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Title: Individual differences in categorical perception of speech: Cue weighting and executive function.

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Abstract

This study examined individual differences in categorical perception and the use of multiple acoustic cues in the perception of the stop voicing contrast. Goals were to investigate whether gradiency of speech perception was related to listeners' differential sensitivity to acoustic cues and to individual differences in executive function. The experiment included two speech perception tasks (visual analogue scaling [VAS] and anticipatory eye movement [AEM]) administered to 30 English-speaking adults in two separate experimental sessions. Stimuli were a /ta/ to /da/ continuum that systematically varied VOT and f_0 . Findings were that some listeners had a more gradient pattern of responses on the VAS task; the listeners who had a gradient response pattern on the VAS task also showed more sensitivity to f_0 on the AEM task. The patterns were consistent across individuals tested on two separate occasions. These results suggest that variability in how categorically listeners perceive speech sounds is consistent and systematic within individuals.

Keywords

individual difference, categorical perception, visual analogue scaling, eye movement, stop voicing contrast, executive function capacity

Individual differences in categorical perception of speech: Cue weighting and executive function

1.0 Introduction

Categorical perception of speech is a foundational principle of our understanding of how individuals process speech. Early research on speech perception observed that listeners perceive speech sounds categorically. That is, there is both a steep identification function in the perception of two speech sounds that are minimally different and a peak in the discrimination function between these two sounds that is centered on this category boundary (e.g., Liberman, Harris, Hoffman, & Griffith, 1957; Liberman, Harris, Kinney, & Lane, 1961). This finding was interpreted as support for the claim that listeners discard irrelevant subphonemic fine phonetic detail and pay attention only to higher-level categorical phonetic information. That is, categorical perception is important because it provides an explanation for how speech perception could be fast and accurate in the face of extreme variability in the acoustic signal, both within and across listeners.

Subsequent research found that listeners attend to – rather than discard – lower-level phonetic detail when processing speech, at least in some conditions. Talker differences, for example, are lexically irrelevant, but listeners consistently perform better in a single-speaker condition as compared to a multiple-speaker condition across a variety of experimental paradigms (e.g., Goldinger, Pisoni, & Logan, 1991; Luce & Lyons 1998; Mullenix, Pisoni, & Martin 1989, among many others). Furthermore, categorical perception is highly task-dependent; listeners perceive speech more categorically in some tasks than in others (e.g., Carney, Widen, & Viemeister, 1977; Schouten, Gerrits, & van Hessen, 2003). Massaro and Cohen (1983) used a Visual Analogue Scaling (VAS) task, in which listeners were given more options to respond continuously than the traditional two-alternative forced choice (2AFC) paradigm and found that listeners' responses were much less categorical. Massaro and Cohen found that the observed distribution of perceptual ratings on the VAS task was better fit with a model that assumed a continuous distribution than with a model that assumed a binary (discrete) distribution with individual listener variation. That is, listeners, as a group, showed *gradient* rather than categorical perception of stimuli on a task (VAS) that asked for a gradient response and categorical rather than gradient perception on a task (2AFC) that asked for a categorical response. However, it should be noted that even on 2AFC tasks, listeners tend to have longer reactions times for stimuli near a category boundary, (Pisoni & Tash, 1974; Studdert-Kennedy, Lieberman & Stevens, 1963; Repp, 1981), suggesting that even the 2AFC task is somewhat sensitive to response gradiency.

The visual world paradigm has also provided evidence for gradient rather than categorical perception of speech (e.g., Clayards, Tanenhaus, Aslin, & Jacobs, 2008; McMurray, Tanenhaus, Aslin, & Spivey, 2003; McMurray, Tanenhaus, Aslin, Spivey, & Subic, 2008; McMurray, Tanenhaus, & Aslin, 2009). For example, McMurray et al. (2003) used this paradigm to show that the proportion of looks to a pictured object is sensitive to changes in within-category acoustic values. The current study also uses an eye-tracking paradigm to explore whether there are individual differences in how categorically listeners perceive speech sounds and, if so, to examine whether these individual differences are related to listeners' sensitivity to sub-phonemic details.

