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Technical Report

Game-Based Augmented Visual Feedback for Enlarging Speech Movements in Parkinson's Disease

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Purpose: The purpose of this pilot study was to demonstrate the effect of augmented visual feedback on acquisition and short-term retention of a relatively simple instruction to increase movement amplitude during speaking tasks in patients with dysarthria due to Parkinson's disease (PD).
Method: Nine patients diagnosed with PD, hypokinetic dysarthria, and impaired speech intelligibility participated in a training program aimed at increasing the size of their articulatory (tongue) movements during sentences. Two sessions were conducted: a baseline and training session, followed by a retention session 48 hr later. At baseline, sentences were produced at normal, loud, and clear speaking conditions. Game-based visual feedback regarding the size of the articulatory working space (AWS) was presented during training.
Results: Eight of nine participants benefited from training, increasing their sentence AWS to a greater degree following feedback as compared with the baseline loud and clear conditions. The majority of participants were able to demonstrate the learned skill at the retention session.
Conclusions: This study demonstrated the feasibility of augmented visual feedback via articulatory kinematics for training movement enlargement in patients with hypokinesia due to PD.
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Parkinson's disease (PD) is the second most common neurodegenerative disease, often resulting in progressive hypokinetic dysarthria and reduced speech intelligibility. The effect of dysarthria on individuals living with PD is substantial, with communication challenges causing social isolation and affecting overall quality of life (Miller, Noble, Jones, & Burn, 2006); yet only 3% to 4% of patients receive speech therapy (Miller, Deane, Jones, Noble, & Gibb, 2011). Furthermore, a relatively limited number of treatment options is available, particularly options that clearly define treatment candidacy (Atkinson-Clement, Sadat, & Pinto, 2015). There is a need for more targeted, individualized treatments to remediate the effects of PD on speech production.

Approximately 45% of patients with PD exhibit significant articulatory deficit as the disease progresses (Logemann, Fisher, Boshes, & Blonsky, 1978). Kinematic studies of oral articulators (e.g., the lips, jaw, and tongue) show a significant effect of the disease on oral movements during speech and speechlike tasks. The most commonly reported speech movement deficit has been hypokinesia, with changes affecting the lips and jaw (Connor, Ludlow, & Schulz, 1989; Darling & Huber, 2011; Forrest & Weismer, 1995; Walsh & Smith, 2012), and the tongue (Weismer, Yunusova, & Bunton, 2012; Yunusova, Weismer, Westbury, & Lindstrom, 2008).

None of the existing interventions target the oral speech movement deficit in PD directly. Amplitude training has been used to overcome hypokinesia and bradykinesia in limb function and in handwriting in PD (Ebersbach et al., 2015; Farley & Koshland, 2005; Nackaerts et al., 2016). The Lee Silverman Voice Treatment—the most well-established treatment approach for the management of hypophonia in PD—presumes that training loudness results in concomitant and

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long-lasting effects on movement amplitude (Farley, Fox, Ramig, & McFarland, 2008). However, empirical evidence of such effects after Lee Silverman Voice Treatment is limited. Research on the effect of loudness manipulations on speech movements shows evidence of increased movement size and velocity of the jaw and lips in speakers with PD (Darling & Huber, 2011; Dromey, 2000), but only limited effect on the tongue (Goozee, Shun, & Murdoch, 2011).

To remediate speech hypokinesia directly, we developed a movement-based treatment framework that provides engaging augmented visual feedback in the form of games. Augmented visual feedback has been successfully used in patients with PD for remediation of parkinsonian gait, writing disturbances, and hypophonia and prosodic abnormalities (Scott & Caird, 1983; Shen & Mak, 2014; Smith & Fucetola, 1995). The rationale for enhancing naturally occurring forms of auditory and proprioceptive feedback through adding a visual modality in PD is motivated by evidence that PD results in a proprioceptive deficit (Klockgether, Borutta, Rapp, Spieker, & Dichgans, 1995; Rickards & Cody, 1997). Instead, patients with PD tend to rely on external cues, particularly visual cues, when processing movement information and learning motor patterns in laboratory and clinical conditions (Adamovich, Berkinblit, Hening, Sage, & Poizner, 2001; Jacobs & Horak, 2006; Vaillancourt, Slifkin, & Newell, 2001). In addition, patients with PD may exhibit cognitive deficit (Caviness et al., 2007). The game design was used to modulate difficulty, provide engagement, and enhance positive reinforcement (Lohse, Shirzad, Verster, Hodges, & Van der Loos, 2013).

The main goal of this proof-of-principle study was to examine whether patients with PD would respond to visual feedback information regarding their articulatory movements and adjust their movement amplitude over the course of training. Previous studies suggested that there might be limitations to the extent of the articulatory movement adjustments in this population (Darling & Huber, 2011; Forrest & Weismer, 1995). Furthermore, the ability to maintain the achieved gain in movement amplitude was tested at a 48-hr retention session. Our main hypothesis is that visual feedback elicits appreciable changes in articulatory kinematics, which would form a foundation for a novel therapeutic intervention.

