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The effects of feedback on volitional manipulation of airway protection during swallowing

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Abstract

Volitional control of autonomic responses, such as heart rate and blood pressure, can be facilitated with the use of augmented feedback. Oropharyngeal swallowing typically includes both volitional and reflexive components, offering a unique opportunity for observing how performance is affected by feedback. Sixteen healthy participants (mean 44 years) completed multiple trials of a novel airway closure technique during swallowing under one of two conditions: 'no feedback' or 'feedback'. The feedback condition included knowledge of performance and knowledge of results. Only the feedback group improved performance across trials ($p = 0.01$), with no difference from baseline seen for the no feedback group ($p = 0.66$). These results show that airway closure during swallowing can be volitionally manipulated with augmented feedback.

Keywords

Augmented feedback; volition; reflex; swallowing; performance

Introduction

An extensive evidence base exists for the role of feedback in motor learning. Much of this literature utilizes voluntary limb movements to demonstrate the effects of augmented feedback (see van Dijk, Jannink, & Hermens, 2005 and; van Vliet & Wulf, 2006 for a review). Augmented feedback involves the use of an external source to supplement task-intrinsic feedback (van Dijk, Jannink, & Hermens, 2005). Interestingly, such feedback can also be used to volitionally override autonomic responses, such as heart rate and blood pressure (Schwartz, Shapiro, & Tursky, 1971; Shapiro, Tursky, Gershon, & Stern, 1969; Shapiro, Tursky, & Schwartz, 1970a, 1970b), and reflexes, such as the H-reflex (Manella, Roach, & Field-Fote, 2013; Thompson, Chen, & Wolpaw, 2009, 2013). When augmented feedback is provided regarding accuracy and goal attainment, subjects demonstrate the ability to alter heart rate and blood pressure separately (Shapiro et al., 1969; Shapiro, Tursky, & Schwartz, 1970a, 1970b), as well as in tandem (Schwartz, Shapiro, & Tursky, 1971). Although these autonomic functions normally occur without intrinsic visual feedback, augmented feedback appears to be crucial for guiding volitional manipulation of these tasks.

Oropharyngeal swallowing offers a unique opportunity for observing how performance is affected by feedback. As swallowing occurs within the enclosed space of the oropharynx, intrinsic feedback is limited, like many autonomic functions. Additionally, oropharyngeal swallowing typically includes both volitional (e.g., chewing or food preparation during the oral phase) and reflexive components (e.g., pharyngeal contraction and airway closure during the pharyngeal phase) (Ertekin, 2011; Humbert & German, 2013). Similar to autonomic functions mentioned above, the pharyngeal response is amenable to volitional override (Hind, Nicosia, Roecker, Carnes, & Robbins, 2001; Kahrilas, Logemann, Krugler, & Flanagan, 1991). As with heart rate, blood pressure, and other tasks not visible during execution, augmented feedback likely plays a crucial role in adapting the motor plan for volitional swallowing maneuvers.

When assessing the merit of various forms of augmented feedback in guiding motor performance, it is important to consider the information required for successful completion of a task. Augmented feedback discussed in the context of motor performance is categorized by whether it provides information on performance (knowledge of performance, or KP) or outcomes (knowledge of results, or KR) (Wulf, Shea, & Lewthwaite, 2010). KP provides information about the movement patterns being executed (Gentile, 1972; Salmoni, Schmidt, & Walter, 1984; Schmidt & Young, 1991), and is also known as kinetic or kinematic (Salmoni, Schmidt, & Walter, 1984; Schmidt & Young, 1991). An example of KP verbal feedback might be “your arm needs to stay closer to your body”. KR provides information regarding the level of goal attainment (Gentile, 1972). An example of KR might be “you missed the target”. KR is typically verbal and terminal (Salmoni, Schmidt, & Walter, 1984), whereas KP by nature can be more variable in presentation (Schmidt & Young, 1991). In physical therapy settings, KR is typically considered to convey redundant information, in that it augments the intrinsic visual feedback that the performer has about the outcome of the movement (Schmidt & Young, 1991). However, KR has proven a crucial component of feedback for gaining volitional control over tasks for which intrinsic visual feedback is not available (Manella, Roach, & Field-Fote, 2013; Schwartz, Shapiro, & Tursky, 1971; Thompson, Chen, & Wolpaw, 2009, 2013). Determining the crucial components of the movement provides insight into the type of feedback required to facilitate performance (Thorpe & Valvano, 2002). When intrinsic feedback is limited (i.e., non-visible tasks) or difficult to interpret, the requirements critical to task performance need highlighting through augmented feedback (Lawrence, Kingston, & Gottwald, 2013). Therefore, to facilitate the required movements of a complex non-visible task, such as swallowing, it is likely that a combination of KP and KR feedback is required.