Because of the early emphasis in the field on categorical perception, there has been little research on individual differences in speech perception. If speech is perceived categorically and acoustically irrelevant detail is discarded, then differences among normal-hearing listeners with typical speech and language development should be minimal and relatively uninteresting. Given this reasoning, researchers focused on differences as a function of different groups or conditions and mostly ignored individual differences. This research has established that the group differences in categorical perception are observed consistently. Developmental studies

1 have reported that children relative to adults, and children with language or reading disorders
2 relative to typically developing children, have both shallower slopes and reduced endpoint
3 values in the probability estimation of choosing one category over the other using a 2AFC
4 paradigm (e.g., Hazan & Barrett, 2000; Joanisse, Manis, Keating & Seidenberg, 2000; Werker
5 & Tees, 1987). A common interpretation of such findings is that evidence of categorical
6 perception indicates a robust perceptual representation of the target phonological contrast.

7
8 The few studies that have examined these individual differences have investigated cue-
9 weighting strategies in speech perception (e.g., Hazan & Rosen, 1991; Idemaru, Holt &
10 Seltman, 2012; Kong & Edwards, 2011). Contrasts between speech sounds are typically
11 signalled by a number of redundant acoustic cues. For example, both voice onset time (VOT,
12 the latency between the oral release and the vocal fold vibration, Lisker & Abramson, 1964) and
13 fundamental frequency (f_0) at voicing onset are cues to the voicing contrast in stop consonants
14 (e.g., Haggard, Summerfield & Roberts, 1981; Kingston & Diehl, 1994; Ohde, 1983; Whalen,
15 Abramson, Lisker & Mody, 1993). Voiced stop consonants in English are associated with a
16 short-lag VOT and a lower fundamental frequency (f_0) at vowel onset while voiceless stops are
17 characterized with a long-lag VOT and a higher f_0 . Using a variety of experimental paradigms,
18 many studies have shown that the VOT cue is primary and the f_0 cue is secondary in the
19 perception of the English voicing contrast (e.g., Abramson & Lisker, 1985; Gordon, Eberhardt
20 & Rueckl, 1993; Whalen et al., 1993; Holt & Lotto, 2006; Francis, Kaganovich & Driscoll-
21 Huber, 2008; Idemaru & Holt, 2011; Francis & Nusbaum, 2002). There is some evidence,
22 however, that there are individual differences in how these two cues are weighted, at least in
23 some experimental conditions (e.g., Haggard et al., 1970; Hazan & Rosen, 1991; Idemaru, Holt
24 & Seltman, 2012; Walley & Carrell, 1983). Haggard et al. (1970) reported that some listeners
25 were more sensitive to f_0 than to VOT in an identification task of voiced and voiceless stop
26 consonants. Stevens and Klatt (1974) also documented that some listeners relied more on VOT,
27 while other listeners relied more on F1 onset frequency (another cue to the voicing contrast) to
28 differentiate voiced and voiceless stops. More recently, Shultz, Francis and Llanos (2012) found
29 that English speakers differed in the extent to which they relied on the secondary cue of f_0 to
30 differentiate /b/ and /p/. Hazan and Rosen (1991) was one of the few studies to focus
31 specifically on individual differences in cue weighting and categorical perception. They found
32 that averaging across participants obscured large individual variability present in the
33 identification curves for a place contrast (/b/-d/ and /d/-g/) between full-cue and reduced-cue
34 conditions. They observed that listeners' identification functions were uniformly steep in the
35 full-cue condition, whereas more individual variability was observed in the categorization
36 slopes in the reduced-cue condition where less redundancy of the acoustic cues was provided.
37 Francis et al. (2008) and Gordon et al. (1993) also observed individual differences in cue
38 weighting in more demanding listening conditions. Both papers propose that listeners tend to
39 rely on primary cues (such as VOT for the English stop voicing contrast) in ideal listening
40 conditions, but adjust their cue-weighting toward secondary cues under less-than-ideal
41 conditions, such as listening to speech in noise, or listening to multiple speakers, or listening
42 when attentional resources are limited. These results are compatible with the concept of
43 *dynamic redistribution of attention* in difficult listening conditions, as proposed by Francis et al.
44 (2008)