Method

Participants

Nine participants diagnosed with PD were selected from a larger group (N = 21) recruited for a study of articulatory movements in PD. The primary inclusion criterion for the present study was the clear presence of hypokinetic dysarthria with reduced intelligibility and perceptual deficits in the articulatory domain (i.e., imprecise consonants, distorted vowels, and short rushes of speech). Speech intelligibility was measured using both a clinical Sentence Intelligibility Test (Yorkston, Beukelman, Hakel, & Dorsey, 2007) as well as a scaling method (Yunusova, Weismer, Kent, & Rusche, 2005). A clinical diagnosis of depression or other psychiatric or neurological disorders beyond PD were the exclusion criteria. The performance on a cognitive screener (the Montreal Cognitive Assessment; Nasreddine et al., 2005) was not an exclusion criterion; a range of scores was desirable. Participant demographic and disease-related characteristics are shown in Table 1. The group included seven men and two women between the ages of 57 and 90 years, recruited at various times postdiagnosis. The patients reported to be optimally medicated for both sessions of the study. None reported significant levels of fatigue before the recording sessions as determined by a questionnaire (Fisk & Doble, 2002).

Experimental Setup

Details regarding the hardware and software architecture were presented elsewhere (Shtern, Haworth, Yunusova, Baljko, & Faloutsos, 2012). Briefly, kinematic data were acquired using the Wave Speech Research System (Northern Digital Inc., Waterloo, ON, Canada). The Wave allows tracking speech movements in real time in three dimensions with high accuracy (Berry, 2011). One 6 degree-of-freedom sensor was attached to the head, and one 5 degree-of-freedom sensor was attached to the tongue with nontoxic dental glue (PeriAcryl90, Glustitch, Delta, BC, Canada). The tongue movements were coupled with those of the jaw. The tongue sensor was attached at midline approximately 10 mm from the tongue tip (M = 10.94, SD = 0.94) and tracked at 100 Hz. Kinematic data were postprocessed using MATLAB (MathWorks, 2014). The postprocessing steps included (a) resampling at a uniform rate and (b) low-pass filtering using a fifth-order Butterworth filter at 15 Hz to remove high-frequency noise.

Sensor positions were accessed using the Wave Real Time Application Programming Interface. Wave proxy—a server that allowed remote access to real-time WAVE data via the Wave Real Time Application Programming Interface—was used to communicate between the data collection computer and the visualization computer. The visual feedback was delivered using Unity3D v4.6.5p1 game engine technologies (Unity Technologies Inc., 2015), and a Microsoft SQL Server (Microsoft Inc., 2014) was used for storing the data. The visualizations were delivered on a 24-in. LCD monitor with 24-bit color resolution. The monitor was positioned approximately 140 cm in front of the participant at eye level.

Measurements

In this study, tongue movement size was represented by a measure of the articulatory working space (AWS; see Figure 1), which was previously shown to be sensitive to movement deficit in dysarthria (Weismer et al., 2012). The AWS metric was determined by a convex hull fit around the tongue movement trajectory produced during a sentence using the Matlab function *convhull*. The AWS was calculated as the volume of the convex hull (mm^3).

Table 1. Demographic and clinical characteristics of the participants.

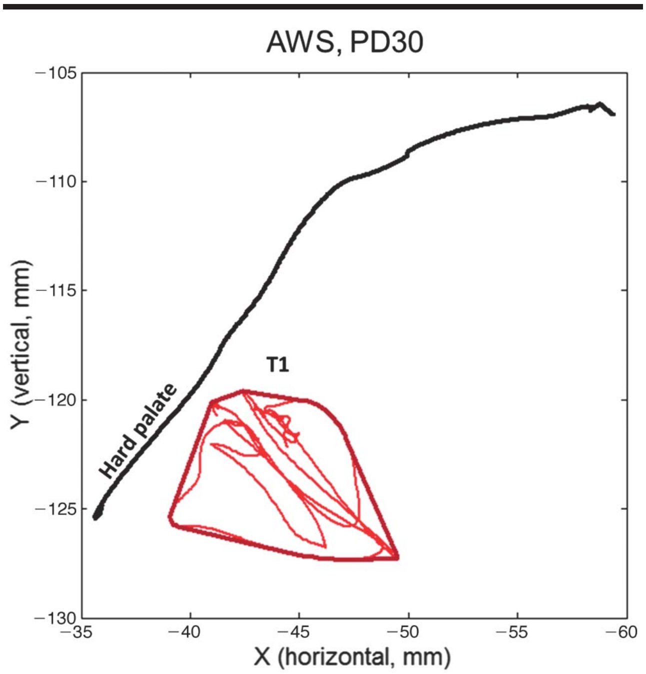
ID	Demographics	Dx (years)	SIT % and Scaled Intelligibility (Z)	MoCA
PD10	F, 57 years	8	93 (–2.2)	29
PD12	M, 63 years	2	96 (–1.2)	26
PD13	F, 78 years	8	91 (–3.5)	29
PD14	M, 90 years	4.5	94 (–0.8)	25
PD18	M, 80 years	11	75 (–3.2)	21
PD20	M, 72 years	3	90 (–4.4)	24
PD25	M, 73 years	2	96 (–1.8)	30
PD27	M, 72 years	3	96 (–1.2)	29
PD30	M, 63 years	4	94 (–2.1)	30

Note. Dx = diagnosed; SIT= Sentence Intelligibility Test; MoCA = Montreal Cognitive Assessment (normal score ≥ 26).

