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**Desirable difficulties in language learning? How talker variability impacts artificial grammar
learning**

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TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Abstract

Contending with talker variability has been found to lead to processing costs but also benefits by focusing learners on invariant properties of the signal. These discrepant findings may indicate that talker variability acts as a desirable difficulty. That is, talker variability may lead to initial costs followed by long term benefits for retention and generalization. Adult participants learned an artificial grammar affording learning of multiple components by 1-, 2- or 8- talkers, tested at 3 time points. The 8-talker condition did not impact learning. The 2-talker condition negatively impacted some aspects of learning, but only under more difficult learning conditions. Across both experiments, generalization of the grammatical dependency was difficult. Taken together, we discovered that high and limited talker variability differentially impact artificial grammar learning. However, talker variability does not act as a desirable difficulty in the current paradigm, as the few evidenced costs were not related to long-term benefits.

Keywords: artificial grammar learning, statistical learning, talker variability, desirable difficulties, contextual interference

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Introduction

During the process of language acquisition, learners must track speech or manual signals in order to infer the underlying generating model. A well-known challenge for hearing learners is that the input is typically produced by a variety of talkers with distinct vocal characteristics, reflecting variables such as gender, topic, and dialect. Because of these distinct vocal characteristics, the same speech category can differ greatly in its realization (see Boland, Kaan, Valdés Kroff, & Wulff, 2016; Peterson & Barney, 1952). How does exposure to these kinds of variability impact learning? Previous research has indicated that talker variability can lead to processing costs for learners across the lifespan (Jusczyk et al., 1992; Mullennix et al., 1989; Ryalls & Pisoni, 1997). However, increased talker variability can also be helpful for language learning (e.g. Rost & McMurray, 2009); by focusing learners on invariant properties of the signal across talkers it may help learners to abstract the core principles of linguistic structure (e.g. Graf Estes, 2012; Houston & Jusczyk, 2000). Gleaning insight from studies of long-term learning, these discrepant findings might suggest that talker variability during learning may act as a desirable difficulty for the learner (Bjork, 1994), initially introducing a challenge for learners to overcome, followed by better retention and generalization.

One method that reliably produces a desirable difficulty is presenting materials in a variable manner, such as interleaving or spacing trials, which results in temporary interference for the learner (e.g. Bjork, 1994). While this pattern has been extensively studied in non-linguistic domains (e.g. learning motor movements, Shea & Morgan, 1979), it has more recently been investigated in the language domain (Bjork & Kroll, 2015). For example, interleaving 5 different second language grammatical structures, compared to blocking presentation of each type, led to the largest number of errors during training, but highest accuracy on a grammaticality judgment task after a week long delay (Nakata & Suzuki, 2019). Similarly, spacing between presentations benefitted L2 vocabulary learning, specifically for semantically unrelated words (Nakata & Suzuki, 2019; see also Suzuki et al., 2019)

Here we ask whether including talker variability during training is another way of presenting materials in a variable manner to elicit a desirable difficulty. While the majority of studies have focused

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

on varying *how* the input itself is presented to learners (e.g. interleaved and spaced practice), varying the stimuli itself may have a similar effect. Supporting this notion, previous research suggests that increasing the number of exemplars in an artificial grammar learning task allows both infant and adult learners to learn a non-adjacent dependency, which they were unable to do when there is less variability in the exemplars (Gómez, 2002).

Decades of research investigating how learners process talker variability have yielded seemingly conflicting results, suggesting that across tasks and time scales, talker variability can be both helpful and harmful for learning. For example, research on talker normalization (Nusbaum & Magnuson, 1997), the process of extracting the underlying commonalities across speakers, has shown that changes in talker from trial to trial have detrimental effects on word recognition (Mullennix et al., 1989; Creel & Bregman, 2011). Preschool-aged children have greater difficulty identifying familiar words when presented by ten talkers relative to a single talker, though they improve in contending with variability as they age (Ryalls & Pisoni, 1997). Similarly, adults exhibit lower accuracy for word recognition when words are produced by fifteen different talkers (Mullennix et al., 1989). In a more recent study, both adult and child native speakers of Greek learning English words from 4 different talkers exhibited lower accuracy during training relative to those learning the words from a single talker (Giannakopoulou et al., 2017).

However, increased variability can also be beneficial for learning. For example, increased variability can encourage learners to extract invariant properties of the input (Hollich et al., 2002). Rost and McMurray (2009) found that increased talker variability helped 14-month-old infants learn novel minimal pairs that could not be acquired when the words were produced by a single talker, an effect that has similarly been shown for infants learning novel phonotactic rules (Seidl, Onishi, & Cristia, 2014). Preschoolers also benefit from increased talker variability, as 4-year-olds were faster and more accurate to produce novel words when they were spoken by different talkers during training (Richtsmeier et al., 2009).

For adults, increased talker variability appears to be particularly useful in second language (L2) learning contexts. For example, training from multiple talkers can help second language learners acquire a

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

difficult phonemic contrast and generalize it to novel talkers (Lively et al., 1993; Logan et al., 1991).

Further, multi-talker stimuli facilitate the acquisition and generalization of lexical tones by L2 learners even in the absence of experimenter feedback (Liu & Zhang, 2016). Talker variability has also been found to help adult second language learners acquire L2 vocabulary (e.g. Barcroft & Sommers, 2005; Sinkeviciute, Brown, Brekelmans, & Wonnacott, 2019). Together, these results suggest that while high talker variability may be challenging for speech processing, it can also be beneficial for multiple aspects of language learning, for both infants and adults.

The research reviewed thus far focused on the costs and benefits associated with high talker variability (i.e., from many talkers). Limited talker variability, which we define as two talkers, has also been found to produce helpful and detrimental effects for learners, depending on the experimental task. Limited talker variability is thought to encourage learners to track talker-specific information, conflating talker and linguistic information in the initial stages of processing (Goldinger, 1998). That is, learners may come to associate specific linguistic patterns (e.g. phonotactic or grammatical; see Kamide, 2012; Weatherhead & White, 2016) with specific talkers. This can lead to an advantage in processing speed that results from hearing familiar talkers (e.g. Nygaard & Pisoni, 1998) or from hearing a talker produce the same words across time (e.g. Goldinger, 1998; Palmeri et al., 1993). In fact, limited talker variability seems to be particularly useful for learning talker-specific information (see also Choi & Shukla, 2021). For example, when learners are presented with multiple underlying regularities (i.e. artificial speech streams), a change in talker that correlates with the change in regularity helps learners separately track each set of statistics, which they are unable to do when both speech streams are produced by the same talker (Antovich & Graf Estes, 2017; Gonzales, Gerken, & Gómez, 2018; Weiss et al., 2009).

As noted, conflating linguistic and indexical information can also interfere with learning. This is particularly true when learners erroneously track talker-specific information instead of integrating regularities across talkers. For instance, when infant learners were presented with a single artificial speech stream presented by two talkers, they did not exhibit learning, possibly because they were tracking talker-specific information rather than aggregating statistical regularities across talkers (Graf Estes & Lew-

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Williams, 2015; see also Hollich, Jusczyk, & Brent, 2002). Adult L2 learners exhibited lower accuracy in identifying stress patterns when produced by two talkers relative to a single talker, suggesting that they may have encoded the stress patterns as talker-specific rather than abstracting regularities across talkers (Schwab & Dellwo, 2017). Taken together, limited talker variability can be beneficial when each talker is correlated with a linguistic pattern and talker-specific information is informative. Conversely, limited variability appears to be detrimental for identifying regularities across talkers.

In sum, a case can be made that both high and limited talker variability can pose challenges (Graf Estes & Lew-Williams, 2015; Houston & Jusczyk, 2000; Mullennix et al., 1989; Ryalls & Pisoni, 1997) and be beneficial for learning (e.g. Clopper & Pisoni, 2004; Rost & McMurray, 2009). However, these costs and benefits have been observed across different tasks, spanning word recognition and learning, acquiring phonotactic or stress patterns, and extracting statistical regularities. Consequently, it is difficult to infer whether the costs may be related to downstream benefits. Therefore, our study sought to determine whether varying the input by introducing talker variability (high or limited) could act as a desirable difficulty, such that initial costs lead to later benefits. Participants were taught an artificial grammar in one of three talker variability conditions: a 1-Talker condition (i.e. no talker variability), a 2-Talker condition (i.e. limited talker variability) and an 8-Talker condition (i.e. high talker variability).

As the costs and benefits of talker variability may only be evident for some components of learning (e.g., word learning, abstracting regularities), we adopted a grammatical gender artificial grammar learning paradigm that spanned multiple aspects of learning. Our task was based on Arnon and Ramscar (2012), who presented participants novel labels for familiar objects. The objects were divided into two categories, each of which was assigned an article to mirror grammatical gender without phonological or semantic cues to signal class membership. Learners acquired both the noun labels and the article-noun pairings (though learning of the latter depended on training order, see Arnon & Ramscar, 2012) with nouns learned better than the article-noun pairs. In the present study, in addition to teaching novel object labels and article-noun pairings, we added a phonological cue to the nouns to signal category membership, allowing us to test generalization to novel stimuli that conformed to the phonological

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

pattern. As we predicted that talker variability may be particularly useful for learning novel contrasts (as in e.g. Lively et al., 1993; Rost & McMurray, 2009), the phonological cue in Experiment 1 was rather subtle. In Experiment 2, the phonological cue was more overt, to simplify the task. As desirable difficulties can only be evidenced by testing at multiple time points, participants were tested on all three components of the artificial grammar task at three time points over the course of a week. Testing at multiple time points further allows for insight into patterns of retention for multiple components of an artificial grammar. We also included a working memory task (N-back), allowing us to investigate whether differences in performance were related to differences in working memory capacity, as other studies have found that individual differences in perceptual aptitude influence whether learners benefit from talker variability (Dong et al., 2019; Perrachione et al., 2011). As bilingual experience has been shown to impact how learners process different talkers (e.g. Bregman & Creel, 2014), we restricted our study to monolingual adults, which is the most homogenous sample with respect to language background.

Thus, in the current manuscript we aim to address the following questions:

RQ1: Do high and limited talker variability during learning act as a desirable difficulty, as evidenced by lower initial accuracy but better long-term retention and generalization?

RQ2: What are patterns of retention across three components of artificial grammar learning?

Experiment 1

Participants

Participants were 144 monolingual American English speakers (20 males, mean age = 18.85 years; $sd = 1.50$) recruited from an Intro to Psychology course who received course credit for participation, 48 participants were assigned to each condition. Due to a foreign language requirement, all but one participant reported experience learning another language, though they self-rated their proficiency at 3.36 ($sd = 1.34$) on a 10-point scale, and none self-rated above 6 (criteria previously used to identify bilingual participants; Poepel & Weiss, 2016). For the majority (133/144) of participants, the language they reported experience with has grammatical gender (Spanish, French, Italian). An additional 59

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

participants were recruited but excluded due to not returning for the Delayed Test ($n = 19$), reporting high proficiency in a language other than English or learning a language other than English prior to the age of 8 ($n=14$), not following instructions ($n=7$), technical difficulties ($n = 7$), or reporting low-effort (self-reporting 5 or below on a 10-point scale; $n=12$; see Mitchel & Weiss, 2010, 2013)¹. Informed consent was obtained from all participants prior to participation.