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46 In our own previous research (Kong & Edwards, 2011), we also observed individual differences
47 in how categorically a voicing contrast was perceived as well as a difference in cue-weighting
48 strategies. We found that some listeners had a gradient response pattern while others had a
49 categorical response pattern when asked to differentiate between a voiced and voiceless stop
50 consonant using a VAS task. Using an anticipatory eye movement paradigm (AEM,
51 McMurray, Tanenhaus, Aslin, and Spivey, 2003), we found that the same listeners who had a
52 more gradient response pattern on the VAS task were much more sensitive to the secondary cue
53 of f_0 . That is, listeners who were more sensitive to f_0 on the AEM task were also more likely to
54 use the entire scale from /d/ to /t/ to characterize stimuli that differed in both VOT and f_0 . By
55 contrast, individuals who were less sensitive to f_0 on the AEM task had a more categorical
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response pattern on the VAS task; they were more likely to rely primarily on the endpoints of the scale to characterize the same set of stimuli. These findings were important because they provided evidence that individual differences in cue-weighting of a secondary cue (*f0*) were associated with how categorically listeners perceived the same contrast in an off-line task (VAS). Still, the study was methodologically limited in the conclusions that it could draw for two reasons. First, listeners were tested only once, so it was impossible to determine whether the individual differences that were observed were related to differences in strategies that listeners might choose during a particular session or to consistent individual differences across participants. Furthermore, differences between categorical and gradient patterns of VAS responses were determined by visual inspection alone and listeners who were not clearly categorical or clearly gradient were excluded from the analysis. The current study was designed to address the limitations of the previous study by testing listeners in two separate sessions and by developing a measure to quantify the “gradiency” of their response patterns on the VAS task.

A secondary goal of this study was to explore whether individual differences in gradiency of response on the VAS task might be related to individual differences in executive function. Executive function refers to “a general-purpose control mechanism that modulates the operation of various cognitive subprocesses (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; p.50)” such as inhibiting distraction, expanding working memory, planning, controlling attention, shifting between tasks, updating and monitoring information (Karpicke, Conway, and Pisoni, 2007; Festman, Rodriguez-Fornells & Münte, 2010; Bialystok & Craik, 2010). While several studies have observed individual differences in patterns of cue-weighting, these studies have not addressed what might cause these differences (e.g., Hazan & Rosen, 1991; Kong & Edwards, 2011; Idemaru, Holt & Seltman, 2012). We hypothesized that individual differences in individual differences in sensitivity to sub-phonemic details in speech perception might be related to individual differences in executive function. While the relationship between executive function and speech perception has not been studied extensively in young adults with normal hearing, it has been studied in populations with hearing impairment. For example, it is well-known that inhibitory processes decrease as a function of aging and it has been posited that one explanation for older listeners’ difficulty in understanding speech in noise is related to their problems with inhibiting the processing of irrelevant information – i.e., background noise (Gordon-Salant & Fitzgibbon, 2004). Humes (2002) found that digit span, a measure of working memory, was a significant predictor of speech recognition scores in older adults with hearing aids. Recent research by Pisoni and colleagues has focused on whether individual differences in executive function can explain individual differences in word and sentence recognition in children with cochlear implants and normal-hearing children listening to vocoded speech (which simulates the auditory degradation of a cochlear implant). Karpicke et al. (2007) found, in a study of normal hearing children aged 5 to 8 years, that individual differences in a measure of inhibition were significantly correlated with individual differences in a sentence recognition task with vocoded speech. Most relevant to the current study is a study by Weiss, Gerfen, and Mitchel (2010). Weiss and colleagues investigated the ability of young normal-hearing adults to attend to multiple cues (statistical and duration cues) to word segmentation. When both cues were of equal strength, individual differences in successful word segmentation were related to individual differences on the Simon task, a measure of inhibitory control. Given the findings of Weiss et al. (2010) as well as previous studies with different populations, we wondered if individual differences in the gradiency of response on a VAS task and perceptual weighting of a secondary cue to voicing (*f0*) might be related to individual differences in executive function capacity. Such a finding would provide further support for the claim that the individual differences in sensitivity to *f0* observed by Kong and Edwards (2011) are consistent properties of individual listeners. More generally, the finding would provide experimental evidence that listeners’ speech processing strategies are modulated by their executive function capacity.

To summarize, the purpose of this paper was to examine whether individual differences in processing speech categories were consistent and systematic within a speaker. We were

interested in confirming the observation of an earlier small-scale study by Kong and Edwards (2011) that listeners who had a more gradient response pattern on a visual analogue scaling task were more likely to utilize a secondary cue in online processing (the AEM task). This study expands on the previous study in several respects: we tested a larger group of participants two times with the same AEM and VAS tasks and we developed a method to quantify the gradiency of participants' response patterns on the VAS task. We also investigated whether individual differences in processing speech (gradiency of response and weighting of f_0 , a secondary cue) were related to individual differences in executive function capacity.

