The Effects of Transcutaneous Auricular Vagus Nerve Stimulation on Language Retention in College-Aged Students

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Learning and retaining a new language is significantly more difficult as an adult compared to during childhood, with existing research showing that children are much more likely to attain native-like frequency than adolescents and adults (Abrahamsson & Hyltenstam, 2008). One possible reason for this increased difficulty is the sensitive period of language. This period, beginning in infancy and ending around puberty, is often characterized by the brain's high level of neuroplasticity, as well as the rapid onset of neural pruning and synaptogenesis seen in infants and young children (Mundkur, 2005; Silveira-Moriyama, 2017). It is often theorized that if a child does not acquire any language during this period, then there is a chance they might never be able to do so, as the brain's base neural formations have already been established and are increasingly difficult to change after specialization that comes with age (Johnson, 2005). The ending of the sensitive period of language is correlated with an abrupt and dramatic decline in neuroplasticity, formation, and migration—further complicating the task of acquiring language (Hurford, 1991). Another factor closely related to the decline in neuroplasticity, and therefore the increased difficulty of language learning with age, is the decline of the body's production of brain-derived neurotrophic factor, an important endogenous protein that acts as a neurotransmitter modulator. *BDNF* is essential in neuronal plasticity and migration, and therefore, the process of learning and memory (Bathina & Das, 2015). Research suggests that levels of *BDNF* that are too high or too low negatively correlate with levels of learning and retention of taught materials across several disciplines (Cunha et al., 2010).

While language becomes increasingly difficult to acquire, learning a second language later in life remains desirable and sometimes even necessary for many. There are many cognitive benefits of bilingualism, such as improved memory (Morales et al., 2013), problem-solving and critical-thinking skills (Kharkhurin, 2012), as well as enhanced concentration (Bialystok & Craik, 2010), ability to multitask (Poarch & Bialystok, 2015; Winata et al., 2021), and better-listening skills (Kharkhurin, 2012). In addition to these effects, multilingualism has been shown to stave off mental aging and the effects of cognitive decline by up to five years in susceptible populations (Craik et al., 2010; Van den Noort et al., 2006). Additionally, considering the increasingly global economy and environment seen today, bilingualism is becoming more and more necessary to facilitate interactions between those speaking different languages in day-to-day life. As of 2011, it was estimated that over 20 million people in the United States have a preferred language other than English, prompting a call for a more multilingual workforce and society in the future (Jauregui, 2015). Furthermore, research has shown that with the growth seen in today's multilingual workforce, businesses are now increasingly seeking to hire such individuals (Damari et al., 2017). The demand for bilingual workers has more than doubled in the past ten years, and this number is projected to only continue to climb (New American Economy, 2018). Considering these various cognitive, physical, and economic benefits of bilingualism, our society has seen an explosion of options and methods available to assist in the process of language learning.

Despite the appeal and need for learning new languages in adulthood, the existing learning tools are not optimal. In addition to traditional classroom options, there are numerous virtual apps that claim to help in attaining fluency in a new language, including examples such as Duolingo, Babbel, and Rosetta Stone. While these apps provide easy access regardless of place or time, research has shown mobile learning is less effective in improving important aspects of language learning, such as speaking, reading, and writing skills (Gangaimaran & Pasupathi, 2017). Another issue of mobile language learning is the absence of a social element and therefore the loss of the interpersonal practice of language learning (Miangah & Nezarat, 2012), something that has been shown to be critical from the time of infancy onward (Kuhl, 2004). Additionally, the increasing popularity of virtual reality has prompted interest in its use in language learning. However, there are several limitations to this technology, namely the lack of flexibility, increased distractions, and high price (Parmaxi, 2020). In addition to these methods, the use of podcasts has seen a surge in popularity in terms of language learning. While the use of podcasts can promote listening comprehension and intercultural competence, it does not help learners in terms of reading and writing abilities, and learners are more likely to listen to a podcast outside of their level of understanding—something that might further complicate the process of learning (Chartrand, 2016). Furthermore, each of these methods have shown to be greatly time-consuming and not effective for everyone, making users less likely to persist (Gangaimaran & Pasupathi, 2017; Parmaxi, 2020). Lastly, these methodologies have resulted in poor retention rates of learned information that do not help a learner achieve fluency—perhaps the most important aspect of language learning (Bathina & Das, 2015; Friðriksdóttir & Arnbjörnsdóttir, 2015). These disadvantages of current language learning tools demonstrate that while there are benefits to these options, further advancements are needed in the realm of technology for language acquisition and long-term retention.