Protocol and Speaking Tasks

The participants attended two sessions: (a) a baseline and training session and (b) a retention session. They produced sentences loaded with lingual consonants: *Shark shook the shabby ship* [sh], *Sean shut the shiny shack* [sh], *Tom towed the tin table* [t], *Todd told the timid tale* [t], and *Super Sue sat sewing* [s, untrained]. At baseline, the sentences were first produced at a normal speaking rate and style and then in loud and clear conditions (three repetitions each), elicited following standard verbal instructions (Tjaden, Sussman, & Wilding, 2014). These recordings served as a reference to document consistency of the measure pretreatment and to descriptively compare the speaking condition to training effects. A training module, which immediately followed the baseline recording, consisted of two training blocks and a recording of an untrained sentence. For each training block, participants produced 15 repetitions of the training sentences [sh, t] with visual feedback, detailed below. Fifteen repetitions of the untrained sentence [s] were practiced without visual feedback after either Block 1 or Block 2. Participants were instructed to produce sentences using large tongue movements while speaking. This instruction was delivered once, at the beginning of the training, and the participants monitored their success using only the game feedback thereafter. The experimenter (second author) did not interfere with the training unless there were some substantial difficulties (e.g., sensor fell off, or initially a patient did not understand the instructions).

Figure 1. Tongue blade (T1) movement trajectories produced by a patient with Parkinson's disease (PD30) during the sentence "Sally sells seven spices" read at a normal speech rate and loudness. The tongue movement trajectory is enclosed by a convex hull, representing the articulatory working space (AWS), and shown relative to the hard palate.



For the training sentences, visual feedback regarding the movement size was delivered immediately after the sentence was spoken and showed how large the movements were and if the latest production was better/bigger than the previous one. We chose a terminal feedback strategy on the basis of studies suggesting that continuous feedback during movement execution may interfere with learning motor skills due to increased cognitive load while processing dual information channels (Ballard et al., 2012; Hodges & Franks, 2001).

Participants had self-control over the selection of the trials on which they chose to see visual feedback. The self-control of visualization trials was chosen over the "forced" feedback option on the basis of the existing literature, which indicates better long-term retention with this training method (Wulf, 2007). Visualizations were presented at a 50% schedule, on the basis of previous studies suggesting that reduced feedback frequency is more beneficial for long-term retention than frequent feedback (Chiviacowsky, Campos, & Domingues, 2010; Wulf & Shea, 2004). A retention session was scheduled 48 hr after training. During this session, a cue was provided to patients to use "larger movements as they were practiced previously." Each sentence was repeated three times during this session.

The feedback was delivered in the form of interactive games. The online supplemental video (see online Supplemental Material S1 and S2) shows visualizations that were used in the training. They were the “fish” and “dragon” and presented in random order during the training session. Both visualizations were meant to represent the size of the sentence AWS. The lower bound of the AWS target was set to be at a midpoint between AWS values obtained in normal and clear speaking conditions. The absolute upper bound value was set at 300% of the lower bound, empirically determined to be outside of the normal, typical production range. The range between the lower and the upper bounds determined the “game” space. With repetitions, the lower bound was adjusted on the basis of the participant’s best performance as the game progressed. The fish net expanded with each production, whereas the dragon breathed fire at longer ranges, when training was successful. The development of these interactive visualizations involved participatory design practices conducted over numerous pilot sessions. These sessions involved computer scientists, graduate students, and clinicians using visualization prototypes, surveys, and informal conversation as probes (Clemensen, Larsen, Kyng, & Kirkewold, 2007).

Statistical Analyses

An A-B-A design was used to evaluate the change in AWS for each participant during the study. Descriptive statistics (means and standard deviations) were used to summarize AWS at the baseline, training (Block 1 and Block 2), and retention phases. Trained and untrained sentences were assessed separately. To quantify the magnitude of the training effect on AWS, we used a variation of Cohen’s d statistic as described by Busk and Serlin (1992). The effect sizes were calculated per sentence for each phase of the study (baseline–training; baseline–retention) and averaged across sentences. The original benchmark of Cohen’s d statistic was used (where ≥ 0.2 = small, ≥ 0.5 = medium, and ≥ 0.8 = large; Cohen, 1988), as there are currently no other benchmarks for this statistic in the dysarthria literature, to the best of our knowledge.

Results

Figure 2 shows a summary of changes with training for a single speaker (PD30) by sentence. This speaker was chosen as his performance was representative of others, with a single exception (PD13). Although AWS differed substantially across sentences, the direction of change was similar between trained sentences and across phases, with large increases in movement size (on average, approximately 300% in Block 1 and 250% in Block 2 across all sentences). The untrained sentence AWS also increased during training. The effect remained at retention, showing approximately 180% increase in AWS relative to baseline for all but one sentence that showed a reduction in AWS in the final session.