Stimuli

All stimuli are available on OSF (<https://osf.io/zrmqh/>). The stimuli consisted of 60 novel objects, 60 novel words (hereafter *nouns*), and 2 novel articles adapted from previous experiments (Arnon & Ramscar, 2012; Poepel & Weiss, 2016, see Appendix S1). Twenty-four of the novel objects-word pairs were used during familiarization, with the remainder used at test. The objects consisted of black and white complex line drawings. Eight objects appeared in the stimuli used by Creel, Aslin, and Tanenhaus (2008) and served as a template for creating the remaining objects (using MS Paint[®]). The objects were converted to a .jpeg file format with a size of 150 by 150 pixels. All of these objects were used in a previous experiment (Poepel & Weiss, 2016). All of the novel nouns were created using English phonology, and ranged from 2 to 3 syllables, ending with a vowel. All final syllables were CV, while syllables that occurred earlier in the word could be CV, CVC, or CCV. Half of the nouns ended in a front /a/ vowel (Category 1), while the other half ended with a back /ɑ/ vowel (Category 2). The articles were two monosyllabic artificial words, *sem* and *bol*, used in a previous study (Arnon & Ramscar, 2012).

The auditory stimuli were recorded by 8 female native talkers of American English who were asked to produce the vowel contrast. We recorded each word and article in a sentence frame. Each target word (article, noun) was spliced from the sentence frame in which it occurred in its correct position. For example, all nouns were recorded in sentence final position (e.g. ‘This is a barcha’), while each article was recorded in sentence initial position. This was done to ensure consistency in pronunciation across conditions. The trained talkers were recorded in a soundproof booth using a Dynamic[®] microphone connected to a Marantz[®] recorder. The procedure for the recordings was as follows: the first trained talker

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

(LK) read a sentence out loud, and then each talker was asked to repeat the sentence. This was done to ensure that phonetic features (such as vowels and flaps) remained relatively consistent across talkers.

Background noise was removed from the recordings using the Noise Reduction feature in Audacity[®]. Each word was subsequently normalized to a maximum amplitude using the Normalization feature in Audacity[®], such that peak volume remained consistent across all talkers. The articles and nouns were concatenated to form noun phrases (e.g., Sem barcha). The noun phrases were created such that the article was always perfectly correlated with one of the two categories of nouns, the article-category pair was counterbalanced across participants. This resulted in an underlying regularity between the article and vowel ending of the nouns, which we refer to as the category rule.

Design

Participants were assigned to one of three conditions: 1-Talker, 2-Talker, and 8-Talker. In the 1-Talker condition, all stimuli were presented by a single talker (counterbalanced between 2 talkers), and hence did not have between-talker variability. In the 2-Talker condition, all stimuli were presented by two talkers (the same 2 talkers that were counterbalanced for the 1-Talker condition); participants heard each item produced by each talker. In the 8-Talker condition, stimuli were presented by all 8 talkers, resulting in high between-talker variability during familiarization; as each item was repeated 5 times, not all talkers produced all items, but each instance of an item was produced by a different talker. For trials in the 2-Talker and 8-Talker conditions, the talker varied randomly trial-by-trial (i.e., familiarization was not blocked by talker). Participants heard a single talker at test (one of the two used in the 1- and 2- talker conditions), which was counterbalanced across participants and was always one heard during familiarization (see Appendix S2 for counterbalancing and Appendix S3 for the mean pitch of experimental talkers).

Procedure

Participants were seated at a computer in a sound attenuated booth and instructed that they would learn novel names for novel objects. They were asked to listen through headphones and told that they would be asked questions about what they learned. During familiarization, participants viewed a picture

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

of one of the objects on the screen and heard a noun phrase describing the object. Each of the 24 objects used during familiarization was repeated 5 times, in randomized order, for a total of 120 trials. Each image remained on the screen for 5 seconds, then the program automatically advanced to the next image and corresponding noun phrase. Following familiarization, participants completed three test types (described below) that were conducted at three time points (see Figure 1A). The first test (Immediate Test) occurred immediately after familiarization, while the second test occurred 15 minutes later (Short Delay Test). During the 15 minute delay, participants completed an N-back task of working memory and a Language History Questionnaire (Li et al., 2006). Participants subsequently returned a week later to complete the third test (Long Delay Test).

Each test type consisted of 12 test items, totaling 36 items per test phase. For all of the tests, participants viewed a single image on the screen, and heard two noun phrases, separated by a 1s pause. Participants were then asked to choose which noun phrase correctly described the image (by pressing “1” for the first option or “2” for the second). The image remained on the screen until the participant made a response. The order of the sentences heard during all tests was counterbalanced across trials, such that half the trials presented the correct sentence first, and half the incorrect sentence first.

The first test type asked whether participants had learned the noun-object mappings (hereafter Noun Test). During the Noun Test, participants always heard noun phrases consisting of the correct article, paired with either the correct or an incorrect noun (see Figure 1B). The competitor noun was always from the same category, so that it occurred with the same article during familiarization. Twelve of the object-noun pairs (six per category) from familiarization were used for the noun test across all testing phases. The second test type (Article Test) investigated learning of the article-noun pairings. Participants heard two noun phrases consisting of the correct noun, and either the correct or incorrect article. The 12 object-noun pairs from familiarization not used for the noun test were used for the article test across all testing phases. The last test type assessed participants’ ability to generalize the category rule to novel instances (Generalization Test). Participants heard phrases containing a single novel label that matched one of the category rules (e.g. *veama* matched Category 1, *bosaw* matched Category 2). One of the noun

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

phrases contained the article *sem* and the other noun phrase contained the article *bol* (e.g. *Sem veama* versus *Bol veama*, see Figure 1B). While participants had not previously encountered the object nor label, if they inferred the category rule, they should select the correct noun phrase based on the article correctly matching the phonological category of the word. The thirty-six novel objects and labels not used during familiarization were used for the generalization test, 12 at each of the three testing phases. The generalization test was very similar to the Article Test, the critical difference is that in the Article Test, participants responded to article and noun pairs that they heard during familiarization, whereas in the Generalization Test, the nouns and objects were novel. In order to succeed on the Generalization Test, participants had to acquire and generalize the category rule, whereas for the Article Test they could respond correctly by either learning the rule or recalling instances from familiarization. During the experiment, participants completed the Generalization test first, to minimize additional exposure to the familiarized items before generalization, followed by the Noun and Article test².

A.

B.

Figure 1. A. Timeline of the experiment. B. Examples of familiarization and test trials.

Working memory

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Participants also completed the N-back test of working memory that consisted of four conditions (adapted from Hakun & Johnson, 2017). In the compare condition, participants judged whether two letters, presented side by side, were the same. In all other conditions, participants viewed one letter at a time for 2000ms each, followed by a 500 ms ISI. During the 1-back condition, participants were asked to judge whether the current letter was the same as the letter presented right before it. For the 2-back and 3-back conditions, participants had to judge whether the current letter matched the letter presented two or three letters before it respectively. The letters used during the task were: B, F, K, H, M, Q, R and Y. Each block type (1-back, 2-back, 3-back) consisted of 15 trials, with 4 trials per block requiring a “yes” response. Overall accuracy was calculated for each participant by averaging performance on the 1-back, 2-back and 3-back conditions. For each condition, trials at the beginning of the block that could not have been responded to according to the rule were excluded (e.g. the first trial in the 1-back condition, as no trial occurred before it). Internal consistency (Cronbach’s alpha) for this N-back task ranged from 0.86 (Exp 1) to 0.89 (Exp 2).

Results

All analyses were conducted in R (R Core Team, 2017) using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2015), all data and analyses scripts can be found on OSF (<https://osf.io/zrmqh/>). Three separate models were conducted, one each for Noun, Article and Generalization Tests. We conducted a logistic mixed effects analysis investigating performance across the Immediate, Short Delay and Long Delay tests based on condition. Test time (Immediate, Short Delay and Long Delay), Talker Variability condition (1-Talker, 2-Talker, 8-Talker) and the interaction between these variables were fixed effects; N-back performance and talker used at test were entered as covariates; with by-participant and by-item random effects added to the model³. The contrasts for talker variability conditions test the effect of Talker Variability compared to No Variability (contrasts: 1-Talker = 1, 2-Talker = -.5, 8-Talker = -.5) and then compared the two Talker Variability conditions to each other (contrasts: 1-Talker = 0, 2-Talker = 1, 8-Talker = -1). The contrasts for test time address RQ2, testing differences between the Immediate and Short Delay test (contrasts: Immediate = 1, Short Delay = -1, Long Delay = 0) and the Immediate and

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Short Delay tests to the Long Delay test (contrasts: Immediate = -.5, Short Delay = -.5; Long Delay = 1).

The interactions between these two contrasts asks whether patterns of retention or forgetting differ across talker variability conditions, addressing RQs 1 and 2.

The final model formula is as follows: $\text{Accuracy} \sim \text{TalkerVariabilityCondition} * \text{Test time} + \text{Nback} + \text{Test Talker} + (1 + \text{TalkerVariabilityCondition} | \text{Subject}) + (1 | \text{Item})^4$

Visual inspection of residual plots did not reveal any obvious deviations from normality or homoscedasticity. Raw performance across all test types, test times and conditions, can be found in Figure 2 and Table 1, along with estimated means and 95% confidence intervals from the models. See Appendix S4 for full model tables.

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Figure 2. Experiment 1 raw mean accuracy (y-axis) across test time (panels labeled 1, 2, 3), condition (on x-axis). Test type (Noun, Article, Generalization) are each plotted separately. Error bars reflect 95% CI. The black line indicates chance performance (50%).

Table 1. Mean and SDs across test type, test time and condition. T-tests reflect comparison against chance (50%) performance. * denote above chance performance after correcting for multiple comparisons (Bonferroni corrected p-value = .005).