During oropharyngeal swallowing, the characteristics of the patterned pharyngeal response are largely predicated on the sensory properties of the bolus being ingested. For example, duration of upper esophageal sphincter (UES) opening (Hoffman, Ciucci, Mielens, Jiang, & McCulloch, 2010) increases with bolus volume; laryngeal vestibule closure (LVC) duration increases with the time the bolus remains in the pharynx (Power, Hamdy, Singh, Tyrrell, Turnbull, & Thompson, 2007), and bolus volume (Logemann et al., 1992); and the duration of pharyngeal clearance increases with greater viscosity (Cassiani, Santos, Parreira, & Dantas, 2011). Research has shown that as well as being modified by sensory inputs, various pharyngeal events can be altered as a by-product of volitional maneuvers. Such changes include pharyngeal clearance pressures (Boden, Hallgren, & Witt Hedstrom, 2006; Bulow, Olsson, & Ekberg, 1999; Hind et al., 2001; Hiss & Huckabee, 2005; Huckabee, Butler, Barclay, & Jit, 2005; Huckabee & Steele, 2006; Ohmae, Sugiura, & Matumura, 2000; Steele & Huckabee, 2007; Witte, Huckabee, Doeltgen, Gumbley, & Robb, 2008), UES opening (Kahrilas et al., 1991; Regan, Walshe, Rommel, & McMahon, 2013), and laryngeal vestibule closure (Hind et al., 2001). Despite the knowledge that volitional maneuvers incidentally result in adaptations to components of swallowing that are largely brainstem

mediated, it is unknown whether any one of these components can be volitionally manipulated through direct instruction and feedback. Additionally, it is unclear what factors can influence the characteristics of these modifications. It may be the case that augmented feedback can facilitate varied modifications of these events. If so, then direct volitional control of these events may prove useful in the case of sensory deficits, when these events are less responsive to the sensory characteristics of a bolus.

This study aimed to elucidate the effects of KP and KR augmented feedback on performance of a volitional swallowing maneuver. No previous studies have tested whether specific components of the pharyngeal swallow response can be volitionally manipulated with direct instruction and feedback. Furthermore, the effects of augmented feedback on varying the characteristics of pharyngeal swallowing components have never been tested. This information will provide insight into the effects of instruction and feedback on subsequent pre-motor planning and improvement of a novel swallowing task.

Methods

Participants

16 healthy adults (mean age: 44 years, range 18 – 49; 8 male) were recruited for this study. Participants reported a negative history of swallowing, speech, and voice problems, as well as neurological disease. Procedures were approved by the appropriate institutional review board. All participants signed written informed consent. Data were collected by 2 of the authors.

Procedures

Study design—All participants performed a swallowing task a total of 8 times in the following order: (1) baseline saliva trial; (2) six performance saliva trials, then; (3) one water trial. The purpose of the water trial at the end of the session was to determine whether feedback impacts how task performance generalizes to a new swallowing context. (Study design, Figure 1).