Figure 3 provides a summary of change in AWS in baseline conditions (normal, loud, clear), training (Block 1 and 2), and retention phases, calculated as percentage change relative to normal condition. On average, our data showed an approximate 63% increase in AWS in loud and 90% increase in clear conditions across speakers; the responses varied between different speakers (SD = 48%, range = −22% to 146% in loud; SD = 71%, range = −4% to 180% in clear). Relative to the normal baseline, training amplitude with visual feedback resulted in a 244% average increase in AWS during training (SD = 199%, range = 5% to 550%) and 212% increase at retention (SD = 212%, range = −58% to 540%). Eight of nine patients increased their movement range > 50% using visual feedback (verbal cue + visualization), as compared with changes in the loud (4/9) and clear (6/9) conditions. Eight of nine patients maintained this gain at retention.

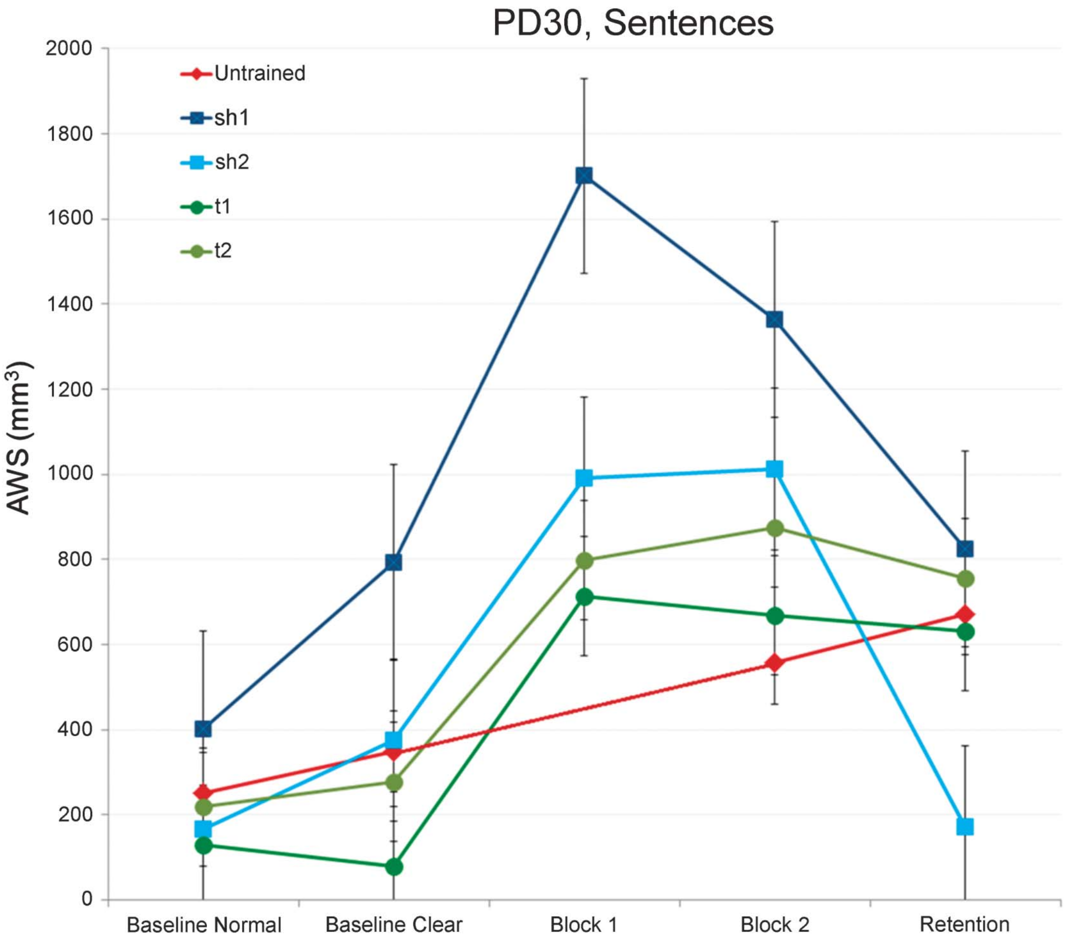
Table 2 summarizes the results in the form of effect sizes for trained sentences. Large effect sizes were revealed for all but one participant. A single participant (PD13) produced minimal change in AWS during training. Table 3 shows effect sizes calculated for the untrained sentence. For the majority of cases, trained and untrained sentences responded similarly (i.e., large effect sizes were recorded for all sentences).

Discussion

Using kinematic traces as the bases of augmented visual feedback treatment of motor dysfunctions is relatively common (Huang, Wolf, & He, 2006); to the best of our knowledge, however, articulatory movement signals have not been used in the treatment of dysarthria in PD. The centrality of the auditory-acoustic information in learning and relearning speech articulation might be one important reason for the neglect of this approach. However, not everyone can effectively use auditory information in motor recovery. For example, auditory learning may be impeded by auditory sensory loss in later life. Furthermore, it is accepted that speech acquisition relies on the interplay between auditory and somatosensory channels (Golfinopoulos, Tourville, & Guenther, 2010). Oral somatosensation can be impaired due to neurodegenerative diseases such as PD (Schneider, Diamond, & Markham, 1986). Additional sensory modalities, specifically vision, may become beneficial and supportive during motor practice.