	Immediate		Short Delay		Long Delay	
	Mean(sd)/ Estimated Mean 95% CI	t-test	Mean(sd)/ Estimated Mean 95% CI	t-test	Mean(sd)/ Estimated Mean 95% CI	t-test
Noun						
1-Talker	80.0(16) 84[78,89]	t(47) = 13.0, p <.001 *	81.1(14) 85[79,90]	t(47) = 15.6, p<.001*	71.2(20) 75[67,82]	t(47) = 7.43, p<.001*
2-Talker	75.7(18) 80[73,86]	t(47) = 10.1 p<.001*	75.9(16) 80[73,86]	t(47) = 11.2, p<.001*	69.3(17.5) 73[65,80]	t(47) = 7.61, p<.001*
8-Talker	77.4(18) 82[75,88]	t(47) = 10.8, p<.001*	76.2(20) 81[74,87]	t(47) = 9.27, p<.001*	67.5(20) 72[63,80]	t(47) = 6.22, p<.001*
Article						
1-Talker	59.2(15) 60[54,64]	t(47) = 4.13, p<.001*	57.6(14) 58[53,63]	t(47) = 3.82, p<.001*	58.7(16) 59[54,64]	t(47) = 4.37, p<.001*
2-Talker	51.0(20) 51[44,58]	t(47) = .36, p = .71	51.0(18) 51[44,58]	t(47) = .41, p = .68	50.7(21) 51[44,58]	t(47) = .23, p = .82
8-Talker	60.6(15) 61[55,66]	t(47) = 4.81, p <.001*	61.5(13) 62[56,67]	t(47) = 6.03, p<.001*	57.8(16) 58[53,63]	t(47) = 3.39, p=.001*
Generalization						

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

1-Talker	52.1(17) 52[48,56]	t(47) = .87, p=.38	46.4(15) 46[42,51]	t(47) = 1.67, p=.10	47.4(17) 47[43,52]	t(47) = 1.12, p=.27
2-Talker	53.6(14) 53[49,57]	t(47) = 1.78, p = .08	47.4(16) 47[43,52]	t(47) = 1.12, p=.27	50.9(17) 52[47,56]	t(47) = .36, p=.72
8-Talker	50.1(20) 50[46,55]	t(47) = .06, p=.95	54.7(16) 55[51,59]	t(47) = 1.99, p=.05	47.5(17) 48[43,52]	t(47) = .97, p=.33

Noun test

As can be seen in Table 1, performance exceeded chance across all test times and conditions, even after Bonferroni correction for multiple comparisons. The logistic mixed effects model (marginal r-squared = .03; conditional r-squared = .26) for the Noun Test revealed an effect of Test Time, such that performance at the Immediate test and the Short Delay test ($M = 78$, $SD = 17$) was significantly higher than at the Long Delay test ($M = 69$, $SD = 19$), $\beta = -.52$, $SE = .07$, $z = 7.19$, $p < .001$. There was no difference in performance between the Immediate and the Short Delay test, $\beta = -.005$, $SE = .088$, $z = -.062$, $p = .95$, suggesting that forgetting occurred only after the longer delay. Performance did not significantly differ between the 1-Talker condition and the 2- and 8- Talker conditions, $\beta = .20$, $SE = .18$, $z = 1.13$, $p = .26$, or between the 2-talker and 8-talker conditions, $\beta = -.05$, $SE = .22$, $z = .22$, $p = .83$ indicating that talker variability condition did not impact word learning. The effect of the talker used at test was not significant, $\beta = .14$, $SE = .17$, $z = .83$, $p = .41$. None of the interactions were significant (Immediate vs. Short Delay X 1-Talker vs. 2 and 8 Talker: $\beta = -.10$, $SE = .19$, $z = -.55$, $p = .58$; Immediate vs. Short Delay X 2-Talker vs. 8-Talker: $\beta = -.10$, $SE = .21$, $z = .49$, $p = .62$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = -.12$, $SE = .15$, $z = .76$, $p = .45$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = .17$, $SE = .17$, $z = .98$, $p = .33$. There was, however, an effect of N-back performance, $\beta = 1.75$, $SE = .60$, $z = 2.93$, $p = .003$, such that better performance on the working memory task was correlated with higher accuracy on the noun test, $r = .08$, $p < .001$.

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Article test

As seen in Table 1, participants in the 2-Talker condition never exceeded chance, while those in the 1- and 8-Talker conditions did at all three time points. The logistic mixed effects model for the Article Test (marginal r-squared = .009; conditional r-squared = .07) revealed no effects of Test Time, such that performance did not change from the Immediate to the Short Delay test, $\beta = -.007$, $SE = .071$, $z = -.1$, $p = .92$; nor from the Immediate and Short Delay tests to the Long Delay, $\beta = -.041$, $SE = .061$, $z = -.68$, $p = .50$, suggesting that participants who performed above chance on the Immediate Test did not forget the article-noun mappings over the course of the experiment. While performance did not differ between the 1-Talker condition and the two talker variability conditions, $\beta = .12$, $SE = .08$, $z = 1.43$, $p = .15$, performance between the 2- and 8-Talker conditions did differ, $\beta = -.38$, $SE = .12$, $z = 3.04$, $p = .002$, as participants in the 2-Talker ($M = 51$, $SD = 19$) condition exhibited lower accuracy than those in the 8-Talker condition ($M = 60$, $SD = 15$; see Table 1). The effect of the talker used at test was not significant, $\beta = -.017$, $SE = .08$, $z = -.21$, $p = .83$, and the effect of N-back was not significant, $\beta = .31$, $SE = .29$, $z = 1.08$, $p = .28$. None of the interactions were significant (Immediate vs. Short Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .09$, $SE = .15$, $z = -.60$, $p = .55$; Immediate vs. Short Delay X 2-Talker vs. 8-Talker: $\beta = -.03$, $SE = .18$, $z = .17$, $p = .86$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .08$, $SE = .13$, $z = .60$, $p = .54$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = .14$, $SE = .15$, $z = .94$, $p = .35$).

Generalization test

As seen in Table 1, participants did not exceed chance at any test time, regardless of condition, after Bonferroni correction for multiple comparisons. The logistic mixed effects model for the Generalization test (marginal r-squared = .005; conditional r-squared = .008) revealed no effect of Test Time, such that performance did not change from the Immediate to the Short Delay, $\beta = .092$, $SE = .07$, $z = 1.35$, $p = .18$, nor from the Immediate and the Short Delay to the Long Delay, $\beta = -.073$, $SE = .06$, $z = 1.23$, $p = .22$. There was also no effect of Condition, such that performance did not differ between the 1-talker and the talker variability conditions, $\beta = -.09$, $SE = .062$, $z = 1.43$, $p = .15$, nor between the 2-talker

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

and the 8-talker condition, $\beta = -.008$, $SE = .072$, $z = .12$, $p = .91$. There was, however, a significant interaction between the 2-talker and 8-talker condition, and the Immediate and Short Delay tests, $\beta = -.41$, $SE = .168$, $t = 2.44$, $p = .015$, such that for the 2-talker condition, performance decreased from the Immediate ($M = 54$, $SD = 14$) to the Short Delay test ($M = 47$, $SD = 16$) while for the 8-talker condition performance increased from the Immediate ($M = 50$, $SD = 20$) to the Short Delay test ($M = 55$, $SD = 16$; see Table 1). As all raw mean comparisons did not exceed chance after correcting for multiple comparisons, we do not interpret this interaction further. All other interactions were not significant (Immediate vs. Short Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .21$, $SE = .15$, $z = 1.43$, $p = .15$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = -.0002$, $SE = .13$, $z = -.002$, $p = .99$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = .25$, $SE = .15$, $z = 1.69$, $p = .09$). The effects of N-back ($\beta = .33$, $SE = .21$, $z = 1.45$, $p = .10$) and talker used at test ($\beta = .05$, $SE = .06$, $z = 0.88$, $p = .38$) were not significant.

Discussion

We investigated whether talker variability during learning of an artificial grammar acted as a desirable difficulty. Participants were taught an artificial grammar that afforded learning of three components: nouns that labeled objects, article-noun pairings, and generalization of a category rule, and tested at three time points. Talker variability did not impact learning of the object labels, as performance did not differ across talker variability conditions. By contrast, limited talker variability did impact learning the article-noun pairs, as participants in the 2-Talker condition did not exhibit learning at any time point, while those in the 1-Talker and 8-Talker conditions exceeded chance at all time points. Lastly, talker variability did not impact generalization to novel exemplars, as participants did not exceed chance regardless of talker variability condition. Across the board, retention was robust and not dependent on talker variability condition.

The lack of generalization could suggest that participants learned only the specific token and article combinations due to not being able to hear the vowel contrast, which is not contrastive in

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

American English (the dialect of participants in the experiment). In order to address this possibility, we conducted an additional experiment testing whether a novel group of participants could distinguish between the vowels at the end of the words when the words were presented in isolation. Results from this can be found in Appendix S5 and suggest that participants may have been able to hear the vowel difference. If so, lack of generalization could suggest that despite noticing the difference, participants did not notice it as a defining feature of the category. Given the lingering uncertainty of how the difficult contrast impacted performance, in Experiment 2 we explored this issue further by using a more salient vowel contrast.

Experiment 2

In Experiment 1, we modified a task previously used by Arnon and Ramscar (2012), but added a subtle phonological cue to category structure, to enable us to test an additional component of learning: generalization of the grammar to novel exemplars. Comparing performance on the article-noun pairs in Experiment 1 to the results reported by Arnon and Ramscar (2012) suggests that accuracy was quite similar, and the addition of the phonological regularity did not appear to impact performance. It is possible that the phonological cue may have been too difficult (though participants could hear the vowel difference, see Appendix S5), as overall accuracy on the test of generalization was low. In Experiment 2, we investigated whether an easier vowel contrast (/i/ vs. /a/) would lead to better learning of the category rule, as reflected by better performance on the tests of the article-noun pairs and perhaps generalization. The methods were identical to those described previously except for the easier vowel distinction.

Participants

Participants were 147 monolingual English speakers (23 males, mean age = 18.43 years; $sd = 0.71$) recruited from an Intro to Psychology course and received course credit for participation. Forty-eight participants were assigned to the 1-Talker condition, 47 to the 2-Talker condition, and 52 to the 8-Talker condition. Due to a foreign language requirement, all but two participant reported experience learning another language, though they self-rated their proficiency at 3.4 ($sd = 1.36$) on a 10-point scale,

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

and none self-rated above 6. The majority (130/147) reported exposure with a language that has grammatical gender (Spanish, French, Italian). An additional 83 participants were recruited but excluded due to not returning for the Delayed Test ($n = 27$), reporting high proficiency in a language other than English or learning a language other than English prior to the age of 8 ($n = 25$), technical difficulties ($n = 10$), not following directions ($n = 2$), or reporting low-effort (self-reporting 5 or below on a 10-point scale on either day; $n = 19$; see Mitchel & Weiss, 2010, 2013)⁵.

Stimuli

The stimuli were the same as those used in Experiment 1, but now half of the words ended in an /i/ vowel, while the other half ended with a back /a/ vowel (Category 2). The stimuli were recorded by the same 8 talkers used in Experiment 1, see Appendix S3 for mean pitch across experimental talkers.

Procedure

The procedures and conditions were identical to those used in Experiment 1.