The task—The participants were expected to perform a volitional laryngeal vestibule closure (vLVC) maneuver. The maneuver begins with a swallow and involves volitionally prolonging LVC for at least 2 seconds. LVC greater than 2 seconds was selected as it reflects volitional control, given that LVC averages in natural swallowing conditions (i.e., swallowing without a therapeutic technique) range from 0.48 – 0.61 s (± 0.02 - ± 0.06 SE) (Logemann et al., 1992). The maneuver is similar to a commonly used therapeutic swallowing maneuver called the Mendelsohn maneuver. However, the vLVC maneuver has several important differences that warrant it being classified as a distinct maneuver, rather than a modification of the Mendelsohn maneuver. The first difference is the goal of the maneuver. The Mendelsohn maneuver was designed (Kahrilas et al., 1991; Logemann & Kahrilas, 1990), and is currently used clinically for augmenting opening of the upper esophageal sphincter (UES) (McCullough, Kamarunas, Mann, Schmidley, Robbins, & Crary, 2012; McCullough & Kim, 2013). The maneuver was developed based on Mendelsohn's work showing the importance of laryngeal elevation in providing traction force on the cricoid cartilage in facilitating UES opening (Mendelsohn & McConnel, 1987). Conversely, the vLVC maneuver described here is designed to facilitate laryngeal vestibule closure. Influencing UES opening is optimal to facilitate passageway of the bolus through the pharynx. Alternatively, influencing laryngeal vestibule closure is optimal for ensuring airway protection during swallowing. Secondly, instructions for the Mendelsohn maneuver involves telling participants to volitionally prolong laryngeal elevation at the peak of the swallow (Boden, Hallgren, & Witt Hedstrom, 2006; Ding, Larson, Logemann, &

Rademaker, 2002; Kahrilas et al., 1991; McCullough et al., 2012; McCullough & Kim, 2013). Conversely, the vLVC maneuver instructs patients to volitionally prolong the closure of the laryngeal vestibule that is achieved during a swallow. We instruct patients to hold their adam's apple up as high and as long as they can, like the Mendelsohn maneuver. However, unlike the Mendelsohn maneuver, maintaining this elevation in isolation is not sufficient. Lastly, The Mendelsohn maneuver uses volition to prolong laryngeal elevation. The anticipated effect is that it will have indirect effects on UES opening. Therefore, the target physiologic event (UES opening) is influenced through volitional control over a different physiologic event (laryngeal elevation). The vLVC maneuver involves direct instruction to modify the closure of the laryngeal vestibule. Therefore, volitional control is used to directly control the target outcome. Targeting prolonged LVC allowed us to assess the effect of feedback on subjects' ability to volitionally control a predominantly brainstem mediated swallowing event. The control mechanisms of LVC are considered reflexive in nature when it occurs in the context of airway protection during swallowing. Therefore, our direct instruction was to swallow and hold the thyroid notch up as high and as long as possible, while closing the airway. As an additional cue, participants were told that they should not be able to breathe while performing the task.

Instructing the task and obtaining baseline vLVC performance—Participants were seated upright in view of a monitor displaying real-time videofluoroscopy (VFS). A lateral view still-shot of the participants' oropharyngeal anatomy was used for instructional purposes. Participants were oriented to the oral cavity, the pharynx, and the laryngeal vestibule. They were then instructed to palpate their thyroid notch and observe its movement during a saliva swallow. The still-shot was used to describe laryngeal vestibule closure associated with the previously palpated laryngeal excursion. Participants were directed to attempt successful performance of vLVC while watching real-time VFS. Attention was drawn to the contact between the arytenoid cartilages and the base of the epiglottis. If a small opening occurred between these structures, but elevation of the structures was maintained, this was explained to the participant as it happened. Participants were given a maximum of five attempts to achieve LVC duration of 2 sec or greater. These baseline attempts were completed with saliva and inter-trial intervals determined by the participant (1 minute on average). Verbal feedback was provided immediately during all attempts, concurrently with access to the visual display of the VFS. The first baseline attempt for which the participant achieved LVC closure of at least 2 sec was considered their baseline trial. The average number of baseline attempts required to achieve LVC of at least 2 sec was two, with the range between one and four trials.

