the swallow. (b) The variability of the nasal pressure signal during the pause. (c) The swallow noninspiratory.

Figure 4. Determine the respiratory phase after the swallow (1, blue shaded area) met the criterion of > 10.0301 cm H₂O and > 1301 -ml/s slope.

MathWorks, Inc.). A slope of ± 30 ml/s in the lung volume signal was determined to represent true inspiratory or expiratory activity. Using these criteria, the accuracy of the software program's analysis of respiratory phase could then be confirmed. It should be noted that the analysis of the range of pressure in the nasal excluded the offset of the characteristic swallow noninspiratory pressure observed just after the

end of the respiratory pause (Brodsky et al., 2012; Paydarfar et al., 1995; see Figure 3).

Lung Volume

Based on the respiratory inductance plethysmography signal data collected during the lung volume calibration (Spirobag) task and the tidal volume task, the midpoint of

Figure 5. Upper graph: nasal pressure (cm H₂O). Lower graph: lung volume (ml). The respiratory phase before and after the swallow is easily confirmed by visual inspection. The swallow is (1) preceded and (2) followed by a positive value in the nasal pressure signal before and after the swallow.

Table 1. Nasal variability in participants.

Group	Nasal minimum (cm H ₂ O)	Nasal maximum (cm H ₂ O)	Maximum absolute value of cm H ₂ O
Group 1			
KA (F)	-0.009	0.009	0.009
AH (F)	-0.017	0.015	0.017
MA (F)	-0.009	0.009	0.009
AC (M)	-0.025	0.023	0.025
KP (F)	-0.009	0.009	0.009
PV (F)	-0.009	0.009	0.009
KW (F)	-0.009	0.010	0.010
MF (M)	-0.027	0.009	0.027
ME (F)	-0.023	0.017	0.023
MD (F)	-0.016	0.026	0.026
Group 2			
JK (M)	-0.014	0.012	0.014
KJ (F)	-0.013	0.014	0.014
UW (F)	-0.014	0.005	0.014
MT (M)	-0.014	0.014	0.014
SB (F)	-0.014	0.014	0.014
MC (F)	-0.014	0.013	0.014
SS (F)	-0.012	0.013	0.013
KB (F)	-0.012	0.014	0.014
CH (F)	-0.016	0.017	0.017
JK (F)	-0.015	0.013	0.015
MM (F)	-0.014	0.019	0.019
AB (F)	-0.013	0.012	0.013
AT (M)	-0.012	0.014	0.014
TDO (M)	-0.011	0.010	0.011
CP (F)	-0.016	0.014	0.016
KG (F)	-0.012	0.009	0.012
SS (F)	-0.014	0.013	0.014
LR (F)	-0.010	0.014	0.014
BC (F)	-0.015	0.013	0.015
AB (M)	-0.015	0.014	0.015

estimated resting tidal lung volume was calculated (in voltage and converted to milliliters). The program determined if the lung volume signal at swallow onset was above or below this midpoint.

Performance Feedback

Based on the software program's analysis of respiratory phase and lung volume, the word "Correct" was displayed on the computer screen if swallow occurred at mid-to-low tidal volume. The words "Lungs too full" were displayed on the screen if swallow onset occurred above midpoint in the lung volume signal. The word "Inhaling" was displayed if swallow onset occurred during inspiration (lung volume slope was positive). In cases on which no swallow was produced by the participant, the word "Missed" was displayed (see Figure 6).

Accuracy of the Software

Swallow Onset

The percentage of trials for which the program correctly detected swallow onset was compared to the standard method, off-line manual annotation by the examiner (see Figure 6). Percent accuracy of the software program's swallow detection to the manual annotation of the swallow

was also compared between Groups 1 and 2 to determine which threshold criterion (group) had the highest accuracy of swallow detection.

Statistical Analysis

Swallow Onset

A two-tailed *t* test (released 2017, IBM SPSS Statistics for Windows, Version 25.0, IBM Corp.) was used to test for differences in the accurate detection of onset of the swallow at each pressure threshold criterion: nasal pressure of less than ± 0.010 cm H₂O (Group 1) and nasal pressure of less than ± 0.015 cm H₂O (Group 2). The effect size to determine the statistical difference between the swallow detection rate in the two groups was calculated using a Hedges's *g* test, the recommended method when using a sample size $n < 20$ (Hedges, 1981).

Respiratory Phase

The respiratory phase at the onset of the swallow was confirmed off-line using the established criteria (expiration and inspiration of < 0.028 cm H₂O in the nasal signal and a slope of < 30 ml/s in the lung volume signal) and then compared to the result of the software program's analysis.