Results

All analyses were conducted in R (R Core Team, 2017) using the *lme4* package (Bates, Maechler, Bolker & Walker, 2015). Performance for participants in all three conditions can be found in Figure 3 and Table 2.

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Figure 3. Experiment 2 raw accuracy across all three time points, test types and conditions. Error bars reflect 95%CI. The black horizontal line indicates chance performance (50%).

Table 2. Experiment 2 Mean and SDs, as well as estimated marginal means and 95% CI across test type, test time and condition. T-tests reflect comparison against chance (50%) performance. Asterisks denote above chance performance after correcting for multiple comparisons (Bonferroni corrected p-value = .005).

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

	Immediate		Short Delay		Long Delay	
	Mean(sd)/ Estimated mean – 95%CI	t-test	Mean(sd)/ Estimated mean – 95%CI	t-test	Mean(sd)/ Estimated mean – 95%CI	t-test
Noun						
1-Talker	77.1(18) 80[73,86]	t(47) = 10.48, p < .001*	77.1(16) 80[73,86]	t(47) = 11.87, p < .001*	71.5(17) 75[66,82]	t(47) = 8.91, p < .001*
2-Talker	75.2(17) 79[71,86]	t(46) = 10.17 p < .001*	73.8(18) 78[69,84]	t(46) = 8.85, p < .001*	67.4(19) 71[61,79]	t(46) = 6.24, p < .001*
8-Talker	75.3(18) 79[72,85]	t(51) = 10.0, p < .001*	74.0(18) 78[70,84]	t(51) = 9.52, p < .001*	69.1(16) 73[64,80]	t(51) = 8.40, p < .001*
Article						
1-Talker	61.(12) 61[56,67]	t(47) = 6.34, p < .001*	61.6(15) 62[56,67]	t(47) = 5.39, p < .001*	59.2(18) 59[53,64]	t(47) = 3.56, p = .002*
2-Talker	65.4(13) 66[61,71]	t(46) = 8.44, p < .001*	60.8(16) 61[56,66]	t(46) = 4.57, p < .001*	56.6(23) 57[51,62]	t(46) = 1.96, p = .056
8-Talker	64.9(13) 66[60,70]	t(51) = 8.38, p < .001*	60.9(11) 62[56,67]	t(51) = 7.22, p < .001*	60.1(14) 61[55,66]	t(51) = 5.19, p < .001*
Generalization						
1-Talker	51.9(14) 52[48,56]	t(47) = .93, p = .35	45.1(16) 45[41,49]	t(47) = 2.15, p = .037	51.9(16) 52[48,56]	t(47) = .85, p = .40
2-Talker	49.1(15) 49[45,53]	t(46) = .41, p = .68	51.9(16) 52[47,56]	t(46) = .83, p = .40	54.4(16) 54[50,58]	t(46) = 1.93, p = .059
8-Talker	51.9(14) 52[48,56]	t(51) = .96 p = .34	50.5(15) 51[48,56]	t(51) = .24, p = .81	49.5(15) 50[46,54]	t(51) = .23, p = .81

Noun test

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Performance was above chance at all time points, regardless of condition (see Table 2). The logistic mixed effects model for the Noun Test (marginal r -squared = .012, conditional r -squared = .236) revealed an effect of Test Time, such that performance at the Immediate test and the Short Delay test ($M = 75$, $SD = 18$) was significantly higher than at the Long Delay test ($M = 69$, $SD = 17$), $\beta = -.36$, $SE = .07$, $z = 5.09$, $p < .001$. There was no difference in performance between the Immediate and the Short Delay test, $\beta = -.051$, $SE = .084$, $z = .615$, $p = .54$, suggesting that forgetting occurred only after the longer delay. Performance did not significantly differ between the 1-Talker and the talker variability conditions, $\beta = .12$, $SE = .17$, $z = 0.70$, $p = .48$, or between the 2-talker and 8-talker conditions, $\beta = -.03$, $SE = .20$, $z = -.17$, $p = .86$, indicating that talker variability condition did not impact word learning. The effect of the talker used at test ($\beta = -.01$, $SE = .16$, $z = -.36$, $p = .98$) and N-back ($\beta = .91$, $SE = .45$, $z = 1.87$, $p = .06$) were not significant, and neither were any of the interactions, (Immediate vs. Short Delay X 1-Talker vs. 2 and 8 Talker: $\beta = -.09$, $SE = .18$, $z = -.52$, $p = .60$; Immediate vs. Short Delay X 2-Talker vs. 8-Talker: $\beta = .008$, $SE = .20$, $z = .04$, $p = .97$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .03$, $SE = .15$, $z = .22$, $p = .83$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = -.08$, $SE = .17$, $z = -.49$, $p = .62$).

Article test

Participants in all three conditions exhibited above-chance performance at the Immediate and Short Delay tests, and those in the 1- and 8-Talker conditions continued to do so even after the Long Delay while those in the 2-Talker condition exhibited more forgetting (see Table 2). The logistic mixed effects model (marginal r -squared = .004; condition r -squared = .051) for the Article Test revealed an effect of Test Time, such that performance at the Immediate test and the Short Delay test ($M = 63$, $SD = 13$) was significantly higher than at the Long Delay test ($M = 59$, $SD = 18$), $\beta = -.172$, $SE = .06$, $z = 2.83$, $p = .005$. There was no difference in performance between the Immediate and the Short Delay test, $\beta = .12$, $SE = .07$, $z = 1.724$, $p = .08$, suggesting that forgetting occurred only after the longer delay. Performance did not significantly differ between the 1-Talker and the talker variability conditions, $\beta = -.05$, $SE = .087$,

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

$z = -.60, p = .55$, or between the 2-talker and 8-talker conditions, $\beta = -.05, SE = .10, z = -.54, p = .59$

indicating that talker variability condition did not impact learning of the article-noun pairs. The effect of the talker used at test ($\beta = -.03, SE = .08, z = .42, p = .67$) and N-back ($\beta = .29, SE = .26, z = 1.13, p = .26$) were not significant, and neither were any of the interactions, (Immediate vs. Short Delay X 1-Talker vs. 2 and 8 Talker: $\beta = -.21, SE = .15, z = -1.37, p = .17$; Immediate vs. Short Delay X 2-Talker vs. 8-Talker: $\beta = .03, SE = .17, z = .17, p = .87$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .10, SE = .13, z = .75, p = .45$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = -.16, SE = .15, z = -1.10, p = .27$).

Generalization test

Performance never exceeded chance after correcting for multiple comparisons (see Table 2). The logistic mixed effects model (marginal r-squared = .003, conditional r-squared = .004) for the Generalization Test revealed no difference between the Immediate and the Short Delay test ($\beta = .07, SE = .07, z = 1.06, p = .29$), and no difference between the Immediate and Short Delay tests relative to the Long Delay test ($\beta = .08, SE = .06, z = -1.32, p = .19$). There were also no difference between conditions (1-Talker vs. 2 and 8 Talker: $\beta = -.07, SE = .06, z = -1.13, p = .26$; 2 talker vs. 8 talker: $\beta = .04, SE = .07, z = .55, p = .58$). There was, however, a significant interaction between the 1-talker and talker variability conditions and the Immediate and Short Delay tests, $\beta = .30, SE = .15, t = 2.06, p = .04$. For the 1-talker condition, performance decreased from the Immediate ($M = 52, SD = 14$) to the Short Delay test ($M = 45, SD = 16$) while it did not for the talker variability conditions (Immediate: $M = 51, SD = 15$; Short Delay: $M = 51, SD = 15$; see Table 2). As performance did not exceed chance after correcting for multiple comparisons, we do not interpret this interaction further. None of the other interactions were significant (Immediate vs. Short Delay X 2-Talker vs. 8-Talker: $\beta = -.17, SE = .16, z = -1.04, p = .30$; Immediate and Short Delay vs. Long Delay X 1-Talker vs. 2 and 8 Talker: $\beta = .10, SE = .13, z = .78, p = .44$; Immediate and Short Delay X 2-Talker vs. 8-Talker; $\beta = .22, SE = .14, z = -1.57, p = .12$). The effect of the talker

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

used at test ($\beta = -.03$, $SE = .06$, $z = -.60$, $p = .55$) and N-back ($\beta = .18$, $SE = .18$, $z = 1.05$, $p = .30$) were not significant.

Discussion

In Experiment 2, we modified the artificial grammar such that the vowel contrast across the two categories was easier to distinguish. Across all test types, there was no effect of talker variability condition. Further, even participants in the 2-Talker condition learned the article-noun pairs, which is likely due to the change in the vowel contrast across experiments. Simplifying the vowel contrast may have resulted in less interference from the 2-talker condition (as the categories were clearer) but did not impact the ability to generalize in any of the conditions. Thus, Experiment 2 suggests that when categories are easier to distinguish, limited talker variability does not impose a challenge for learning in the context of this experimental task.

General Discussion

Across two experiments, we investigated the impact of talker variability on multiple aspects of artificial grammar learning asking whether talker variability might act as a desirable difficulty for the learner. Participants were taught an artificial language that afforded learning three types of information (object labels, article-noun pairs, and a category rule) by 1, 2, or 8 talkers, and then were tested at three time points: immediately after familiarization, after a short 15-minute delay, and after a long 1-week delay. In Experiment 1, participants exhibited learning and retention of the nouns regardless of talker variability condition, suggesting that changes in the number of talkers did not have a detrimental impact on learning. By contrast, only participants in the 1- and 8-talker conditions exhibited learning of the article-noun pairs. In Experiment 2, we used an easier vowel contrast to signal category identity and replicated results on the noun test while boosting learning of the article-noun pairs in the 2-Talker condition. Across both experiments, performance on the generalization test hovered near chance, suggesting that participants learned the frozen article-noun combinations, but did not acquire the long-distance dependency. We also tested whether performance on the artificial grammar task was related to

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

working memory abilities. We found that working memory predicted learning on the noun test, though this effect was only significant in Experiment 1.

Talker variability as a desirable difficulty

If talker variability acted as a desirable difficulty for artificial grammar learning, we would have expected to see initially lower performance for participants in the talker variability conditions relative to the baseline 1-talker condition, followed by benefits for retention or generalization to novel exemplars. While previous research suggests that contending with rapid changes in talker negatively impacts word recognition even for adults (Mullennix et al., 1989), here we found that high talker variability does not pose an additional challenge for artificial grammar learning. Limited talker variability, however, did lead to challenges for learners, but only for learning the article-noun pairs in Experiment 1. As participants had to integrate the input across the two talkers (as both talkers produced exemplars from both categories), tracking talker-specific information seems to have interfered with learning, as has been shown in previous research (Graf Estes & Lew-Williams, 2015). Overall, however, we did not find any evidence that talker variability is beneficial for learning. Thus, we do not find support for the notion that talker variability acts as a desirable difficulty, at least in the context of our task, as the only evidenced cost did not result in a long-term benefit.