Participant groups—On completion of the baseline trial, participants were randomly assigned to one of 2 groups: no feedback group (N = 7; mean age: 27 years, range 18 – 42; 5 male) or feedback group (N = 9; mean age: 30 years, range 20 – 49; 3 male).

Performing the 6 saliva and 1 water vLVC tasks—Participants then performed 7 additional vLVC swallows in their respective groups. All participants were directed to increase their vLVC hold time with each successive trial. Access to the visual VFS display was removed at this point for all participants, but researchers used VFS to provide cues about LVC to the feedback group. VFS was also recorded for offline analysis in all participants. Each participant completed 6 performance saliva vLVC trials to assess changes in performance over trials, then one 5 ml water vLVC trial to assess generalization of the task to a new swallowing context. Participants were told of the water trial only immediately prior to that trial. They were instructed to attempt the same maneuver as previous trials, except a teaspoon amount of water would be swallowed instead of their saliva. They were cued to initiate the water swallow as they were with the saliva swallows, to allow

simultaneous VFS recording. The average inter-trial interval for all 7 post-baseline trials was 90 sec to avoid fatigue.

Feedback

Feedback group: Because successful performance of the vLVC task required kinematic accuracy and goal attainment, the feedback group received both types of feedback: knowledge of performance (kinematic accuracy) and knowledge of results (goal attainment). Each feedback component is described below:

KP feedback: The purpose of KP feedback was to increase awareness about the status of the laryngeal vestibule (either open or closed) during task performance. Participants were told that once they swallowed, a lack of verbal feedback would signify that closure was being maintained. As with the baseline attempts, verbal feedback was provided regarding any change in contact between the base of the epiglottis and the arytenoid cartilages. Participants were advised that they would receive verbal feedback from the researcher, who was monitoring LVC, about the state of the laryngeal vestibule while performing the vLVC task.

KR feedback: The purpose of KR is to provide information about whether the vLVC prolongation goal of successive increases had been reached. During vLVC performance, participants were given an audio cue at the time of their previous best trial. This provided a tangible goal to facilitate increased LVC hold beyond the previous best time (i.e., the audio cue). It also eliminated the need to monitor the time goal, and therefore decreased distractions. For the first saliva vLVC performance, the audio cue was set for the duration of their baseline performance.

No feedback group: No feedback was given on accuracy or duration of hold.

Videofluoroscopy—All swallows were recorded with videofluoroscopy. The goal of the vLVC maneuver was to maintain extended closure of the laryngeal vestibule. Videofluoroscopy is the only imaging method by which the kinematic movements of laryngeal vestibule closure can be confirmed, i.e., other biofeedback modalities, such as surface electromyography and pharyngeal manometry do not provide information on this physiologic mechanism. Therefore, to provide accurate KP and KR feedback the researcher was required to observe and give feedback based on videofluoroscopic data. Videofluoroscopic data were acquired in the sagittal plane at 30 frames per second. From the digital recording, image sequences were viewed in real time on a monitor and exported to an image processing computer system where they were archived for offline analysis. The field of view included the oral cavity, pharynx, laryngeal vestibule, subglottal air column, and upper esophagus, including the upper esophageal sphincter. A simultaneously recorded time-code was used for data analysis.

Data analysis—The recorded VFS file was cropped so each swallow was a single video clip. Each swallow clip was assigned a code for blinded, frame-by-frame analysis by a laboratory technician. Our primary outcome variable was LVC duration, which is defined as duration of contact between the arytenoids and epiglottis base during the swallow (Bisch, Logemann, Rademaker, Kahrilas, & Lazarus, 1994; Logemann et al., 1992; Park, Kim, Ko, & McCullough, 2010; Power, Hamdy, Goulermas, Tyrrell, Turnbull, & Thompson, 2009; Power et al., 2007)

Statistical analysis—Using SPSS (Version 19, IBM SPSS Statistics), linear mixed-effects models (Gelman & Hill, 2007) were used to estimate the effect of feedback group on