Engaging a visual channel in speech rehabilitation in PD has not been well explored beyond treatment of speaking rate (Adams, Page, & Jog, 2002) and dysphonia (Krause, Smeddinck, & Meyer, 2013; McNaney et al., 2016). We set to find out whether visual information about a parameter of motion (i.e., its overall size) would facilitate changes in the articulatory performance of patients with PD with hypokinetic dysarthria and intelligibility impairment. Our results suggested that patients, initially prompted by a verbal cue, benefited from a visual channel while learning to use consistently large motions when speaking. The majority of participants were able to use visual feedback to implement increased amplitude instructions. These increases were larger than those obtained with either loud or clear speech cues. Eight of nine patients were able to use visual feedback and increase the range of speech motions beyond

Figure 2. Mean and standard error of articulatory working space (AWS) obtained on multiple repetitions of the trained [sh, t] and untrained [s] sentences during baseline (normal, clear), training (Block 1, Block 2), and retention, for a single speaker with Parkinson's disease (PD).



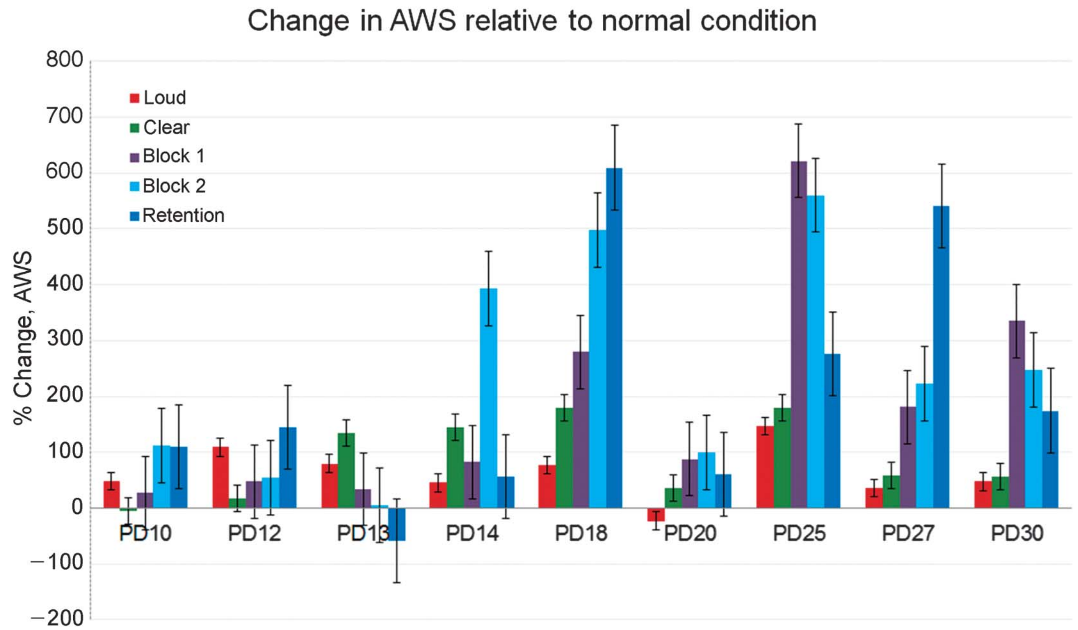
those observed with loud/clear cues. The magnitude of the effect differed greatly between participants, however. Participant characteristics (e.g., age, cognitive status, speech intelligibility) did not explain the range of training responses. Interestingly, the participant with the lowest Sentence Intelligibility Test score (PD18) was among those with the largest magnitude of change in AWS. One participant was not able to use the visual information at all and did much better with the clear speech instructions, commenting on the insufficiency of the feedback available on only 50% of the trials during training. The schedule of feedback in PD motor rehabilitation is still a matter of debate. At least one study suggested that best performance at retention might be achieved with a 100% feedback strategy for these patients (Guadagnoli, Leis, Van Gemmert, & Stelmach, 2002).

Trained and untrained sentences revealed notable changes in AWS after training. This is not surprising considering that we were training an overall strategy of "large movements," which would be applicable across all sentences. Sentence effects, however, need to be considered in more detail in the future, as different sentences seem to have responded to instructions and training by different magnitudes of change. We currently do not know to what extent these differences are driven by the phonetic content of the stimuli, the nature of the movement trajectories, and other factors related to speaker variability (e.g., anatomic characteristics and speaking rates/styles).

Likewise, responses to training were often similar between Block 1 and Block 2; effect sizes were similar, descriptively speaking, in six of eight successful training responders. This was surprising, as we would have expected a better performance later during training (Block 2). It appears that speakers might adapt to using visual feedback to adjust articulatory movements nearly right away (everyone tended to request for feedback on AWS early within the blocks) and reach quickly the upper limits of their performance. The focus in later repetitions/blocks may therefore be on consolidation of the large movement pattern, rather than on the continued increase in movement size. It would be interesting, in future studies, to examine if speakers produce large movements with greater stability (i.e., reduced variability) over time.