While talker variability may not act as a desirable difficulty, we discovered that high and limited talker variability differentially impact learning on the same task, but only when the categories were more difficult to distinguish. That is, the addition of limited talker variability in Experiment 1 inhibited learning of the articles across all three time points (see also Brown & Gaskell, 2014 for sustained talker-specificity effects). In comparison, when the categories were easier to distinguish (Experiment 2), participants exhibited similar levels of learning regardless of talker variability condition. This pattern of results suggests that when the task is more challenging and two talkers produce the input, learners may be most likely to track talker-specific information, which in this case interfered with learning as both talkers produced both categories. Thus, limited talker variability may only be helpful in challenging situations when it perfectly corresponds to changes in structure. Under these circumstances, previous studies have

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

found it can be used as a learning support, perhaps drawing attention to the talker-specific change (e.g. Antovich et al., 2020; Graf Estes & Lew-Williams 2015; Weiss et al., 2009; Zinszer & Weiss, 2012).

A lack of evidence that talker variability acts as a desirable difficulty in the current task does not rule out the possibility that it could in other settings. For example, it is possible that challenges associated with processing talker variability may be evident during learning, rather than during the retrospective test. Additionally, talker variability may act as a desirable difficulty for only some aspects of language learning. For example, benefits associated with high talker variability have been found when learners need to acquire contrastive features of the input in their first or second language (e.g. Lively et al., 1993; Logan et al., 1991; Rost & McMurray, 2009). Given the problem of invariance described at the outset of this article, it is possible that talker variability may be most likely to act as a desirable difficulty when learning phonological properties of language (such as minimal pairs). Future research should continue to investigate whether talker variability acting as a desirable difficulty is a viable proposition for other aspects of language learning.

Retention of Learning

The current study also established a pattern of retention for learning several components of an artificial language at multiple time points in adults, demonstrating that participants retain learned information after short and (relatively) long delays after a brief familiarization period, without any reexposure. Importantly, patterns of retention were not moderated by variability during learning. Previous research has shown that adults can retain names of novel objects learned in a cross-situational statistical learning task (CSSL) after a week long delay (Vlach & Sandhofer, 2014). In our study, participants retained both the novel object labels and the article-noun pairs (when they were learned). These results add to a growing body of literature indicating that information learned during artificial language studies can lead to lasting memory traces (Arciuli & Simpson, 2012; Frank et al., 2013; Kóbor et al., 2017), even after a substantial period of no exposure (e.g. 5 months, see Morgan-Short et al., 2012), which is essential for understanding how artificial language studies can scale up to real world applications.

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Previous research suggests that retrieval practice, the act of spacing tests throughout the learning process, can be helpful for improving memory (see Balota et al., 2007; Cepeda et al., 2006 for reviews). However, the amount of time between tests is also important, as younger adults benefit more from a short lag between tests relative to a longer lag (Maddox & Balota, 2015). In the current study, participants engaged in two retrieval attempts on day 1 (immediately and 15 minutes after familiarization), followed by a long-term retention test a week later. It is possible that these repeated tests boosted retention, though only for the trained exemplars (noun and article test) and not for generalization. While previous research suggests that one retrieval attempt is sufficient for eliciting better long term learning (Adesope et al., 2017; Rowland, 2014 for meta-analyses), an open question for future research is whether either the immediate or the brief delay was more beneficial for long-term retention, as testing shortly after introducing a novel concept could be particularly beneficial for second language learning contexts.

The role of individual differences

Individual differences may also affect whether talker variability acts as a desirable difficulty. Previous research suggests that working memory is related to various aspects of vocabulary and grammar learning, for both L1 and L2 learners (e.g. Martin & Ellis, 2012; Verhagen & Leseman, 2016). Thus, we included a working memory task that assesses on-line monitoring, updating, and manipulation (Owen et al., 2005) to identify possible individual differences that may affect performance on the task. We found that working memory was only related to word learning in Experiment 1, but individual differences in working memory capacity did not predict performance on any other aspects of learning.

Additionally, individual motivation to learn may be an important factor in eliciting desirable difficulties. For example, Suzuki, Nakata, and Dekeyser (2019) argue that, for second language learning, desirable difficulties may in part be related to learner-specific factors such as motivation. They argue that deliberate practice (Ericsson, 2006), which should bring out the learner's near maximum effort by requiring full attention and taking place outside one's comfort zone, may be critically important for understanding when a difficult learning condition may be desirable. Thus, we may not have found evidence that talker variability acted as a desirable difficulty if processing talker variability was not

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

challenging for learners. A measure of perceived difficulty or individual aptitude (Perrachione et al., 2011) for contending with talker variability could be helpful for future research to gain a better understanding of whether processing changes in talker increases difficulty. Further, the implicit nature of this task does not allow us to know the strategies participants used in order to learn the components of the artificial grammar. That is, some participants could have been more deliberate in their approach to the task, trying to figure out the regularities. Talker variability may have different effects depending on the learning strategy (or lack thereof) that participants employed.

Grammatical dependencies

The category rule was designed to simulate grammatical gender, which some languages use to categorize nouns into subclasses based on linguistic or arbitrary criteria (Corbett, 1991). These languages often require gender agreement, matching the grammatical gender of the noun with other grammatical classes that carry gender markings, such as adjectives and articles (see Grüter, Lew-Williams, & Fernald, 2012, Carstens 2000). While some languages (e.g. Italian and Spanish) mark grammatical gender with a phonological rule (as in the current experiment), not all languages with grammatical gender have similarly transparent rule assignment. Further, across languages, assignment of gender is largely arbitrary (Corbett, 1991). Considering the arbitrary nature of this grammatical dependency, it is not surprising that it is notoriously difficult for second language learners to acquire, in particular if their first language does not use grammatical gender (e.g. Dewaele & Véronique, 2001; Montrul, Foote, & Perpiñán, 2008; White, 2003).

Our findings provide an additional source of evidence that this type of grammatical dependency is difficult for monolingual English speakers to acquire. More generally, learners often struggle to acquire grammatical concepts that are not present in the native language via implicit learning. This difficulty has also been highlighted in studies using BROCANTO2, a fully productive artificial language based on universal requirements for natural language, which also has gender agreement between articles, nouns and adjectives (Morgan-Short et al., 2010, adapted from Friederici et al., 2002). Even after extensive practice participants did not exhibit ceiling performance for discriminating between correct and incorrect

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

sentences in which gender agreement was violated (Morgan-Short et al., 2010). Thus, training over much longer periods of time may be particularly important for learning grammatical constructs that do not exist in the native language.

Limitations

The artificial grammar used in these experiments was designed to afford learning of multiple aspects of grammar to explore whether difficulty in one aspect of learning might yield benefits for another. One limitation of this approach is that the artificial grammar was quite challenging for learners, as evidenced by a lack of generalization. As we expected a benefit for talker variability to be most evident for abstracting the category rule and generalizing to novel exemplars, the lack of generalizable knowledge limits the possible conclusions that can be drawn. Thus, it is possible that desirable difficulties may only emerge in limited contexts such as learning phonological contrasts. Another possible limitation is that there was insufficient variability to incur a processing cost, as the input in the current experiments was provided by only female speakers. In experiments reporting deficits for adult learners, such as Mullennix, et. al (1989), there were 7 male and 8 female talkers, a greater number of talkers and a potentially wider range of acoustic variability.

Conclusions and Future Directions

In two experiments, we demonstrated that high and limited talker variability differentially impact learning, but do not act as a desirable difficulty in the context of artificial grammar learning. Nevertheless, as we noted earlier in the paper, talker variability does impose costs under some conditions and benefits in others. While our research did not delineate a relationship between these patterns, the question is still well worth pursuing. Future research should explore manipulations that can enhance learning and generalization in this paradigm. For example, increasing the length of exposure may allow participants more time to notice the non-adjacent category rule. Alternatively, adding a communicative aspect to increase motivation in the task, such as in studies using BROCANTO2 (e.g. Friederici et al., 2002), may lead to more deliberate effort on behalf of the participants. Lastly, future research should also

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

investigate how the age of the learner and their previous language experience may be crucial factors in how acoustic variability influences learning.

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Endnotes

1. All participants received credit for the parts of the study they completed, regardless of the effort rating they provided. Effort rating did not differ across conditions: 1-Talker = 8.41, 2-Talker = 8.27, 8-Talker = 8.55
2. We do not provide reliability indices (e.g. Cronbach's Alpha) for the artificial grammar test as each trial tested knowledge of a specific item, making reliability indices difficult to interpret.
3. We investigated whether the addition of an interaction between Talker Variability condition and Nback would improve model fit. Model comparisons revealed that including these interactions did not improve model fit.
4. Models were optimized using the "bobyqa" optimizer, as they did not converge otherwise. The maximal random effects structure that converged for most models was (1+TalkerVariabilityCondition|Subject) + (1|Item), for two of the models (Exp2 Article and Exp 1 Generalization), this did not converge, so the random effects structure was (1|Subject) + (1|Image) and (1|Subject) respectively.
5. Effort rating for Experiment 2 did not differ across conditions (1-Talker = 8.12; 2-Talker = 8.21; 8-Talker = 8.33)

References

- Adesope, O. O., Trevisan, D. A., & Sundararajan, N. (2017). Rethinking the Use of Tests: A Meta-Analysis of Practice Testing. *Review of Educational Research*, 87(3), 659–701.
<https://doi.org/10.3102/0034654316689306>
- Antovich, D. M., Gluck, S. C., Goldman, E. J., & Graf Estes, K. (2020). Journal of Experimental Child Specificity of representations in infants ' visual statistical learning. *Journal of Experimental Child Psychology*, 193, 104772. <https://doi.org/10.1016/j.jecp.2019.104772>
- Antovich, D. M., & Graf Estes, K. (2017). Learning across languages: bilingual experience supports dual language statistical word segmentation. *Developmental Science*, November 2016, e12548.
<https://doi.org/10.1111/desc.12548>
- Arciuli, J., & Simpson, I. C. (2012). Statistical learning is lasting and consistent over time. *Neuroscience Letters*, 517(2), 133–135. <https://doi.org/10.1016/j.neulet.2012.04.045>
- Arnon, I., & Ramscar, M. (2012). Granularity and the acquisition of grammatical gender: How order-of-acquisition affects what gets learned. *Cognition*, 122(3), 292–305.
<https://doi.org/10.1016/j.cognition.2011.10.009>
- Balota, D. a., Duchek, J. M., & Logan, J. (2007). Is expanded retrieval practice a superior form of spaced retrieval? A critical review of the extant literature. *The Foundations of Remembering: Essays in Honor of Henry L Roedinger, III*, 83–105.
- Barcroft, J., & Sommers, M. S. (2005). *Effects of Acoustic Variability on Second Language Vocabulary Learning*. 387–414. <https://doi.org/10.1017/s0272263105050175>
- Bates, D., Mächler, M., Bolker, B., & Walker, D. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1-48.
<https://doi.org/10.18637/jss.v067.i01>
- Bjork, R. A. (1994). Memory and metamemory considerations in the training of human beings. In *Metacognition: Knowing about knowing*. (pp. 185–205).
<https://doi.org/10.7551/mitpress/4561.003.0011>