LVC across performance trials. The 6 saliva vLVC practice trials compared with baseline were assessed with one model (to assess improvements in performance), and the water vLVC compared with baseline was assessed with another (to assess generalization to a new swallowing context). There was a fixed effect of trial, feedback group, and trial within feedback group, with the intercept and effects of each allowed to vary between participants. Trial was included as a covariate. Confidence intervals were calculated for the estimated effects to indicate the degree of uncertainty in the estimation of the parameters. If the interaction effect of feedback group by trial was significant, the regression coefficient estimates produced by the model were used to assess the fixed effects of feedback group in improvement across trials. Statistical analyses were performed on the raw data (LVC sec). Inter-rater reliability (20% of the data) and intra-rater reliability (5% of the data) were analyzed using single-measure intraclass correlation coefficients (ICCs) with an absolute agreement definition.

Results

Inter- and intra-rater reliability

Inter-rater and intra-rater reliability showed excellent agreement with an ICC of 1.000 for each measure.

Saliva vLVC performance trials

There was a significant interaction effect of group by trial ($p = 0.014$). Estimates of fixed effects showed that the feedback group changed significantly ($p = <0.014$) across saliva performance trials (see Table 1). The estimated change was an increase in LVC of 1.94 sec (95% CI = .40, 3.45) per trial. There was no evidence that the no feedback group either increased or decreased their LVC duration across practice trials compared with baseline (Table 1). Group means and confidence intervals for each are shown in Figure 1, expressed as a percentage change from baseline.

Water vLVC trial

There was no significant effect of trial ($p = 0.132$) or interaction effect of group by trial ($p = 0.217$), suggesting neither groups increased or decreased their LVC duration for the water vLVC trial compared with baseline (Table 1). Group means and confidence intervals for each are shown in Figure 1 expressed as a percentage change from baseline.

Discussion

This is the first controlled study to assess the effects of augmented feedback on swallowing. This study found that simple, holistic KP feedback combined with KR feedback improves performance of vLVC, as defined by our goals, to a significantly greater extent than when no feedback was given. These results show that airway closure during swallowing can be volitionally manipulated with direct instruction and feedback. It also provides evidence that combining feedback on accuracy and goal attainment can modify the extent of volitional control exerted on reflexive components of the pharyngeal swallow response. These findings have implications for the management of dysphagic patients who present with the physiologic abnormality of impaired laryngeal vestibule closure. The ability of patients to volitionally manipulate LVC through instruction and feedback now requires investigation.

Improvement in the feedback group suggests that a combination of accuracy and timing feedback facilitated successful manipulation of the task. Improved performance of a task is judged along an arbitrarily defined dimension, depending on the goals of the movement, or the goals of the experimenter. For example, we could have defined improved performance as

a reduction in the time taken to close the laryngeal vestibule, rather than the duration of hold once closed. As we defined (and guided participants to achieve) successful vLVC as accurate and progressively longer laryngeal vestibule closure, it stands to reason that augmented feedback on both of these aspects improved performance compared with no feedback. This highlights the importance of defining movement goals, and tailoring instruction and feedback according to these goals. However, to ascertain the contribution of KP and KR feedback separately, a design comparing the two feedback types in isolation to combined KP and KR feedback is required.

Despite improvement across the saliva trials, water vLVC performance did not improve from baseline for the feedback group. Two possibilities may account for this finding. Every trial preceding the water trial was completed with saliva. Therefore, the lack of improvement may reflect a specificity of training phenomenon. Repeating this design and training water vLVC performance instead of saliva would determine whether lack of generalization to saliva swallows would be observed in this circumstance. Unfortunately, due to limitations in VFS time, we were unable to determine whether performance eventually improved across several water vLVC trials following the saliva vLVC training. It is also possible that the ability to exert volitional control over the swallow is decreased by the presence of a bolus. Sensory information responsible for autonomic control may override volitional movements to prioritize swallowing safety. It should be noted that although water vLVC trials did not improve, they maintained the same performance level as baseline saliva vLVC trials for both groups, indicating that some volitional control of airway protection occurred with water vLVC performance. Whether such maintenance of ability exists in patient populations requires exploration.