One possible method of improving language learning is the addition of neuromodulation, and more specifically, noninvasive transcutaneous auricular vagus nerve stimulation (taVNS). One technique used to provide taVNS to patients and participants is through the use of the Parasym™ device (Parasym, Ltd., London, UK). With this device, a small, copper-plated electrode is clipped onto the left tragus, with the electrode delivering a low-level electrical current to its posterior. This clip on the ear is attached to the device itself via a wire, and users are able to control stimulation intensity and frequency using the device. With this technology, it is possible to noninvasively stimulate the auricular branch of the vagus nerve, resulting in differences in neural plasticity comparable to invasive forms of vagal nerve stimulation (Redgrave et al., 2018; Yakuna et al., 2018). Both transcutaneous auricular vagus nerve stimulation and invasive vagus nerve stimulation have been shown to enhance neural plasticity in tested populations (Silveira-Moriyama, 2017; Snow, 1989; Weng et al., 2019), as well as boost associative memory (Tabuchi et al., 2002), spatial working memory (Sun et al., 2021), and emotional memory (Ventura-Bort et al., 2021). It has also been shown that vagus nerve stimulation boosts the gene expression of brain-derived neurotrophic factor, a key molecule that is involved in neuroplasticity and changes in the brain relating to learning and memory (Follesa et al., 2007; Choy et al., 2008; Tabuchi et al., 2002). Prior data suggest that taVNS might also be useful in a language-based application. Previous research conducted in our lab has shown that noninvasive transcutaneous auricular vagus nerve stimulation is an effective intervention in both memory-based reading comprehension and letter-sound learning (Thakkar 2020; 2023).

Considering the struggle of acquiring a second language in adulthood, and the benefits of taVNS demonstrated, the current study was designed to examine the effect of taVNS on learning and recall of a novel language. We recruited typically developing young adults who received taVNS to the left ear while completing a language learning program within the lab. Retention of learned words was evaluated prior to, immediately after, and one week following training.

METHOD

Participants

Participants screened for eligibility in the present study include 31 (*N* = 19 female) college-aged students ranging in age from 18–35 years old who were recruited through an online participant pool. All individuals were screened for age, IQ, reading, memory, and attention for inclusion in this study through the measures listed below. Inclusion criteria for this study include (a) being a native English speaker, (b) being within 18 and 35 years of age, (c) having a nonverbal IQ score of at least 85, (d) having achieved scores of 90 or above on all reading measures administered, (e) having no medical implants, (f) having no diagnosis of a learning disability, and (g) having no use of certain medications, such as SSRIs or ADHD medication. Research suggests that these medications may alter the function of neurotransmitter systems activated through the use of invasive forms of vagal stimulation (Husley et al., 2016; 2019), and were therefore excluded to minimize any potential interference with stimulation and performance.

Prior to starting training of the Palauan language, participants completed a background survey examining family history and personal background, history of reading and motor development, as well as medical history. In addition to this, participants completed an array of assessments measuring nonverbal intelligence (the matrices subtest of the KBIT-2) (Kaufman et al., 2004), timed single-word reading of both printed words and phonemically regular nonwords (the Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the TOWRE-2) (Torgesen et al., 2012), untimed single-word reading of both printed words and phonemically regular nonwords (the Word Identification and Word Attack subtests of the WRMT-3) (Woodcock et al., 2011), rapid autonomic naming and processing of digits and letters (the rapid digit naming and rapid letter naming subtests of the Comprehensive Test of Phonological Processing) (Wagner et al., 2013), and both short- and long-term memory functioning (the design memory, number letter, and verbal recall subtests of the Wide Range Assessment of Memory and Learning) (Sheslow & Adams, 2009). These tests allowed for the assessment of IQ, reading, and memory needed for inclusion in the study, and were used as a measure of baseline reading performance.