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- Bjork, R. A., & Kroll, J. F. (2015). Desirable Difficulties in Vocabulary Learning. *The American Journal of Psychology*, 128(2), 241–252. <https://doi.org/10.5406/amerjpsyc.128.2.0241>
- Boland, J. E., Kaan, E., Valdés Kroff, J., & Wulff, S. (2016). Psycholinguistics and variation in language processing. *Linguistics Vanguard*, 2(s1), 3–12. <https://doi.org/10.1515/lingvan-2016-0064>
- Bregman, M. R., & Creel, S. C. (2014). Gradient language dominance affects talker learning. *Cognition*, 130(1), 85–95. <https://doi.org/10.1016/j.cognition.2013.09.010>
- Brown, H., & Gaskell, M. (2014). The time-course of talker-specificity and lexical competition effects during word learning. *Language, Cognition and Neuroscience*, 29(9), 1163–1179. <https://doi.org/10.1080/23273798.2014.916409>
- Carstens, V. (2000). Concord in minimalist theory. *Linguistic inquiry*, 31(2), 319–355. <https://doi.org/10.1162/002438900554370>
- Cepeda, N. J., Pashler, H., Vul, E., Wixted, J. T., & Rohrer, D. (2006). Distributed practice in verbal recall tasks: A review and quantitative synthesis. *Psychological Bulletin*, 132(3), 354–380. <https://doi.org/10.1037/0033-2909.132.3.354>
- Choi, M., & Shukla, M. (2021). A New Proposal for Phoneme Acquisition: Computing Speaker-Specific Distribution. *Brain Sci.* 2021, 11, 177. <https://doi.org/10.3390/brainsci11020177>
- Clopper, C. G., & Pisoni, D. B. (2004). Effects of talker variability on perceptual learning of dialects. *Language and Speech*, 47(Pt 3), 207–239. <https://doi.org/10.3758/BF03212142>
- Corbett, G. (1991). Gender. In *Cambridge. Cambridge University press*. <https://doi.org/10.1017/cbo9781139166119>
- Creel, S. C., Aslin, R. N., & Tanenhaus, M. K. (2008). Heeding the voice of experience: The role of talker variation in lexical access. *Cognition*, 106(2), 633–664. <https://doi.org/10.1016/j.cognition.2007.03.013>
- Creel, S. C., & Bregman, M. R. (2011). How talker identity relates to language processing. *Language and*

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Linguistics Compass, 5(5), 190-204. <https://doi.org/10.1111/j.1749-818x.2011.00276.x>

Dewaele, J.-M., & Véronique, D. (2001). Gender assignment and gender agreement in advanced French interlanguage: a cross-sectional study. *Bilingualism: Language and Cognition*, 4(03), 275–297.

<https://doi.org/10.1017/S136672890100044X>

Dong, H., Clayards, M., Brown, H., & Wonnacott, E. (2019). The effects of high versus low talker variability and individual aptitude on phonetic training of Mandarin lexical tones. *PeerJ*, 2019(8), 1–45. <https://doi.org/10.7717/peerj.7191>

Ericsson, K. A. (2006). The Influence of Experience and Deliberate Practice on the Development of Superior Expert Performance. *The Cambridge Handbook of Expertise and Expert Performance*, 683–704. <https://doi.org/10.1017/cbo9780511816796.038>

Frank, M. C., Tenenbaum, J. B., & Gibson, E. (2013). Learning and Long-Term Retention of Large-Scale Artificial Languages. *PLoS ONE*, 8(1), 1–6. <https://doi.org/10.1371/journal.pone.0052500>

Friederici, A. D., Steinhauer, K., & Pfeifer, E. (2002). Brain signatures of artificial language processing: evidence challenging the critical period hypothesis. *Proceedings of the National Academy of Sciences of the United States of America*, 99(1), 529–534. <https://doi.org/10.1073/pnas.012611199>

Giannakopoulou, A., Brown, H., Clayards, M., & Wonnacott, E. (2017). High or low? Comparing high and low-variability phonetic training in adult and child second language learners. *PeerJ*, 5, e3209. <https://doi.org/10.7717/peerj.3209>

Goldinger, S. D. (1998). Echoes of Echols? An episodic theory of lexical access. *Perception and Psychophysics*, 105(2), 251–279. <https://doi.org/10.1037/0033-295x.105.2.251>

Gómez, R. L. (2002). Variability and detection of invariant structure. *Psychological Science*, 13(5), 431–436. <https://doi.org/10.1111/1467-9280.00476>

Gonzales, K., Gerken, L., & Gómez, R. L. (2018). How who is talking matters as much as what they say to infant language learners. *Cognitive psychology*, 106, 1–20. <https://doi.org/10.1016/j.cogpsych.2018.04.003>

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- Graf Estes, K. G. (2012). Infants generalize representations of statistically segmented words. *Frontiers in Psychology*, 3(OCT), 1–14. <https://doi.org/10.3389/fpsyg.2012.00447>
- Graf Estes, K. G., & Lew-Williams, C. (2015). Listening Through Voices: Infant Statistical Word Segmentation Across Multiple Speakers. *Developmental Psychology*, 51(11), 1–12. <https://doi.org/10.1037/a0039725>
- Grüter, T., Lew-Williams, C., & Fernald, A. (2012). Grammatical gender in L2: A production or a real-time processing problem? *Second Language Research*, 28(2), 191–215. <https://doi.org/10.1177/0267658312437990>
- Hakun, J. G., & Johnson, N. F. (2017). Dynamic range of frontoparietal functional modulation is associated with working memory capacity limitations in older adults. *Brain and Cognition*, 118(August), 128–136. <https://doi.org/10.1016/j.bandc.2017.08.007>
- Hollich, G. J., Jusczyk, P. W., & Brent, M. (2002). *Talker Variability and Infant Word Learning*. <http://hollich.psych.purdue.edu/TalkerVaryPoster2002.pdf>
- Houston, D. M., & Jusczyk, P. W. (2000). *The Role of Talker-Specific Information in Word Segmentation by Infants*. 26(5), 1570–1582. <https://doi.org/10.1037/0096-1523.26.5>
- Jusczyk, P. W., Pisoni, D. B., & Mullennix, J. W. (1992). Some consequences of stimulus variability on speech processing by 2-month-old infants. *Cognition*, 43, 253–291. [https://doi.org/10.1016/0010-0277\(92\)90014-9](https://doi.org/10.1016/0010-0277(92)90014-9)
- Kamide, Y. (2012). Learning individual talkers' structural preferences. *Cognition*, 124(1), 66–71. <https://doi.org/10.1016/j.cognition.2012.03.001>
- Kóbor, A., Janacsek, K., Takács, Á., & Nemeth, D. (2017). Statistical learning leads to persistent memory: Evidence for one-year consolidation. *Scientific Reports*, 7(1), 760. <https://doi.org/10.1038/s41598-017-00807-3>
- Li, P., Sepanski, S., & Zhao, X. (2006). Language history questionnaire: A web-based interface for

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- bilingual research. *Behavior Research Methods*, 38(2), 202–210.
<http://www.ncbi.nlm.nih.gov/pubmed/16956095>
- Liu, J., & Zhang, J. (2016). The effects of talker variability and variances on incidental learning of lexical tones. *Tonal Aspects of Languages 2016*, 2016(May), 23–27. <https://doi.org/10.21437/tal.2016-5>
- Lively, S. E., Logan, J. S., & Pisoni, D. B. (1993). Training Japanese listeners to identify English /r/ and /l/. II: The role of phonetic environment and talker variability in learning new perceptual categories. *The Journal of the Acoustical Society of America*, 94(3), 1242–1255.
<https://doi.org/10.1121/1.408177>
- Logan, J. S., Lively, S. E., & Pisoni, D. B. (1991). Training Japanese listeners to identify English /r/ and /l/: A first report. *The Journal of the Acoustical Society of America*, 89(2), 874–886.
<https://doi.org/10.1121/1.1894649>
- Maddox, G. B., & Balota, D. a. (2015). Retrieval practice and spacing effects in young and older adults: An examination of the benefits of desirable difficulty. *Memory & Cognition*.
<https://doi.org/10.3758/s13421-014-0499-6>
- Martin, K. I., & Ellis, N. (2012). The role of phonological short-term memory and working memory in L2 grammar and vocabulary learning. *Studies in Second Language Acquisition*, 34(3), 379–413.
<https://doi.org/10.1017/s0272263112000125>
- Mitchel, A. D., & Weiss, D. J. (2010). What's in a face? Visual contributions to speech segmentation. *Language and Cognitive Processes*, 25(4), 456–482. <https://doi.org/10.1080/01690960903209888>
- Mitchel, A. D., & Weiss, D. J. (2013). Visual speech segmentation: using facial cues to locate word boundaries in continuous speech. *Language and Cognitive Processes*, 3798(April 2014), 1–10.
<https://doi.org/10.1080/01690965.2013.791703>
- Montrul, S., Foote, R., & Perpiñán, S. (2008). Gender Agreement in Adult Second Language Learners and Spanish Heritage Speakers: The Effects of Age and Context of Acquisition. *Language Learning*, 58(3), 503–553. <https://doi.org/10.1111/j.1467-9922.2008.00449.x>

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- Morgan-Short, K., Finger, I., Grey, S., & Ullman, M. T. (2012). Second language processing shows increased native-like neural responses after months of no exposure. *PLoS One*, 7(3), e32974. <https://doi.org/10.1371/journal.pone.0032974>
- Morgan-Short, K., Sanz, C., Steinhauer, K., & Ullman, M. T. (2010). Second language acquisition of gender agreement in explicit and implicit training conditions: An event-related potential study. *Language Learning*, 60(1), 154–193. <https://doi.org/10.1111/j.1467-9922.2009.00554.x>
- Mullennix, J. W., Pisoni, D. B., & Martin, C. S. (1989). Some effects of talker variability on spoken word recognition. *The Journal of the Acoustical Society of America*, 85(1), 365–378. <https://doi.org/10.1121/1.397688>
- Nakata, T., & Suzuki, Y. (2019). EFFECTS of MASSING and SPACING on the LEARNING of SEMANTICALLY RELATED and UNRELATED WORDS. *Studies in Second Language Acquisition*, 41(2), 287–311. <https://doi.org/10.1017/S0272263118000219>
- Nusbaum, H., & Magnuson, J. (1997). Talker Normalization : Phonetic Constancy as a Cognitive Process. *Talker Variability and Speech Processing*, 109–132. <https://doi.org/10.1121/1.2028337>
- Nygaard, L. C., & Pisoni, D. B. (1998). Talker-specific learning in speech perception. *Perception & Psychophysics*, 60(3), 355–376. <https://doi.org/10.3758/BF03206860>
- Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*, 25(1), 46–59. <https://doi.org/10.1002/hbm.20131>
- Palmeri, T. J., Goldinger, Stephen, D., & Pisoni, D. B. (1993). Episodic encoding of voice attributes and recognition memory for spoken words. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 19(2), 309. <https://doi.org/10.1037/0278-7393.19.2.309>
- Perrachione, T. K., Lee, J., Ha, L. Y. Y., & Wong, P. C. M. (2011). Learning a novel phonological contrast depends on interactions between individual differences and training paradigm design. *The Journal of the Acoustical Society of America*, 130(1), 461–472. <https://doi.org/10.1121/1.3593366>