2.0 Perception experiments

Two speech perception experiments (VAS and AEM) were conducted to explore whether there were individual differences in gradiency (or categoricity) of response on a VAS task and, if so, whether these differences were related to listeners' differential sensitivity to f_0 on two perception experiments. Both the VAS and AEM tasks were administered twice, separated by about a week to evaluate whether listeners showed consistent response patterns over two test sessions. In addition to the speech perception experiments, all listeners were evaluated on several measures of executive function and a measure of non-verbal IQ.

2.1 Participants

The participants were 30 native English-speaking adults with no self-reported history of speech, language, or hearing problems (24 females, 6 males, age range: 18 to 24 years). All participants were undergraduate students at the University of Wisconsin-Madison and either received course credit or were compensated for their participation.

2.2 Stimuli

The stimuli were pseudo-synthetic consonant-vowel (CV) syllables that were constructed to make a continuum from /ta/ to /da/. They were synthesized using words (*tot* and *dot*) produced by an adult male speaker from Wisconsin. We selected one token of /da/ and we systematically varied both VOT and f_0 to create the continuum. VOT values were manipulated by excising a portion of the burst release/aspiration from /ta/ and pasting it before the voicing onset of the /da/ token. Six different log-scale steps of VOT were included: 9ms (original VOT of /da/), 13ms, 19ms, 28ms, 40ms, and 59ms. Log-scale steps were chosen because of the non-linear nature of perceptual sensitivity to changes in VOT values. At each VOT step, we replaced the original f_0 value during the vowel (165 ms. duration) with one of five different sustained f_0 values (98Hz, 106Hz, 114Hz, 122Hz, and 130Hz: Whalen et al. [1993]) using Praat (Boersma & Weenink, 2014). A total of 30 different stimuli (a 6-step VOT $\times$ 5-step f_0 continuum) were created. CV syllables rather than words were used as stimuli in both experimental tasks for two reasons: one, we wanted to minimize any lexical confounds such as word frequency; and two, we wanted the same stimuli for both tasks and the VAS task did not include visual prompts.

2.3 Tasks

There were two experimental tasks, a visual analogue scaling task (VAS) and an anticipatory eye movement task (AEM). In a VAS rating task, individuals are asked to scale a psychophysical parameter by indicating their percept on an idealized visual display. In our VAS task, an arrow was displayed on the computer monitor immediately after each stimulus was played. One end of the arrow was labeled as the 'd' sound and the other end of the arrow was labeled as the 't' sound. Listeners were instructed to click anywhere on the arrow, based on their judgment of how close the stimulus was to either /da/ or /ta/. Listeners heard the same 30 stimuli items three times in random order. It should be noted that the number of stimuli items on the VAS task presented in each experimental session was relatively low (90 items), relative to many speech perception experiments (e.g., Lieberman et al., 1961; Pisoni & Tash, 1974; Massaro & Cohen, 1983).