Of the 38 participants who initially completed screening and achieved adequate scores on baseline measures, three were excluded for the use of exclusionary medications and/or having an exclusionary diagnosis, and four for failure to complete the study due to withdrawal or a cease of communication. Considering these exclusions, the final sample of the study included 31 participants that met the necessary qualifications (descriptive statistics of standard scores are presented in Table 1). After screening, participants were randomized into sham taVNS (*N* = 11) or active taVNS (*N* = 20). Within the active taVNS group, participants were randomly assigned to one of two frequency parameters, with participants receiving either 5 Hz (*N* = 10) or 25 Hz (*N* = 10) stimulation. These parameters were chosen using a combination of prior work in our lab (Thakkar, 2020; 2023) and the observation of frequencies used in other research labs investigating the use of taVNS (Llanos et al., 2020). Thus, a main goal of the current study was to evaluate whether stimulation frequency affects the outcome of taVNS paired training.

Prior to the start of the study, all participants provided written informed consent of the study. After completion of the study, participants were compensated for their time and effort with course credit. This study was approved by the Institutional Review Board at Texas Christian University.

Training session and taVNS procedures

After being screened for the aforementioned inclusion criteria, participants were scheduled for two study sessions via email. During the first session of the study, participants completed a one-hour training session in which they were presented with 30 novel Palauan nouns, the respective English translations, and images of the nouns. During this time and according to randomization, the participants received sham, 5 Hz, or 25 Hz stimulation to the posterior of the left tragus. Knowledge of the Palauan nouns were measured before, immediately after, and one week following training, as described under 'Assessment of Palauan Language.'

All participants of the study were fitted with a one-quarter inch diameter gold-plated copper electrode attached to the Parasym device used for stimulation. The stimulation-delivering electrode was placed at the posterior tragus of the left ear in order to stimulate the auricular branch of the vagus nerve through the use of a low-grade electrical current (electrode placement presented in Figure 1). Of those receiving stimulation, conditions were held constant with square, biphasic pulses of 200 µs pulse width being delivered only during the time stimuli was presented. During the training session, stimulation was manually turned on and off by a trained researcher.

Prior to the beginning of training and the onset of stimulation, a customized level of intensity was measured for each participant to ensure comfort and minimize any possible distraction. This level of intensity was determined by acquiring four measurements during a thresholding procedure: two measures of minimum threshold and two just prior to the onset of pain or irritation (example of thresholding measures presented in Table 2). For those receiving active stimulation, current intensity was the average of the four threshold points. Those randomized into the sham group did not receive any stimulation during the process of training.

After the thresholding measure, all participants were trained via exposure to a picture of the Palauan noun positioned below the Palauan and English translations of the word (example of stimuli presented in Figure 2). Each picture and both translations would be shown for two seconds before moving on to the next set of a picture and its respective translations. After being presented five new words, participants were asked to perform a knowledge check in which they would be presented the Palauan translation and asked to select the correct English translation from four words given, using the keys 1 through 4 on the keyboard (example of knowledge check presented in Figure 3). This process repeated with five more blocks, each consisting of five new words. At the halfway point of the training session, participants had the option to take a short break and rest their eyes. At this point, the training procedure repeated again.

Participants in the active taVNS groups received stimulation only during exposure blocks, and stimulation was turned off during knowledge checks. For participants in the sham group, the device was turned off without their knowledge, and the act of increasing stimulation of the device was feigned to promote the belief that stimulation was administered. To ensure blinding to participants, the device was hidden behind a barrier for all sessions.

Assessment of the Palauan Language

An assessment of the knowledge of the thirty novel Palauan nouns was given before and immediately after training, as well as one week later, to examine short- and long-term recall of the words. During the initial assessment, participants were presented with these thirty novel Palauan nouns and asked to answer with the correct English translation, provide their best guess, or respond with "unknown." After receiving training, and once again a week later, participants were once again presented with the same thirty Palauan nouns and given the same instructions to measure their short- and long-term recall. This measure was scored by percent of answers correct to compare recall between the groups.