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- Peterson, G. ., & Barney, H. . (1952). Control Methods Used in a Study of the Vowels. *The Journal of the Acoustical Society of America*, 24(2), 175–184. <https://doi.org/10.1121/1.1906875>
- Poepel, T. J., & Weiss, D. J. (2016). The influence of bilingualism on statistical word learning. *Cognition*, 152, 9–19. <https://doi.org/10.1016/j.cognition.2016.03.001>
- Richtsmeier, P. T., Gerken, L., Goffman, L., & Hogan, T. (2009). Statistical frequency in perception affects children's lexical production. *Cognition*, 111(3), 372–377. <https://doi.org/10.1016/j.cognition.2009.02.009>
- Rost, G. C., & McMurray, B. (2009). Speaker variability augments phonological processing in early word learning. *Developmental Science*, 12(2), 339–349. <https://doi.org/10.1111/j.1467-7687.2008.00786.x>.Speaker
- Rowland, C. F. (2014). The effect of testing versus restudy on retention: a meta-analytic review of the testing effect. *Psychological Bulletin*, 140(6), 1432–1463. <https://doi.org/10.1037/a0037559>
- RStudio Team (2019). *RStudio: Integrated development environment for r*. Boston, MA: RStudio, Inc. Retrieved from <http://www.rstudio.com/>
- Ryalls, B. O., & Pisoni, D. B. (1997). The Effect of Talker Variability on Word Recognition in Preschool Children. *Dev Psychol.*, 33(3), 441–452. <https://doi.org/10.1037/0012-1649.33.3.441>
- Schwab, S., & Dellwo, V. (2017). Intonation and talker variability in the discrimination of Spanish lexical stress contrasts by Spanish, German and French listeners. *The Journal of the Acoustical Society of America*, 142(4), 2419–2429. <https://doi.org/10.1121/1.5008849>
- Seidl, A., Onishi, K. H., & Cristia, A. (2014). Talker Variation Aids Young Infants' Phonotactic Learning. *Language Learning and Development*, 10(4), 1–24. <https://doi.org/10.1080/15475441.2013.858575>
- Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory*, 5(2), 179–187. <https://doi.org/10.1037/0278-7393.5.2.179>

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

- Sinkeviciute, R., Brown, H., Brekelmans, G., & Wonnacott, E. (2019). The role of input variability and learner age in second language vocabulary learning. *Studies in Second Language Acquisition*, 41(4), 795–820. <https://doi.org/10.1017/S0272263119000263>
- Suzuki, Y., Nakata, T., & Dekeyser, R. (2019). The Desirable Difficulty Framework as a Theoretical Foundation for Optimizing and Researching Second Language Practice. *Modern Language Journal*, 103(3), 713–720. <https://doi.org/10.1111/modl.12585>
- Verhagen, J., & Leseman, P. (2016). How do verbal short-term memory and working memory relate to the acquisition of vocabulary and grammar? A comparison between first and second language learners. *Journal of Experimental Child Psychology*, 141, 65–82. <https://doi.org/10.1016/j.jecp.2015.06.015>
- Vlach, H. A., & Sandhofer, C. M. (2014). Retrieval dynamics and retention in cross-situational statistical word learning. *Cognitive Science*, 38(4), 757–774. <https://doi.org/10.1111/cogs.12092>
- Weatherhead, D., & White, K. S. (2016). He Says Potato, She Says Potahto: Young Infants Track Talker-Specific Accents. *Language Learning and Development*, 12(1), 92–103. <https://doi.org/10.1080/15475441.2015.1024835>
- Weiss, D. J., Gerfen, C., & Mitchel, A. D. (2009). Speech Segmentation in a Simulated Bilingual Environment: a Challenge for Statistical Learning? *Language Learning and Development : The Official Journal of the Society for Language Development*, 5(1), 30–49. <https://doi.org/10.1080/15475440802340101>
- White, L. (2003). Fossilization in steady state L2 grammars: Persistent problems with inflectional morphology. *Bilingualism: Language and Cognition*, 6(2), S1366728903001081. <https://doi.org/10.1017/S1366728903001081>
- Zinszer, B. D., & Weiss, D. J. (2012). When to hold and when to fold: detecting structural changes in statistical learning. In *Proceedings of the annual meeting of the Cognitive Science Society* (Vol. 35, No. 35).

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Stimuli used in Experiments 1 and 2

Appendix S2. Design counterbalancing table

Appendix S3. Mean pitch for experimental talkers

Appendix S4: Experiment 1 and Experiment 2 model tables

Appendix S5. Final vowel discrimination for Experiment 1 stimuli

Supporting information for: Bulgarelli, F., Weiss, D. J., Desirable difficulties in language learning?

How talker variability impacts artificial grammar learning. Article accepted in Language Learning.

Appendix S1. Stimuli used in Experiments 1 and 2

Novel objects and nonce words used in Experiments 1 and 2. Category 1 objects ended in /-a/ in Experiment 1 (E1) and in /-i/ in Experiment 2 (E2), both options are listed here.

Table S1.

Category 1				Category 2			
Object	Label	Object	Label	Object	Label	Object	Label
E1:Gotca E2:Gotki		E1:Tarrena E2:Tarreni		Pilkaw		Pangalaw
E1:Peadla E2:Peadli		E1:Klorda E2:Klordi		Tenderaw		Haseraw
E1:Prittera E2:Pritteri		E1:Sooba E2:Soobi		Higgeraw		Daintaw
E1:Fispa E2:Fispi		E1:Grintera E2:Grinteri		Foungeraw		Zibaw
E1:Veama E2:Veami		E1:Tifa E2:Tifi		Drockaw		Naretaw
E1:Feecha E2:Feechi		E1:Barcha E2:Barchi		Bosaw		Koobaw
E1:Glinka E2:Glinki		E1:Chosta E2:Chosti		Tallotaw		Pluntaw
E1:Durroba E2:Durrobi		E1:Patcheta E2:Patcheti		Cheemaw		Jefaw
E1:Lummora E2:Lummori		E1:Tolara E2:Tolari		Perminaw		Gipaw

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

E1:Dulcha E2:Dulchi		E1:Bema E2:Bemi		Theckeraw		Massetta w
E1:Sarna E2:Sarni		E1:Suncha E2:Sunchi		Kitaw		Tomaw
E1:Vaba E2:Vabi		E1:Pedlina E2:Pedlini		Plockaw		Blepaw
E1:Scowna E2:Scowni		E1: Briskala E2: Briskali		Doffaw		Franaw
E1:Poska E2:Poski		E1:Narbeda E2:Narbedi		Cridaw		Cornicka w
E1:Parioda E2:Pariodi		E1: Binka E2: Benki		Murleraw		Glockaw

Appendix S2. Design counterbalancing table

Table S2. Design counterbalancing table. Talkers used in each familiarization and test condition.

Condition	1-Talker		2-Talker		8-Talker	
Familiarization	LK	TW	LK + TW	LK + TW	All 8 (LK, TW, MP, RF, NS, SW, KM, BS)	All 8 (LK, TW, MP, RF, NS, SW, KM, BS)
Test	LK	TW	LK	TW	LK	TW

Appendix S3. Mean pitch for experimental talkers

We measured pitch (F0) for each word recorded by every speaker in order to provide some measure of cross-speaker acoustic differences. Tables S4-1 and S4-2 displays the averages and standard deviations for each speaker (identified by their initials), for each experiment. The bolded speakers are those used during the test phase in all conditions.

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Table S3-1: Average pitch and standard deviations in Hertz for stimuli recorded by each speaker in Experiment 1. Bolded speakers are used in all testing phases.

Talker	LK	TW	MP	RF	NS	SW	KM	BS
Average pitch in Hz (sd)	199.84 (20.5)	177.17 (25.3)	183.46 (31.48)	179.53 (21.69)	169.74 (16.08)	199.71 (16.85)	228.8 (22.48)	261.01 (24.46)

Table S3-2. Average pitch and standard deviations in Hertz for stimuli recorded by each speaker in Experiment 2. Bolded speakers are used in all testing phases.

Talker	LK	TW	MP	RF	NS	SW	KM	BS
Average pitch in Hz (sd)	217.15 (13.13)	184.56 (18.69)	193.29 (21.93)	182.96 (11.31)	168.34 (13.27)	199.24 (9.07)	226.81 (16.29)	267.31 (23.55)

Appendix S4. Experiment 1 and Experiment 2 model tables

Table S4-1:

Fixed effects table for Experiment 1 Noun test

term	estimate	std.error	statistic	p.value
(Intercept)	-0.30	0.59	-0.51	0.61
1-Talker/2&8-Talker	0.20	0.18	1.13	0.26
2-Talker/8-Talker	-0.05	0.22	-0.22	0.83
Immediate/ShortDelay	-0.01	0.09	-0.06	0.95
Immediate&ShortDelay/LongDelay	-0.52	0.07	-7.19	0.00
Nback	1.75	0.60	2.93	0.00
TestTalker	0.14	0.17	0.83	0.41

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

1-Talker/2&8-Talker:Immediate/ShortDelay	-0.10	0.19	-0.55	0.58
2-Talker/8-Talker:Immediate/ShortDelay	-0.10	0.21	-0.49	0.62
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	-0.12	0.15	-0.76	0.45
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	0.17	0.17	0.98	0.33

Table S4-2:

Random effects table for Experiment 1 Noun test

group	term	estimate
Subject	sd__(Intercept)	0.83
Subject	cor__(Intercept).1-Talker/2&8-Talker	-0.14
Subject	cor__(Intercept).2-Talker/8-Talker	-0.27
Subject	sd__1-Talker/2&8-Talker	0.53
Subject	cor__1-Talker/2&8-Talker.2-Talker/8-Talker	-0.18
Subject	sd__2-Talker/8-Talker	0.69
Image	sd__(Intercept)	0.43