Figure 6. Upper graph: nasal pressure (cm H₂O). Lower graph: lung volume (ml). Swallow detection and performance feedback: The swallow is annotated by the blue event marker (1). The automated program correctly detected the onset of the swallow ("Correct" and star; 2) during exhalation at a mid-to-low tidal volume.

Table 2. Software program accuracy.

Group	Age (years)	Correct detection of swallow onset	Correct performance feedback
Group 1			
KA (F)	23	70% (21/30)	100% (21/21)
AH (F)	27	41% (12/29)	92% (11/12)
MA (F)	31	100% (30/30)	97% (29/30)
AC (M)	23	80% (24/30)	79% (19/24)
KP (F)	25	37% (11/30)	100% (11/11)
PV (F)	18	83% (24/29)	83% (20/24)
KW (F)	27	97% (29/30)	100% (29/29)
MF (M)	28	87% (26/30)	100% (26/26)
ME (F)	23	50% (15/30)	60% (9/15)
MD (F)	22	70% (21/30)	100% (21/21)
Group 2			
JK (M)	25	70% (21/30)	76% (16/21)
KJ (F)	22	80% (24/30)	13% (3/24)
UW (F)	28	100% (30/30)	100% (30/30)
MT (M)	30	100% (30/30)	100% (30/30)
SB (F)	23	97% (31/32)	97% (30/31)
MC (F)	22	97% (28/29)	100% (29/29)
SS (F)	22	100% (30/30)	100% (30/30)
KB (F)	22	100% (30/30)	100% (30/30)
CH (F)	23	63% (19/30)	100% (19/19)
JK (F)	31	97% (29/30)	97% (28/29)
MM (F)	22	97% (29/30)	100% (29/29)
AB (F)	22	87% (26/30)	100% (29/29)
AT (M)	31	100% (30/30)	100% (26/26)
TDO (M)	23	92% (23/25)	100% (30/30)
CP (F)	26	84% (16/19)	94% (15/16)
KG (F)	23	97% (29/30)	100% (29/29)
SS (F)	22	73% (19/26)	100% (19/19)
LR (F)	23	96% (27/28)	100% (27/27)
BC (F)	29	90% (26/29)	100% (26/26)
AB (M)	29	97% (28/29)	100% (28/28)

Table 3. Group statistics for swallow detection.

Groups 1 and 2	<i>n</i>	<i>M</i>	<i>SD</i>	<i>SEM</i>
0.010 threshold	10	71.5000	22.34701	7.06675
0.015 threshold	20	90.8500	11.19810	2.50397

Lung Volume

To confirm the accuracy of the target mid-to-low lung volume range ($\leq 50\%$), the peak-to-peak lung volume of the resting breaths recorded during the quiet breathing task was compared to the resting breath volume calculated by the automated software program. The calculated lung volume value at the onset of the swallow was confirmed by manually reviewing the recorded milliliters and voltage at the onset of the swallow.

Results

Accuracy of Automated Swallow Onset Detection

A total of 874 swallow trials were analyzed. All bolus volumes trials were combined for analysis. Not all participants completed the full 30 trials due to missed counts during data acquisition. Swallow onset was accurately detected (nasal pressure: ± 0.010 cm H₂O for 0.4 s) in 71% (213 of 298) of the swallow trials for Group 1 participants ($n = 10$, eight women and two men; $M_{\text{age}} = 24.7$ years, range: 18–28 years) and accurately detected (nasal pressure: ± 0.015 cm H₂O for 0.4 s) in 91% (525 of 576) of swallowing trials for Group 2 ($n = 20$, 15 women and five men; $M_{\text{age}} = 24.9$ years, range: 22–31 years). The pause segments of the nasal pressure signals ranged from ± 0.027 to 0.026 cm H₂O, and only 1% of the pressure values were above 0.015 cm H₂O (see Table 1). The mean duration of the pause was 0.579 s, with an *SD* of 0.155 s (see Table 2). Swallow detection accuracy was significantly higher ($M = 91\%$, *SD* = 12%) for Group 2 as compared to Group 1 ($M = 71\%$, *SD* = 22% ; $p = .012$). An effect size of 1.2 was calculated using Hedges's *g*, and an effect size greater than 0.8 suggests a large effect (see Tables 3–5; Hedges, 1981).