Statistical Analysis Plan

A one-way ANOVA was used to compare the sham and active taVNS groups on the standard baseline assessments, and to evaluate any differences in these baseline abilities. Participant characteristics and standard assessment scores by stimulation frequency group are presented in Table 1.

To examine the effect of taVNS on retention of new vocabulary words in a foreign language, we used a repeated measures ANOVA and post hoc tests to compare stimulation frequency groups and retention outcomes at different time points (Figure 4).

Pearson's *r* was used to determine if individual current intensity correlated to retention outcomes in the active taVNS groups. Additionally, this measure was used to determine the correlations between verbal working memory skills and retention outcomes. The Scheffe correction was used to correct for multiple comparisons in both scenarios.

All data was analyzed using SPSS Statistics.

RESULTS

Differences in Baseline Abilities

From a one-way ANOVA analyzing the scores of the baseline standard assessments among the three groups, we found only one significant difference ($F(2, 28) = 3.98$, $p < .05$) with a high effect size ($\eta^2 = .22$)(Table 1). Post-hoc comparisons, using the Scheffe test, were conducted to determine which pairs of the groups differed significantly on baseline measures. Results showed that those receiving 25 Hz stimulation ($M = 10.50$, $SD = 1.35$) performed significantly better than those in the sham ($M = 9.09$, $SD = 2.07$) and 5Hz ($M = 8.10$, $SD = 2.18$) groups on the Design Memory Core subtest of the WRAML-2 (Sheslow & Adams, 2009). This task is primarily a visual working memory task, and this skill has been shown to support object recognition and object-word associations (Samuelson, 2021). Considering the 25 Hz group performed significantly better than others at retention, this finding must be considered in future replications and directions of this work, as it suggests a possibility that improved visual working memory may assist in language retention with taVNS and a visually-based training program.

Significant effects of taVNS on language learning and retention (sham vs active groups)

Next, we evaluated whether taVNS stimulation was associated with improved learning of novel Palauan nouns. Participants were presented with all the trained Palauan words and instructed to provide the correct English translation. This measure was administered immediately after training and one-week post-training. We utilized a repeated measures ANOVA to evaluate the effect of the stimulation group (sham x 5 Hz x 25 Hz) and time point (pre-test x post-test x retention) on translation accuracy. We found significant main effects of stimulation group ($F(2, 82) = 5.7$, $p < .01$) and time point ($F(2, 82) = 202.38$, $p < .01$) on translation accuracy. There was a trend in the interaction between group and time ($F(4, 82) = 2.14$, $p = 0.08$).

Post hoc tests revealed that the main effect was driven by the 25 Hz stimulation group (Figure 4). There was no effect of stimulation on the percent correct of translations immediately after training—whether the participant received sham ($M = 77.27$, $SD = 22.56$), 5 Hz ($M = 82.50$, $SD = 15.43$), or 25 Hz ($M = 90.61$, $SD = 10.52$) of stimulation ($ps > 0.11$). However, there was an effect on outcome retention a week after training. Those receiving 25 Hz stimulation performed significantly better on recalling the English translations of Palauan nouns ($M = 64.33$, $SD = 22.46$) compared to those receiving 5 Hz stimulation ($M = 41.25$, $SD = 19.92$; $p = 0.05$) and compared to those receiving sham stimulation ($M = 36.97$, $SD = 21.44$; $p = 0.01$). These results suggest that efficacy of taVNS is frequency-dependent, and that for language learning, 25 Hz may be the optimal parameter choice.

Current Level and Retention Outcomes

Since each participant received a customized current level tailored to their comfort level, we evaluated the relationship between current intensity and language retention in both active groups using Pearson's *r* correlations. Within the group receiving 5 Hz stimulation, we did not find a significant relationship between current intensity and percentage of words remembered correctly immediately after training ($r(8) = -.60$, $p = .07$), or with a one-week delay ($r(8) = -.51$, $p = .13$)(Table 3). Similarly, within the group receiving 25 Hz stimulation, no relationship was found between current intensity and post-training scores ($r(8) = .01$, $p = .99$), or retention scores ($r(8) = .10$, $p = .79$)(Table 4). These findings suggest that the intensity of stimulation does not influence taVNS efficacy in language retention.