Although the “no feedback” group did not demonstrate successive improvements, they maintained baseline-level vLVC abilities. This suggests that the feedback provided to achieve the baseline trials (detailed visual KP and verbal KP) was sufficient for maintaining the task at the baseline level, but additional feedback was required to make performance gains. The cascade of events that occur during the pharyngeal phase of swallowing mimics autonomic functions, in that sensory feedback is not incorporated once initiated (Humbert, Lokhande, Christopherson, German, & Stone, 2012). This suggests that pre-movement planning of the swallow was modified during the training period, as laryngeal vestibule closure changes remained for both groups.

This study aimed to assess performance in one training session and, therefore, the effects of augmented feedback on long-term retention remains unknown. Future studies are needed to understand the mechanisms underlying improved retention of trained swallowing behaviors. Such investigations should expand the current design to include multiple water vLVC trials within the training session. Maintenance of skills can then be assessed following a period of non-practice to assess the ability to perform the maneuver without feedback and guidance cues i.e., a transfer test. Additionally, inclusion of regular (non-maneuver) water and saliva swallows before and after vLVC training would allow insight into the carryover of airway manipulation into natural swallowing contexts.

The underlying control mechanisms of vLVC performance are unknown. For instance does vLVC involve modification of swallowing kinematics other than just LVC time (i.e. hyoid and laryngeal range of motion)? Does vLVC require inhibition of hyolaryngeal return to rest position after the swallowing patterned response is complete? Unlike the vLVC results presented here, motor skills typically require several training sessions to develop (Luft & Buitrago, 2005). This suggests that the mechanism responsible for successful vLVC is either inhibition of rest, or selection of an alternative motor plan that is already within the repertoire of swallowing movements. This study did not focus on the mechanisms

responsible for successful acquisition of the maneuver. The average number of trials required by participants to achieve vLVC of >2 sec was two, but ranged from one to four trials. This study controlled for performance of baseline attempts (i.e., maintained closure of > 2 sec), rather than number of baseline attempts required. Investigating differences in performance according to the number of trials required to achieve the maneuver may provide some insight into the mechanisms by which the maneuver is achieved. Additionally, this study did not investigate the differential effects of the components of our feedback group (i.e., KP versus KR effects). This was based on the fact that unlike voluntary limb movements, where KR feedback may be considered redundant (Schmidt & Young, 1991), this information is likely to be crucial in successful execution of a non-visible task, such as swallowing. Such information will further elucidate the nature of the relationship between volition and reflexive components of swallowing, and reveal any advantages of feedback on long-term retention of vLVC.

Conclusion

This study offers novel and interesting information regarding the ability to volitionally isolate and modify components of the reflexive pharyngeal swallowing sequence. The results show that simple feedback aimed at augmenting all necessary components of the task can result in improvements in the ability to vary the modified response. This information offers novel opportunities for studying the interface between volitional control and reflexive behaviors. These findings also have implications for rehabilitative efforts to improve airway protection during swallowing through volitional instruction.

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Results

Figure 1.

Results: LVC duration (and 95% confidence intervals) during baseline and subsequent saliva and water vLVC trials expressed as a percentage change from baseline; and **Study design.**

Estimated baseline means, estimated change per trial across saliva vLVC, and estimated change from baseline to water vLVC. Values are in seconds.

Table 1

	Baseline means			Improvement - saliva			Generalization - water		
	Lower	Estimate	Upper	Lower	Estimate	Upper	Lower	Estimate	Upper
Feedback	4.28	10.356	16.432	0.403	1.927	3.45	-16.497	-6.293	3.912
No Feedback	2.739	9.629	16.518	-1.399	-0.256	0.887	-8.372	-0.719	6.935
						<i>p</i>			<i>p</i>
						0.01			0.22
						0.66			0.85