1 In the AEM task, we used the SMART-T program to implement an anticipatory eye movement
2 paradigm using the Tobii 2150 eye-tracker (Shukla, Wen, White & Aslin, 2011). For all trials
3 including six training trials, when an auditory stimulus item was played, a picture (representing
4 either *doggie* or *taco*, words which contain a syllable-initial /da/ or /ta/ in the local dialect)
5 appeared at the bottom of the pipe and moved slowly through the pipe. The /da/ stimuli were
6 paired with the picture of *doggie* and consistently appeared on the left side of the Y-shaped pipe
7 (Figure 1, left panel), while the /ta/ stimuli were paired with the picture of *taco* and consistently
8 appeared on the right side of the pipe (Figure 1, right panel).¹ Listeners were conditioned to
9 make anticipatory looks to either the left or the right side of a Y-shaped pipe based on whether
10 the sound they heard was more similar to /d/ or /t/. The Y-shaped pipe was transparent at the
11 beginning of the training trials so that participants could see the path of the moving picture, and
12 gradually the pipe became opaque during the six training trials. During the experimental trials,
13 the pipe was opaque and the participants had to anticipate on which side the picture would
14 appear based on whether they perceived the auditory stimulus to be /d/ or /t/. The participants
15 were given no other instructions beyond “look at the computer screen.” Each stimulus was
16 presented four times in the AEM task. Ambiguous stimulus items (those with VOT values of
17 19ms or 28ms) appeared twice on the left side of the pipe and twice on the right side in a
18 random order to prevent listeners from responding based on local statistics. While the AEM
19 paradigm has been used extensively in infant research, it has not been used in many adult
20 studies (although Richardson & Kirkham [2004] included an adult control group). We chose the
21 AEM paradigm over the more frequently-used visual world paradigm because the AEM
22 paradigm is ideal for eliciting judgments of multiple presentations of speech stimuli without
23 worrying about lexical confounds.
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27 Listeners participated in two experimental sessions separated by about a week. In the first
28 session, the two tasks of VAS and AEM were counter-balanced, so approximately 50% of the
29 participants did the AEM experiment first and the VAS experiment second, while the other 50%
30 had the reverse order in their first session. In the second experimental session, about half of the
31 returning participants were given the two experiments in the same order as the first session,
32 while the other half were given the experiments in the opposite order.
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35 We also administered several standardized tests during the second test session after the
36 participants had completed the two speech perception tasks. Two subtests from the DKEFS
37 (*Delis-Kaplan Executive Function System*, Delis, Kaplan, & Kramer, 2001) were administered
38 to measure components of executive function: the Trail-Making Task (TMT), and the Color-
39 Word Naming (CW) subtests. The Trail-Making task is a paper-and-pencil task with three
40 conditions. Participants are asked to connect number sequences (e.g., 1 to 2 to 3) in Condition 1,
41 letter sequences (e.g., A to B to C) in Condition 2, and number-letter sequences (e.g., 1 to A to 2
42 to B, etc.) in Condition 3 as quickly as possible. In the Color-Word Naming task, participants
43 are asked to name the font color of a word in three conditions: (1) congruent color-word naming
44 (e.g., the word “red” in a red font), (2) incongruent color-word naming (e.g., the word “red” in a
45 green font), and (3) switch color-word naming (some trials are congruent and some are
46 incongruent). The incongruent and switch conditions of the Color-Word Naming subtests are
47 considered measures of inhibition while Condition 3 of the Trail-Making Task are considered
48 measures of cognitive flexibility or attention switching (Miyake et al., 2000). These subtests
49 were given in a randomized order. Duration and accuracy were obtained for each condition for
50 all two tasks.
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55 ¹ It should be noted that the fact that the /d/-initial word always appeared on the right side of the pipe and
56 the /t/-initial word on the left side across listeners is a design limitation. While this is an experimental
57 confound, it is unlikely to have influenced the results (as it is not very likely that there would have been a
58 consistent looking preference for short VOTs to one side of the screen). A counter-balanced design in
59 which half of the participants received /d/ on the left side and half received /d/ on the right side would
60 have been preferable.
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Non-verbal IQ was assessed using the matrices section of the Kaufman Brief Intelligence Test – 2nd edition (KBIT-2, Kaufman & Kaufman, 2004). This test was given so that we could partial out any general effect of intelligence that might be correlated with executive function (e.g., Friedman, Miyake, Corley, Young, DeFries & Hewitt, 2006; Festman et al., 2010).

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2.4 Analysis

2.4.1 VAS task

For the VAS task, we examined the response patterns of individual listeners. We were interested in two questions: one, were individual listeners more categorical or gradient in their responses patterns; and two, how did individual listeners attend to the different combinations of VOT and $f0$.

First, we examined individual differences in gradiency of response by comparing histograms of click locations (in pixels) for each individual listener. In Kong and Edwards (2011), we had observed non-uniform histogram distributions across subjects; response patterns by some listeners resulted in bipolar peaks at the two ends of the arrow, while response patterns for other listeners resulted in click distributions that were more evenly spread across the entire arrow. To quantify these differences in shape, we constructed a polynomial function fitting the histograms, implemented in R (R Core Team, 2016), and used the coefficients of the quadratic terms as a numerical index of *gradiency* (or categoricity) for each participant. That is, we interpreted larger coefficients from the concave curve shapes as indicating a more categorical response pattern on the VAS task. Conversely, we interpreted smaller coefficients from these curves as indicating a more gradient response pattern on this task. This numerical index could capture varying degrees of spread of the click distributions for most participants (see the response pattern averaged across the entire group in Figure 2 and three individual response patterns in Figure 3). We used this measure of gradiency for four purposes: one, to evaluate whether individual response patterns were similar across the two sessions; two, to evaluate whether gradiency of response on the VAS task was related to sensitivity to VOT or $f0$ on the VAS task; three, to evaluate whether gradiency of response was related to sensitivity to $f0$ on the AEM task; and four, to examine the relationship between gradiency on the VAS task and performance on the two measures of executive function.