Relationships between verbal working memory and language retention

There is existing evidence to suggest that learning a language requires adequate verbal working memory skills (Schwering & MacDonald, 2020). To examine whether baseline verbal working memory skills are associated with taVNS outcomes, we used Pearson's *r* to determine the correlations between verbal working memory and percentage of novel words retained in each experimental group. Specifically, we looked at the correlations between outcome and the verbal recall subtests of the Wide Range Assessment of Memory and Learning (Sheslow & Adams, 2009). We found no significant relationship between scores on the Verbal Learning Core subtest, measuring short-term verbal working memory, with the percentage of words remembered correctly after a one-week delay ($r(29) = .20$, $p = .27$). However, a significant relationship was found between scores on the Verbal Learning Recall subtest, measuring verbal working memory with a delay, and retention outcomes with a one-week delay ($r(29) = .39$, $p = .03$)(Table 5). These findings suggest that one's baseline verbal working memory skills may be associated with taVNS outcomes.

DISCUSSION

The goal of the current study was to evaluate a novel approach to improve the learning and retention of novel vocabulary words in a foreign language by college-aged students. Our results demonstrate that those receiving 25 Hz stimulation significantly improved retention of learned words after one week. However, receiving 5 Hz stimulation was not related to significant improvement in retention. Additionally, there was no effect of taVNS intensity influencing post-training or retention performance. These findings support prior work indicating that taVNS is able to enhance neural plasticity, specifically for tasks that require memory skills (Silveira-Moriyama 2017; Snow, 1989; Wang et al., 2019; Tabuchi et al., 2002; Sun et al.,2021; Ventura-Bort et al., 2021).

Comparison to other language learning interventions

Transcutaneous auricular vagus nerve stimulation is able to enhance learning and neural plasticity, and a growing body of evidence suggests that this noninvasive technology might be as effective at doing so as invasive methods of vagus nerve stimulation (Redgrave et al.,2018; Yakunina et al., 2018). The efficacy of taVNS, combined with its portability, affordability, and noninvasiveness, makes this technology suitable and accessible for use by the general population.

In this study, we observed the efficacy of taVNS at boosting retention of new, novel vocabulary words after a single session of stimulation. The findings from this study suggest that taVNS may be used to accelerate and increase the benefits and properties of various behavioral interventions that require extended periods of time and consistent training. For example, the Foreign Service Institute has determined that basic fluency of a language for an adult requires anywhere between 480 and 720 hours of practice, depending on the language and focus of the learner (US Department of State, 2022). The findings from this study suggest a means to shorten this training time, by pairing a routine language training program with noninvasive vagus nerve stimulation.

Considering the established use of noninvasive vagus nerve stimulation to improve several aspects of memory, future research should examine whether this stimulation improves memory and retention of a language for an extended period longer than one-week post-training. Existing technologies, such as apps, virtual reality, and the use of podcasts, all result in poor retention rates of material learned after an extended period (Bathina & Das, 2015; Friðriksdóttir & Arnbjörnsdóttir, 2015). If the retention results show to be long-lasting, the implementation of taVNS to improve retention outcomes would likely not only be beneficial in conjunction with a training program, as shown in the present study, but would also likely improve retention when used alongside these existing language-learning technologies. Additionally, it would be beneficial to determine whether the use of taVNS can improve the retention of new stimuli not learned in conjunction with stimulation application. The ability to use taVNS technology and have the retention effects continue even short-term after stimulation could be beneficial, as some using the technology might not have access to a personal device of their own. If continued research suggests this possibility, it would further encourage the idea of using this technology in clinical or school environments to improve language learning. Lastly, future research should expand upon the type of stimuli presented with stimulation to determine whether this technology may be used to improve learning in other cognitive areas. The ability of this technology to potentially improve other areas of learning, such as in mathematics, social development, and the arts, could benefit many.

Lastly, research has shown that those with learning disabilities, such as dyslexia, require more time and effort to learn a language than typical readers with existing interventions (Crombie, 1997; 1999). This study was conducted using typically developing participants with average or above-average reading skills and intelligence levels. Thus, results from this study did not determine efficacy of taVNS for language learning and retention in nontypical learners. Further research should include these groups to determine whether taVNS use alongside existing techniques may be used as an intervention for these populations in the general public.