Swallow detection errors on 29% of the swallowing trials (85 of 298) in Group 1 were characterized by (a) the participants holding their breath (a cessation of respiration) prior to the swallow (48%, 41 of 85 trials), (b) nasal pressure being above the established 0.010 –cm H₂O

threshold on 42% (36 of 85) of the trials, (c) the duration of the respiratory pause being less than the duration threshold (0.4 s) on 8% (7 of 85) of the trials (all of these occurred in one participant), or (d) one trial containing an eructation. Detection errors in Group 2 were characterized by (a) prolonged breath holding prior to the swallow on 73% (37 of 51) of the trials or (b) the nasal pressure exceeding the 0.015 -cm H₂O threshold on 25% (13 of 51) of the trials.

Accuracy of Automated Respiratory Phase

The accurate identification of respiratory phase for the swallows that were accurately detected was 87%.

Accuracy of Automated Lung Volume

Accurate detection of estimated lung volume for accurately detected swallows was 100%.

Accuracy of Automated Performance Feedback

Accurate performance feedback was 94% (692 of 738). The trials that were accurately labeled “Correct” by the automated program met both criteria (the swallow onset during expiration and estimated lung volume at $\leq 50\%$ below resting breath on all of the trials). The trials that were labeled “Lungs too full” were accurate on 100% of the trials. Five trials gave incorrect feedback, “Inhaling,” because the program confused inhalation with participant movement. The trials that were labeled “Missed” were all trials in which the nasal pressures exceeded the threshold criteria.

Discussion

The aim of this investigation was to determine if a real-time automated software program could accurately detect the onset of the swallow, respiratory phase, and lung volume at swallow initiation and provide accurate real-time performance feedback on respiration and swallowing when compared to the standard off-line manual analysis.

The program correctly detected swallow onset and provided accurate performance feedback on greater than 90% of the swallowing trials. After adjustment in the threshold parameters based on Group 1 results, a significant improvement in swallow detection was observed in Group 2 (91% vs. 71%, $p = .012$). The majority of the errors in

Table 4. Independent samples test.

Condition	Levene's test for equality of variances		T test for equality of means						
	<i>F</i>	Sig.	<i>t</i>	<i>df</i>	Sig. (two-tailed)	Mean difference	<i>SE</i> difference	95% confidence interval of the difference	
								Lower	Upper
Equal variances assumed	7.241	.012	–3.188	28	.004	–19.35000	6.06971	–31.78323	–6.91677
Equal variances not assumed			–2.581	11.317	.025	–19.35000	7.49725	–35.79507	–2.90493

Table 5. Effect size: Hedges's *g*.

Statistic	0.010 threshold	0.015 threshold
<i>M</i>	71.5	90.85
<i>SD</i>	22.34701	11.1981
<i>N</i>	10	20
Cohen's <i>d</i>	1.09478848	
Hedges's <i>g</i>	1.20132257	

detection for both groups was related to the prolonged breath holding prior to the onset of swallowing because a pause in respiration in the nasal pressure signal also fits the program's criterion for detecting the onset of a swallow. The second most common reason for inaccurate swallow detection was that the nasal pressure during the pause exceeded the set threshold. The reduction in the frequency of this error and hence detection accuracy between Groups 1 and 2 were the direct result of increasing the threshold for the nasal pressure from 0.010 to 0.015 cm H₂O.

The program's calculated lung volume at swallow onset consistently matched the automated feedback provided to the healthy participants in this study. As such, accurate real-time visual performance feedback has high potential to augment RST in patients with swallowing impairment. The real-time performance analysis allows both the clinician and the patient to see the assessment of performance at the end of each trial and a summary of the performance for all trials in each session is produced. The RST protocol requires the patient to meet a threshold of 90% of swallows initiated during expiration at mid-to-low lung volume. In the current administration of the training, the patient's performance is manually assessed by the clinician, who then determines if the patient has met the threshold performance criteria prior to proceeding with additional trials. With automated real-time analysis, the patient can be advanced through training trials without the previously required delays to analyze the patient's performance.

This current investigation conducted all training trials with healthy adults without respiratory disorders or swallowing impairment. Current work in our laboratory includes ongoing refinement of the software program for use with patients with dysphagia who have more variable respiratory–swallow breathing patterns and postural instability as well as swallowing impairments that result in difficulty maintaining a bolus within the oral cavity or clearing ingested material on a single swallow, an issue that contributes to ambiguity in both respiratory and swallowing signals.

Conclusions

A real-time automated software program for the detection of swallow onset, respiratory phase, lung volume range, and performance feedback has been developed and demonstrates a strong potential for augmenting the current RST. The planned application of the software for clinical use and home practice will be tested in future studies

to determine if these features can further improve RST outcomes.

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