Table S4-3:

Fixed effects table for Experiment 1 Article test

term	estimate	std.error	statistic	p.value
(Intercept)	0.04	0.29	0.13	0.90
1-Talker/2&8-Talker	0.12	0.08	1.42	0.15

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

2-Talker/8-Talker	-0.38	0.12	-3.04	0.00
Immediate/ShortDelay	0.01	0.07	0.09	0.92
Immediate&ShortDelay/LongDelay	-0.04	0.06	-0.67	0.50
Nback	0.31	0.29	1.08	0.28
TestTalker	-0.02	0.08	-0.21	0.83
1-Talker/2&8-Talker:Immediate/ShortDelay	0.09	0.15	0.59	0.55
2-Talker/8-Talker:Immediate/ShortDelay	0.03	0.18	0.17	0.86
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	0.08	0.13	0.60	0.55
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	0.14	0.15	0.94	0.35

Table S4-4:

Random effects table for Experiment 1 Article test

group	term	estimate
Subject	sd__(Intercept)	0.19
Subject	cor__(Intercept).1-Talker/2&8-Talker	-0.76
Subject	cor__(Intercept).2-Talker/8-Talker	0.50
Subject	sd__1-Talker/2&8-Talker	0.42
Subject	cor__1-Talker/2&8-Talker.2-Talker/8-Talker	-0.77
Subject	sd__2-Talker/8-Talker	0.76
Image	sd__(Intercept)	0.21

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Table S4-5:

Fixed effects table for Experiment 1 Generalization test

term	estimate	std.error	statistic	p.value
(Intercept)	-0.35	0.19	-1.82	0.07
1-Talker/2&8-Talker	-0.09	0.06	-1.43	0.15
2-Talker/8-Talker	-0.01	0.07	-0.12	0.91
Immediate/ShortDelay	0.09	0.07	1.33	0.18
Immediate&ShortDelay/LongDelay	-0.07	0.06	-1.21	0.23
Nback	0.33	0.20	1.65	0.10
TestTalker	0.05	0.06	0.88	0.38
1-Talker/2&8-Talker:Immediate/ShortDelay	0.21	0.15	1.43	0.15
2-Talker/8-Talker:Immediate/ShortDelay	0.41	0.17	2.44	0.01
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	0.00	0.13	0.00	1.00
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	0.25	0.15	1.69	0.09

Table S4-6:

Random effects table for Experiment 1 Generalization test

group	term	estimate
Subject	sd__(Intercept)	0.11
Image	sd__(Intercept)	0.03

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Table S4-7:

Fixed effects table for Experiment 2 Noun test

term	estimate	std.error	statistic	p.value
(Intercept)	0.48	0.47	1.04	0.30
1-Talker/2&8-Talker	0.12	0.17	0.70	0.48
2-Talker/8-Talker	-0.03	0.20	-0.17	0.86
Immediate/ShortDelay	0.05	0.08	0.61	0.54
Immediate&ShortDelay/LongDelay	-0.36	0.07	-5.09	0.00
Nback	0.91	0.49	1.87	0.06
TestTalker	-0.01	0.16	-0.03	0.98
1-Talker/2&8-Talker:Immediate/ShortDelay	-0.09	0.18	-0.52	0.60
2-Talker/8-Talker:Immediate/ShortDelay	0.01	0.20	0.04	0.97
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	0.03	0.15	0.22	0.83
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	-0.08	0.17	-0.49	0.62

Table S4-8:

Random effects table for Experiment 2 Noun test

group	term	estimate
Subject	sd__(Intercept)	0.64
Subject	cor__(Intercept).1-Talker/2&8-Talker	-0.13
Subject	cor__(Intercept).2-Talker/8-Talker	0.11

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Subject	sd__1-Talker/2&8-Talker	0.89
Subject	cor__1-Talker/2&8-Talker.2-Talker/8-Talker	-0.15
Subject	sd__2-Talker/8-Talker	0.95
Image	sd__(Intercept)	0.48

Table S4-9:

Fixed effects table for Experiment 2 Article test

term	estimate	std.error	statistic	p.value
(Intercept)	0.18	0.24	0.77	0.44
1-Talker/2&8-Talker	-0.05	0.09	-0.59	0.55
2-Talker/8-Talker	-0.05	0.10	-0.54	0.59
Immediate/ShortDelay	0.12	0.07	1.72	0.08
Immediate&ShortDelay/LongDelay	-0.17	0.06	-2.83	0.00
Nback	0.29	0.26	1.13	0.26
TestTalker	0.03	0.08	0.42	0.67
1-Talker/2&8-Talker:Immediate/ShortDelay	-0.21	0.15	-1.37	0.17
2-Talker/8-Talker:Immediate/ShortDelay	0.03	0.17	0.17	0.87
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	0.10	0.13	0.75	0.46
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	-0.16	0.15	-1.10	0.27

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Table S4-10:

Random effects table for Experiment 2 Article test

group	term	estimate
Subject	sd__(Intercept)	0.34
Image	sd__(Intercept)	0.20

Table S4-11:

Fixed effects table for Experiment 2 Generalization test

term	estimate	std.error	statistic	p.value
(Intercept)	-0.07	0.16	-0.46	0.65
1-Talker/2&8-Talker	-0.07	0.06	-1.13	0.26
2-Talker/8-Talker	0.04	0.07	0.55	0.58
Immediate/ShortDelay	0.07	0.07	1.06	0.29
Immediate&ShortDelay/LongDelay	0.08	0.06	1.31	0.19
Nback	0.18	0.18	1.05	0.30
TestTalker	-0.03	0.06	-0.60	0.55
1-Talker/2&8-Talker:Immediate/ShortDelay	0.30	0.15	2.06	0.04
2-Talker/8-Talker:Immediate/ShortDelay	-0.17	0.16	-1.04	0.30
1-Talker/2&8-Talker:Immediate&ShortDelay/LongDelay	0.10	0.13	0.78	0.44
2-Talker/8-Talker:Immediate&ShortDelay/LongDelay	0.22	0.14	1.57	0.12

Table S4-12:

Random effects table for Experiment 2 Generalization test

group	term	estimate
Subject	sd__(Intercept)	0.04

Appendix S5. Final vowel discrimination for Experiment 1 stimuli

Participants in Experiment 1 exhibited difficulty generalizing to novel exemplars. It is possible that participants did not learn to generalize to novel exemplars because they could not hear the difference in the vowels at the end of the words, which served to differentiate the two categories. We investigated this possibility by testing whether a different group of participants could distinguish between the vowels at the end of words when the words were presented in isolation. Participants were presented with pairs of words that either ended in the same vowel or in different vowels, and were instructed to identify whether the final vowel was the same or different across the two words.

S5.1 Participants.

Participants were 177 native English speakers (mean age = 18.93, sd = 1.3, 29 males) recruited from the Psychology Subject Pool. All participants completed another unrelated experiment in the lab prior to completing this task.

S5.2 Stimuli and procedure.

Participants were seated in a sound attenuated booth and instructed that they would be hearing two words separated by a short pause. Their task would be to listen carefully to the sounds that occurred at the end of the words, and after hearing both tokens, to decide whether they were same or different. There was no time limit for responses. On half of the trials, participants heard two words from the same category ending in the same vowel, and on the remaining trials participants heard words from different categories ending in different vowels. Participants completed 28 trials in total. For each participant, all stimuli were presented by a single talker, and the talker was counterbalanced across participants.

S5.3 Results.

Planned t-tests comparing performance to chance levels revealed that participants could accurately determine whether the vowel at the end of a pair of words was the same or different, all $p < .01$. As can be seen in Table A1, there was variability in accuracy on this task across talkers, though performance for all talkers was above chance. Note that the difference between speakers LK and TW (which were used for all tests, and in the 1- and 2-Speaker conditions) was not significant, $t(41.98) = .017$, $p = .99$.

Table A1.

Speaker	Accuracy	Significance
LK	20.15 (2.99)	$t(19) = 9.18$, $p < .001$
TW	20.17 (3.53)	$t(23) = 8.54$, $p < .001$
MP	16.52 (2.71)	$t(20) = 4.26$, $p < .001$
RF	17.81 (2.72)	$t(21) = 6.59$, $p < .001$
NS	16.5 (2.54)	$t(23) = 4.83$, $p < .001$

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

SW	15.71 (2.19)	$t(20) = 3.58, p=.002$
KM	18.73 (2.86)	$t(21) = 7.74, p<.001$
BS	20.22 (2.92)	$t(22) = 10.2, p<.001$

S5.4 Discussion.

In sum, while there is variability in accuracy across talkers, participants performed significantly above chance on this task. Importantly, the two talkers used during all tests produced vowels that were most distinguishable, relative to some of the other talkers, and thus performance on the tests should not have been impacted by differences in clarity across talker. Further, the results highlight the naturalistic variability presented to participants in the experiment, as there is inherent variability in the way individuals produce phonemes (Dorman et al., 1977; Peterson & Barney, 1952).

Performance on this task is also consistent with other phoneme discrimination tasks with difficult phoneme contrasts, where average or peak performance is rarely above 75% (Maye & Gerken, 2000, 2001). Compared to these other phoneme discrimination studies, the current vowel discrimination paradigm is arguably more difficult because participants are asked to discriminate between words that are not minimal pairs, and thus differ in more than just the target phoneme. Due to the process of coarticulation, having different word frames further changes how each vowel is instantiated (Liberman et al., 1967). Therefore, this follow-up revealed that participants can distinguish between the two vowels at above chance levels, but also highlight the difficult nature of the experimental task and provide further justification for Experiment 2 in which learners were presented with an easier vowel contrast.

References

Dorman, M. F., Studdert-Kennedy, M., & Raphael, L. J. (1977). Stop-consonant recognition: Release bursts and formant transitions as functionally equivalent, context-dependent cues. *Perception &*

TALKER VARIABILITY AS A DESIRABLE DIFFICULTY

Psychophysics, 22(2), 109–122. <https://doi.org/10.3758/BF03198744>

Lieberman, A. M., Coopers, F. S., Shankweiler, D. P., & Studdert-Kennedy, M. (1967). Perception of the speech code. *Psychological Review*, 74(6). <https://doi.org/10.1037/h0046234>

Maye, J., & Gerken, L. (2000). Learning phonemes without minimal pairs. *Proceedings of the 24th Annual Boston University ...*, 522–533.

<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.188.5940&rep=rep1&type=pdf>

Maye, J., & Gerken, L. (2001). Learning Phonemes : How Far Can the Input Take Us ? *25th Annual Conference of the BUCLD*, 480–490.

Peterson, G. E., & Barney, H. L. (1952). Control Methods Used in a Study of the Vowels. *The Journal of the Acoustical Society of America*, 24(2), 175–184. <https://doi.org/10.1121/1.1906875>