The rationale for using a treatment approach focused on increasing movement range stems from the accepted

Figure 3. Summary of percentage change in articulatory working space (AWS) for baseline (loud, clear), training (Block 1, Block 2), and retention, relative to the normal condition. PD = Parkinson's disease.



notion of movement reduction (hypokinesia), including those of speech articulators, in PD (Sapir, 2014) and the goal of treatment to target the underlying pathophysiology. The Lee Silverman Voice Treatment, which primarily targets hypophonia in PD, is said to also increase articulatory movement range as a by-product of the simple cue of speaking loud. On average, the PD participants in this study were able to use "loud" and "clear" cues to expand their movement range. However, there were a number of speakers for whom these cues were not sufficient to produce change in AWS; five speakers did not show evidence of articulatory adjustments in loud and three in clear conditions. Our treatment approach specifically draws attention to articulatory movement and hypokinesia, which is at the core of the motor deficit in PD, and results in a substantial improvement in movement size, which is consistent with the notion of task specificity in motor learning (Proteau, Marteniuk, & Lévesque, 1992).

This study was a proof-of-principle pilot project aimed to demonstrate the effect of augmented visual information on training and short-term retention of a relatively simple instruction to increase movement amplitude during speaking tasks. A number of limitations of this work have to be acknowledged. First, it is important to note that the basal ganglia dysfunction may affect later stages of learning, specifically skill automatization, much more than the earlier process of acquisition and consolidation (Doyon et al., 2009). Thus, future studies must be designed to demonstrate the long-term effects of learning a novel task on sustained performance, including generalization of the learned

Table 2. Effect sizes for each participant at training and retention sessions for trained sentences.

Participant ID	Training: Block 1	Training: Block 2	Retention
PD10	2.06*	3.77*	5.49*
PD12	3.81*	2.47*	9.52*
PD13	0.67	0.16	–1.93*
PD14	2.47*	12.24*	1.56*
PD18	10.59*	15.99*	19.16*
PD20	3.12*	5.74*	1.86*
PD25	9.43*	25.44*	12.66*
PD27	26.92*	8.15*	14.12*
PD30	6.90*	8.98*	5.89*

Note. Asterisks indicate large effect sizes.

Table 3. Effect sizes for each participant at training and retention sessions for the untrained sentence.

Participant ID	Training	Retention
PD10	0.58	1.72*
PD12	5.20*	7.83*
PD13	0.09	–0.62
PD14	14.16*	2.63*
PD18	3.10*	8.38*
PD20	1.48*	3.24*
PD25	9.68*	5.49*
PD27	6.76*	19.51*
PD30	3.23*	4.46*

Note. Asterisks indicate large effect sizes.

motor behavior to an everyday task. Second, the primary goal of speech treatment is to improve speech production and/or delay dysarthria onset. Thus, appropriate outcome measures (e.g., speech intelligibility) have to be chosen to document treatment success. Because this was only a short-term learning study, we did not expect that our treatment would affect speech intelligibility in any substantive way. Functional measures are incorporated into the design of ongoing studies focused on the long-term effects of the current approach. Finally, all potential and existing treatment methods and approaches require clear specification of the target behavior and the populations that exhibit this behavior. We inferred movement reduction from an articulatory deficit defined perceptually through reduced intelligibility and presence of imprecise articulation and elevated speaking rate. The relationship between the auditory-perceptual impressions and physiological movement reality is not well established, however. Topologies of the kinematic traces that depend on individual characteristics (e.g., sex, anatomy, dialect) and effect of disease (e.g., specific diagnoses and disease severity) are not yet existent for referencing purposes. Future work needs to continue in the direction of delineating the disease effects on biometric signals, including speech kinematics, and linking them to the clinical perceptual impressions.

In conclusion, this proof-of-principle study demonstrated the usefulness of augmented visual feedback in a form of engaging games in training articulatory movement enlargement in patients with hypokinesia due to PD. Ongoing studies incorporate this approach into a novel treatment paradigm for this underserviced clinical population.

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References

Adamovich, S. V., Berkinblit, M. B., Hening, W., Sage, J., & Poizner, H. (2001). The interaction of visual and proprioceptive inputs in pointing to actual and remembered targets in Parkinson's disease. *Neuroscience, 104*(4), 1027–1041.

Adams, S., Page, D., & Jog, M. (2002). Summary feedback schedules and speech motor learning in Parkinson's disease. *Journal of Medical Speech-Language Pathology, 10*(4), 215–220.

Atkinson-Clement, C., Sadat, J., & Pinto, S. (2015). Behavioral treatments for speech in Parkinson's disease: Meta-analyses and review of the literature. *Neurodegenerative Disease Management, 5,* 233–248.

Ballard, K. J., Smith, H. D., Paramatmuni, D., McCabe, P., Theodoros, D. G., & Murdoch, B. E. (2012). Amount of kinematic feedback affects learning of speech motor skills. *Motor Control, 16,* 106–119.

Berry, J. (2011). Accuracy of the NDI Wave speech research system. *Journal of Speech, Language, and Hearing Research, 54,* 1295–1301.

Busk, P. L., & Serlin, R. C. (1992). Meta-analysis for single case research. In T. R. Kratochwill & J. R. Levin (Eds.), *Single-case research design and analysis: New directions for psychology and education* (pp. 187–212). Hillsdale, NJ: Erlbaum.

Caviness, J. N., Driver-Dunckley, E., Conor, D. J., Sabbagh, M. N., Henz, J. G., . . . Adler, C. H. (2007). Defying mild cognitive impairment in Parkinson's disease. *Movement Disorders, 22,* 1272–1277.