Impact of baseline skills on language retention

Learning a language is a complicated process that requires the use of several lower-level skills, such as verbal, working, semantic, implicit, and episodic memory used in conjunction with other required skills (Chen & Hsieh, 2008; Cook, 1979; Service, 1992). In addition to using these skills, learners are required to determine the meaning of a word and link it to a visual representation of the object and their native translation of the word. In practical use of the language, learners must also be able to use contextual clues when there is something not understood in the foreign language. Since the present study does not examine the effect of taVNS on important aspects of language such as implicit or episodic memory, future research should investigate whether taVNS is capable of improving these skills to further assist the acquisition of language.

Results from this study suggest that one's verbal working memory skills after a delay correlate with retention outcomes of material learned alongside taVNS use. Considering this, future research might suggest that improving one's verbal working memory skills may also improve language retention outcomes when using this technology. It has been shown that techniques such as breaking down information, creating checklists, and developing routines have been beneficial in improving working memory (Alloway & Alloway, 2014), and thus could potentially benefit a learner using taVNS technology for language-learning purposes.

Additionally, research has shown that enhanced working memory benefits a person's cognitive development, ability for learning, and education outcomes across several fields, as well as planning, comprehension, and problem-solving skills (Cowan, 2014). Considering these benefits of improved working memory, it is likely that it will not only benefit retention of learned words, but also other important aspects of language, such as syntax, semantics, and pragmatics.

No effect of current intensity on taVNS efficacy

In existing literature, reports have been made that current intensity influences outcomes of cVNS stimulation in both rat and human populations (Borland et al.,2016; Clark et al.,1999). Results from this study, however, did not determine a relationship between the level of taVNS current intensity and language retention. Further research is needed to determine the importance of intensity in both invasive and noninvasive forms of stimulation. This research will be critical in future implementation of taVNS in clinical approaches and populations.

LIMITATIONS

There are several significant limitations in the present study. First, participants for the study were recruited via an online participant pool. This poses an issue, as most participants in the pool come from mid to high socioeconomic backgrounds, limiting the ability to generalize these findings to the public. Future research should be conducted with a sample that includes a more inclusive range of socioeconomic backgrounds to examine whether the biological and social impacts of a lower SES background influence the efficacy of taVNS on novel language learning and retention.

Additionally, this study only included typical readers, as reading disabilities such as dyslexia, and/or scoring below standard scores on various procedures resulted in exclusion from the study. This research should be expanded upon to include those with reading and language difficulties. There is currently no existing literature on the effects of taVNS in nontypical populations, and this must be changed in order to generalize the results to the public.

Next, further inclusion criteria excluded the use of psychopharmacological medications, such as Adderall, Vyvanse, Ritalin, and SSRIs. There exists plenty of research to suggest that use of these medications may impact the efficacy of various forms of brain stimulation (McLaren et al., 2018; Lozano et al., 2019). Research examining the efficacy of taVNS for language learning in those using psychopharmacological medications should be conducted to ensure successful language learning and retention in these populations.

Lastly, this study solely examined the retention of meaning of novel vocabulary words. This is only one aspect of the complex process of learning a language, and this study did not examine aspects of language such as spelling, speaking, and pronunciation, listening, and using the vocabulary in context. While some of these skills were measured using the baseline assessments at the beginning of the study, they were not assessed as part of language learning. Future studies evaluating taVNS for use as a language learning intervention should be sure to examine its use in these contexts.

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CONFLICTS OF INTEREST

The author has no conflicts of interest to declare.

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Table 1

One-Way ANOVA Results of Scores of Baseline Measures Between Stimulation Frequency Groups *= $p < .05$.