In relating the responses to the acoustics of the stimuli, we constructed mixed-effects regression models to examine how changes in VOT and $f0$ values of the stimuli affected listeners' perception of the /t/-/d/ contrast. The pixel values of the click locations were the dependent variable after being logit-transformed due to the bounded ends of the pixel data. VOT, $f0$ and the interaction between $f0$ and VOT were the fixed effect variables in these models. The responses of individual listeners were considered to be a random effect, so the slopes of VOT and $f0$ were allowed to vary. The regression models were implemented using the *lme4* package in R (Bates, Maechler & Bolker, 2011). Since the *lmer* command in the *lme4* package does not provide *p*-values, we either computed *p*-values based on the parameter estimates and the standard errors by transforming the *t*-distribution into a *z*-distribution or we conducted deviance tests where the full model was compared to a simpler model in order to estimate the effect of a selectively-added or removed factor.

2.4.2 AEM task

The eye gaze data from the AEM task were dichotomously coded: looks to /d/ were coded as '1' and looks elsewhere were coded as '0'. We grouped these discrete observations into a series of temporal bins (50ms bins) within each listener's trials of the same stimuli and calculated the empirical logit of looks to /d/ in each bin as described in Barr (2008). For each VOT condition,

we constructed a mixed-effects model with the estimated logit value of looking to /d/ as the dependent measure and time (temporal bins) as a fixed effect variable, and f_0 as the interaction term. Similarly, for each f_0 condition, we constructed a mixed-effects model with VOT as the interaction term. This type of time-series regression has been proposed as a way to model how looks to a target change over time for the visual world paradigm (e.g., Mirman, Dixon, & Magnuson, 2008; Barr, 2008; Singer & Willett, 2003). To our knowledge, this is the first use of growth curve analysis to model eye-tracking responses from an AEM experimental paradigm. We used an analysis window that began at 200ms after the auditory stimulus onset (because it takes about 200 ms to program an eye movement, Matin, Shao & Boff [1993]) and that ended at the onset of the visual stimulus (the picture of *doggie* or *taco* which appeared on the left or right side of the Y-shaped pipe). The model included three time terms (first order or linear, second order or quadratic, and third order or cubic) using an orthogonal polynomial coding scheme. As described in Mirman et al. (2008), we transformed these time terms so that they were orthogonal to each other in order to eliminate correlations among them. Another advantage of using orthogonal time is that the intercept term is not fixed to a particular temporal bin, but can be interpreted as corresponding to the average shape of the growth curve. The slope of the linear time term is most relevant to our assessment of listeners' sensitivity to changes in VOT and f_0 . Larger absolute values of the first order coefficients indicate that linear slopes are steeper (i.e., faster looks to the /d/ side of the screen). In addition, the intercept term and the second and third order time terms provide information on the shape of the curve independently of the linear term (or slope). Briefly, the intercept describes the overall height of the curve, the quadratic component describes the symmetrical rise (or fall) rate of the curve, and the cubic component describes the asymmetric rise (or fall) rate near the trough (or peak) of the curve (Mirman et al., 2008; Singer & Willett, 2003). The mixed-effect models included random effects of subject and subject-by-stimulus condition, where the intercepts and slope coefficients of the first polynomial time term were allowed to vary. Random effects of the quadratic and cubic components were not included so that we could ascribe random variation solely to the first order time term, the explanatory variable related to the experimental question.

In order to quantify sensitivity to f_0 for individual listeners, we made two sets of comparisons of specific stimulus conditions in the mixed-effects regression models. First, we compared two sets of conflicting vs. cooperating cue conditions. These were: (1) the highest f_0 condition (130Hz f_0) with either the shortest lag VOT (9ms, a conflicting cue condition) or longest lag VOT (59ms, a cooperating cue condition) VOT; and (2) the lowest f_0 condition (98Hz f_0) with either the shortest lag VOT (9ms, a cooperating cue condition) or longest lag VOT (59ms, a conflicting cue condition). We also examined two ambiguous VOT conditions (19ms and 28ms) with either the lowest (98Hz) or highest (130Hz) f_0 conditions.