Chiviacowsky, S., Campos, T., & Domingues, M. R. (2010). Reduced frequency of knowledge of results enhances learning in persons with Parkinson's disease. *Frontiers in Psychology, 1,* 1–6.

Clemensen, J., Larsen, S. B., Kyng, M., & Kirkevold, M. (2007). Participatory design in health sciences: Using cooperative experimental methods in developing health services and computer technology. *Qualitative Health Research, 17,* 122–130.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Connor, N. P., Ludlow, C. L., & Schultz, G. M. (1989). Stop consonant production in isolated and repeated syllables in Parkinson's disease. *Neuropsychologica, 27,* 829–838.

Darling, M., & Huber, J. E. (2011). Changes to articulatory kinematics in response to loudness cues in individuals with Parkinson's disease. *Journal of Speech, Language, and Hearing Research, 54,* 1247–1259.

Doyon, J., Bellec, P., Amsel, R., Penhune, V., Monchi, O., Carrier, J., . . . Benali, H. (2009). Contributions of the basal ganglia and functionally related brain structures to motor learning. *Behavioural Brain Research, 199,* 61–75.

Dromey, C. (2000). Articulatory kinematics in patients with Parkinson disease using different speech treatment approaches. *Journal of Medical Speech-Language Pathology, 8,* 155–161.

Ebersbach, G., Grust, U., Ebersbach, A., Wegner, B., Gandor, F., & Kühn, A. A. (2015). Amplitude-oriented exercise in Parkinson's disease: A randomized study comparing LSVT-BIG and a short training protocol. *Journal of Neural Transmission, 122,* 253–256.

Farley, B. G., Fox, C. M., Ramig, L. O., & McFarland, D. H. (2008). Intensive amplitude-specific therapeutic approaches for Parkinson's disease: Toward a neuroplasticity-principled rehabilitation model. *Topics in Geriatric Rehabilitation, 24,* 99–114.

Farley, B. G., & Koshland, G. F. (2005). Training BIG to move faster: The application of the speed–amplitude relation as a rehabilitation strategy for people with Parkinson's disease. *Experimental Brain Research, 167,* 462–467.

Fisk, J. D., & Doble, S. E. (2002). Construction and validation of a fatigue impact scale for daily administration (D-FIS). *Quality of Life Research, 11,* 263–272.

Forrest, K., & Weismer, G. (1995). Dynamic aspects of lower lip movement in Parkinsonian and neurologically normal geriatric speakers' production of stress. *Journal of Speech and Hearing Research, 38,* 260–272.

Golfinopoulos, E., Tourville, J. A., & Guenther, F. H. (2010). The integration of large-scale neural network modeling and functional brain imaging in speech motor control. *Neuroimage, 52,* 862–874.

Goozee, J. V., Shun, A. K., & Murdoch, B. E. (2011). Effects of increased loudness on tongue movements during speech in nondysarthric speakers with Parkinson's disease. *Journal of Medical Speech-Language Pathology, 19,* 42–53.

Guadagnoli, M. A., Leis, B., Van Gemmert, A. W., & Stelmach, G. E. (2002). The relationship between knowledge of results and motor learning in Parkinsonian patients. *Parkinsonism & Related Disorders, 9,* 89–95.

Hodges, N. J., & Franks, I. M. (2001). Learning a coordination skill: Interactive effects of instruction and feedback. *Research Quarterly for Exercise and Sport, 72,* 132–142.

Huang, H., Wolf, S. L., & He, J. (2006). Recent developments in biofeedback for neuromotor rehabilitation. *Journal of Neuroengineering and Rehabilitation, 3*(11). https://doi.org/10.1186/1743-0003-3-11

Jacobs, J. V., & Horak, F. B. (2006). Abnormal proprioceptive-motor integration contributes to hypometric postural responses of subjects with Parkinson's disease. *Neuroscience, 141,* 999–1009.

Klockgether, T., Borutta, M., Rapp, H., Spieker, S., & Dichgans, J. (1995). A defect of kinesthesia in Parkinson's disease. *Movement Disorders, 10,* 460–465.

Krause, M., Smeddinck, J., & Meyer, R. (2013). A digital game to support voice treatment for Parkinson's disease. In *CHI'13 extended abstracts on human factors in computing systems* (pp. 445–450). New York, NY: ACM Press.

Logemann, J. A., Fisher, H. B., Boshes, B., & Blonsky, E. R. (1978). Frequency and cooccurrence of vocal tract dysfunctions in the speech of a large sample of Parkinson patients. *Journal of Speech and Hearing Disorders, 43,* 47–57.

Lohse, K., Shirzad, N., Verster, A., Hodges, N., & Van der Loos, H. M. (2013). Video games and rehabilitation: Using design principles to enhance engagement in physical therapy. *Journal of Neurologic Physical Therapy, 37,* 166–175.