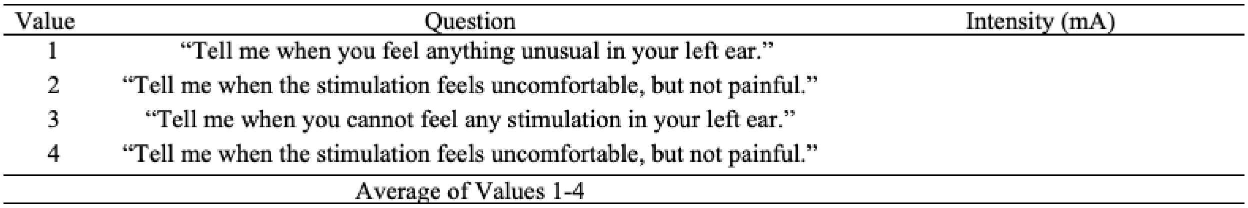
	Sham		5 Hz		25 Hz		*F*(2, 28)	*p*	Partial η^2
	M	*SD*	*M*	*SD*	*M*	*SD*			
KBIT	108.45	13.17	102.20	13.39	105.90	8.91	.71	.50	.05
SWE	109.36	11.16	111.50	11.11	110.40	11.14	.10	.91	.01
PDE	110.82	6.63	110.10	3.84	111.90	7.40	.22	.81	.02
WID	111.27	4.92	107.20	6.94	107.50	9.03	1.09	.35	.07
WA	104.27	5.97	106.60	9.28	102.80	7.89	.61	.551	.04
RDN	11.36	1.36	12.00	1.25	11.70	2.95	.27	.77	.02
RLN	10.82	1.83	11.30	1.64	10.40	3.10	.39	.68	.03
DMC	**9.09**	**2.07**	**8.10**	**2.18**	**10.50**	**1.35**	**3.98**	**.03***	**.22**
VLC	11.27	2.57	10.90	2.42	11.70	1.95	.29	.75	.02
NL	12.27	2.00	13.00	1.56	11.80	2.49	.87	.43	.06
DMR	9.81	2.04	9.60	2.37	11.70	2.45	2.58	.09	.16
VLR	11.18	2.48	10.10	2.33	11.90	2.51	1.37	.27	.09

Note. KBIT = KBIT-2 Matrices subtest of the Kaufman Brief Intelligence Test, 2nd Edition; SWE = Sight Word Error subtest of the Test of Word Reading Efficiency, 2nd Edition; PDE = Phonemic Decoding Efficiency subtest of the Test of Word Reading Efficiency, 2nd Edition; WID = Word Identification subtest of the Woodcock Reading Mastery Test, 3rd Edition; WA = Word Attack subtest of the Woodcock Reading Mastery Test, 3rd Edition; RDN = Rapid Digit Naming subtest of the Comprehensive Test of Phonological Processing, 2nd Edition; RLN = Rapid Letter Naming subtest of the Comprehensive Test of Phonological Processing, 2nd Edition; DMC = Design Memory Core subtest of the Wide Range Assessments of Memory and Learning, 2nd Edition; VLC = Verbal Learning Core subtest of the Wide Range Assessments of Memory and

Learning, 2nd Edition; NL = Number Letter subtest of the Wide Range Assessments of Memory and Learning, 2nd Edition; DMR = Design Memory Recognition subtest of the Wide Range Assessments of Memory and Learning, 2nd Edition; VLR = Verbal Learning Recall subtest of the Wide Range Assessments of Memory and Learning, 2nd Edition.

Table 2

taVNS Thresholding Measurements. Two measurements of minimum threshold, and two just prior to the onset of pain or irritation were averaged to customize current intensity used during training.



Value	Question	Intensity (mA)
1	"Tell me when you feel anything unusual in your left ear."	
2	"Tell me when the stimulation feels uncomfortable, but not painful."	
3	"Tell me when you cannot feel any stimulation in your left ear."	
4	"Tell me when the stimulation feels uncomfortable, but not painful."	
	Average of Values 1-4	

Table 3

Descriptive Statistics and Correlations for Score Outcomes and Stimulation Intensity at 5 Hz

* = $p < .05$

Variable	*N*	*M*	*SD*	1	2	3
1. Post Test	10	75.33	21.90	—		
2. Retention	10	36.67	21.14	**.83***	—	
3. Stimulation Intensity at 5 Hz	10	2.37	.29	-.60	-.51	—

Table 4

Descriptive Statistics and Correlations for Score Outcomes and Stimulation Intensity at 25 Hz

* = $p < .05$

Variable	*N*	*M*	*SD*	1	2	3
1. Post Test	10	90.67	11.63	—		
2. Retention	10	64.33	23.68	**.82***	—	
3. Stimulation Intensity at 25 Hz	10	1.96	.39	.01	.10	—

Table 5

Descriptive Statistics and Correlations for Retention Outcomes and Verbal Learning Core and Recall Measures

* = $p < .05$

Variable	*N*	*M*	*SD*	1	2	3
1. Verbal Learning Core	31	11.29	2.28	—		
2. Verbal Learning Retention	31	11.06	2.48	.68	—	
3. Retention Outcome	31	45.70	25.33	.20	**.39***	—

Figure Captions

Figure 1. Electrode Placement of taVNS Device. Each participant completed the study using a Parasym device, with an electrode delivering low-grade electrical current positioned on the posterior of the left tragus (shown by the small black circle).

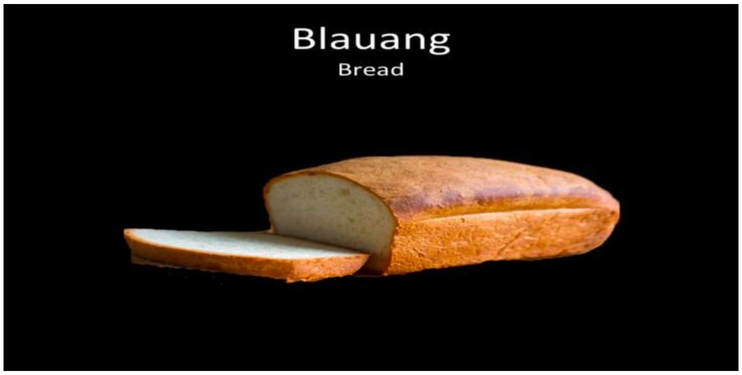


Figure 2. Example of Training Session Stimulus. All participants were trained via exposure to a picture of the Palauan noun positioned below the translation of the word in Palauan, and above the translation of the word in English. Each picture and both translations would be shown for two seconds before moving on to the next set of a picture and its respective translations.

Blauang

Lizard 1. Bread 2. Bow-tie 3. Spider 4.

Figure 3. Example of Knowledge Check. After five words, participants were asked to perform a knowledge check in which they would be presented the Palauan translation and asked to select the English translation from four words given, using the keys 1 through 4 on the keyboard. This process repeated with five more blocks, each consisting of five new words.

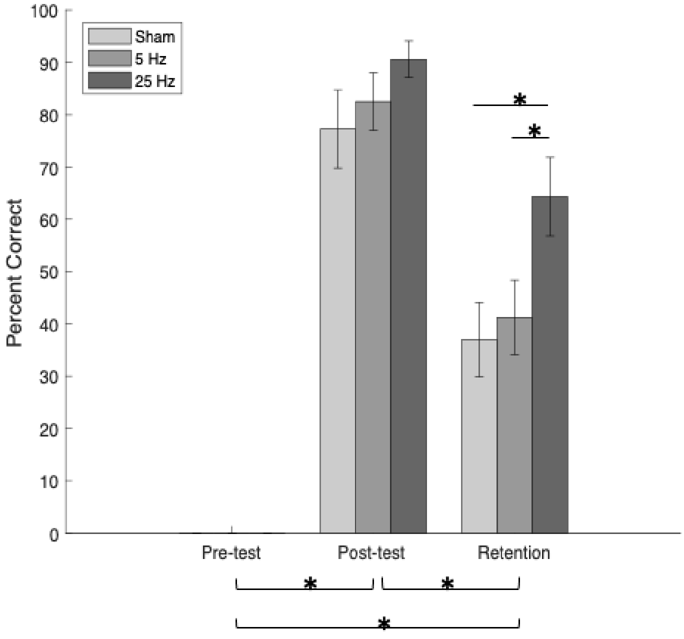


Figure 4. Performance by Stimulation Group. We quantified the percent correct of Palauan to English translations before, immediately after, and one-week following a training session. Those receiving 25 Hz stimulation performed significantly better than those receiving 5Hz or sham stimulation. There was no significant difference between 5Hz and sham groups. Error bars represent standard error of the mean (SEM). * $p < .05$.