MathWorks. (2014). MATLAB (R2014a) [Computer software]. *R2014a*. Retrieved from https://www.mathworks.com/help/releases/R2014a/matlab/index.html

McNaney, R., Othman, M., Richardson, D., Dunphy, P., Amaral, T., Miller, N., … Vines, J. (2016, May). Speeching: Mobile crowdsourced speech assessment to support self-monitoring and management for people with Parkinson's. In *Proceedings of the 2016 ACM SIGCHI Conference on Human Factors in Computing Systems* (pp. 7–12). New York, NY: ACM Press.

Microsoft Inc. (2014). SQL Server 2014 [Computer software]. *Developer Reference for SQL Server 2014*. Retrieved from https://msdn.microsoft.com/en-us/library/dd206988(v=sql.120).aspx

Miller, N., Deane, K. H. O., Jones, D., Noble, E. & Gibb, C. (2011). National survey of speech and language therapy provision for people with Parkinson's disease in the United Kingdom: Therapists' practices. *International Journal of Language and Communication Disorders, 46,* 189–201.

Miller, N., Noble, E., Jones, D., & Burn, D. (2006). Life with communication changes in Parkinson's disease. *Age and Ageing, 35,* 235–239.

Nackaerts, E., Heremans, E., Vervoort, G., Smits-Engelsman, B., Swinnen, S., Vandenberghe, W., … Nieuwboer, A. (2016). Relearning of writing skills in Parkinson's disease after intensive amplitude training. *Movement Disorders, 31,* 1209–1216. https://doi.org/10.1002/mds.26565

Nasreddine, Z. S., Phillips, N. A., Beédirian, V., Charbonneaus, S., Whitehead, V., Collin, I., … Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of American Geriatric Society, 53,* 695–699.

Proteau, L., Marteniuk, R. G., & Lévesque, L. (1992). A sensorimotor basis for motor learning: Evidence indicating specificity of practice. *Quarterly Journal of Experimental Psychology, 44,* 557–575.

Rickards, C., & Cody, F. W. (1997). Proprioceptive control of wrist movements in Parkinson's disease: Reduced muscle vibration-induced errors. *Brain, 120,* 977–990.

Sapir, S. (2014). Multiple factors are involved in the dysarthria associated with Parkinson's disease: A review with implications for clinical practice and research. *Journal of Speech, Language, and Hearing Research, 57,* 1330–1343.

Schneider, J. S., Diamond, S. G., & Markham, C. H. (1986). Deficits in orofacial sensorimotor function in Parkinson's disease. *Annals of Neurology, 19,* 275–282.

Scott, S., & Caird, F. I. (1983). Speech therapy for Parkinson's disease. *Journal of Neurology, Neurosurgery & Psychiatry, 46,* 140–144.

Shen, X., & Mak, M. K. (2014). Balance and gait training with augmented feedback improves balance confidence in people with Parkinson's disease: A randomized controlled trial. *Neurorehabilitation and Neural Repair, 28,* 524–535.

Shtern, M., Haworth, M. B., Yunusova, Y., Baljko, M., & Faloutsos, P. (2012). A game system for speech rehabilitation. *Motion in Games, 7660,* 43–54.

Smith, M. C., & Fucetola, R. (1995). Effects of delayed visual feedback on handwriting in Parkinson's disease. *Human Movement Science, 14,* 109–123.

Tjaden, K., Sussman, J. E., & Wilding, G. E. (2014). Impact of clear, loud, and slow speech on scaled intelligibility and speech severity in Parkinson's disease and multiple sclerosis. *Journal of Speech, Language, and Hearing Research, 57,* 779–792.

Unity Technologies, Inc. (2015). Unity 3D (Version 4.6.5p1) [Computer software]. *Unity Manual*. Retrieved from https://docs.unity3d.com/460/Documentation/Manual/index.html

Walsh, B., & Smith, A. (2012). Basic parameters of articulatory movements and acoustics in individuals with Parkinson's disease. *Movement Disorders, 27,* 843–850.

Weismer, G., Yunusova, Y., & Bunton, K. (2012). Measures to evaluate the effects of DBS on speech production. *Journal of Neurolinguistics, 25,* 74–94.

Wulf, G. (2007). Self-controlled practice enhances motor learning: Implications for physiotherapy. *Physiotherapy, 93,* 96–101.

Wulf, G., & Shea, C. (2004). Understanding the role of augmented feedback: The good, the bad, and the ugly. In A. M. Williams & N. J. Hodes (Eds.), *Skill acquisition in sport: Research, theory, and practice* (pp.121–144). London: Routledge.

Vaillancourt, D. E., Slifkin, A. B., & Newell, K. M. (2001). Visual control of isometric force in Parkinson's disease. *Neuropsychologia, 39,* 1410–1418.

Yorkston, K., Beukelman, D., Hakel, M., & Dorsey, M. (2007). *Sentence Intelligibility Test*. Lincoln, NE: Madonna Rehabilitation Hospital.

Yunusova, Y., Weismer, G., Kent, R. D., & Rusche, N. M. (2005). Breath-group intelligibility in dysarthria: Characteristics and underlying correlates. *Journal of Speech, Language, and Hearing Research, 48,* 1294–1310.

Yunusova, Y., Weismer, G., Westbury, J. R., & Lindstrom, M. J. (2008). Articulatory movements during vowels in speakers with dysarthria and healthy controls. *Journal of Speech, Language, and Hearing Research, 51,* 596–611.