We reasoned that comparing listeners' performance in a conflicting f_0 cue condition (shortest lag VOT and highest f_0 or longest lag VOT and lowest f_0) to a cooperating f_0 cue condition (longest lag VOT and highest f_0 or shortest lag VOT and lowest f_0) would best capture individual listeners' sensitivity to f_0 . That is, in the competing cue conditions, listeners who were less sensitive to f_0 would continue to attend primarily to VOT, even if the VOT information and the f_0 information were in conflict. For these listeners, we expected that there would continue to be steep linear slopes in the shortest lag VOT condition, yielding large linear slope differences between the two VOT conditions (9ms VOT and 59ms VOT). By contrast, we hypothesized that listeners who were more sensitive to f_0 would attend to f_0 information in the conflicting cue conditions. Therefore, these listeners would have relatively less steeper linear slopes in the shortest lag VOT condition, producing smaller linear slope differences between the two VOT conditions. To test this hypothesis, we subtracted the random effects coefficient of the 59ms VOT condition (estimated at the subject-by-condition level) from that of the 9ms VOT condition in the highest f_0 condition. Similarly, we subtracted the random effect coefficient of the 9ms VOT condition from that of the 59ms VOT condition in the lowest f_0 condition.

We also analyzed two ambiguous VOT conditions (19ms and 28ms) in a similar manner in order to examine individual listeners' sensitivity to f_0 , as previous studies have shown that a redundant secondary cue plays a more important role when the primary cue is ambiguous (Abramson & Lisker, 1985; Whalen et al., 1993). We expected that listeners who were more sensitive to f_0 in general would be better able to take advantage of this secondary cue in the ambiguous VOT conditions. That is, we predicted that the listeners who were more sensitive to f_0 would have relatively greater linear slope differences between the high (130Hz) and low (98Hz) f_0 conditions in the two ambiguous VOT conditions. By contrast, we predicted that the listeners who were less sensitive to f_0 would have relatively smaller linear slope differences between these two conditions. To calculate these slope differences for individual listeners, we subtracted the random effects coefficient of the 130Hz f_0 condition (estimated at the subject-by-condition level) from that of the 98Hz f_0 condition.

Based on the results of Kong and Edwards (2011), we hypothesized that listeners who were more categorical on the VAS task would rely less on the secondary cue of f_0 , whereas the listeners who were more gradient on this task would be more sensitive to the f_0 cue. To test this hypothesis, we examined whether these measures of individuals' sensitivity to f_0 in the AEM task -- the difference in linear slope coefficients between the two VOT conditions in the high f_0 condition difference in linear slope coefficients between the two f_0 conditions in the ambiguous VOT conditions -- were correlated with our gradiency measure from the VAS task.

2.4.3 Cognitive measures in relation to gradiency of speech perception and sensitivity to f_0

We examined whether our measure of gradiency was related to measures of executive function and non-verbal IQ using partial correlations. For the two executive function subtests, we used response time to complete the task as the raw score and then obtained standard scores from the DKEFS manual. (Differences in accuracy across participants were minimal.) We used standard scores from the KBIT-2 as the measure of non-verbal IQ. To explore the relationship between gradiency and our measures of executive function, we completed two analyses. In the first analyses, we partialled out the effect of non-verbal IQ and then examined the relationship between our gradiency measure from the VAS task and each of the two executive function measures. In the second analysis, we partialled out both the effect of non-verbal IQ and one executive function measure and then examined the relationship between the gradiency measure and the other executive function measures. We also examined whether the two executive function measures were correlated with our measures of sensitivity to f_0 from the AEM task (linear slope differences between models for the 9 ms and 59 ms VOT conditions in the highest f_0 condition and linear slope differences between models for the 98Hz and 130Hz f_0 conditions in the ambiguous VOT condition). Again, we performed two partial correlations, one in which only non-verbal IQ was partialled out and a second in which one of the executive function measures was also partialled out. The analyses were implemented using the *pcor.test* command of the *ppcor* package in R (Kim, 2012). We used a Bonferroni correction of the p value because of the multiple comparisons. Accordingly, the significance level was set at $p < 0.0125$ which was equivalent to $p < 0.05$ if running a single test.

3.0 Results

3.1 VAS task

Figure 2 shows the click distributions of the VAS task for all listeners (leftmost column) and the average ratings as a function of VOT and f_0 (center columns). The responses from the first session are shown in the top panels and those from the second session are shown in the bottom panels.

The histogram in the top left panel exhibited two global peaks at each end of the continuum indicating listeners' overall tendency to perceive the stimuli categorically. However, it can be observed that there were click responses between the two peaks suggesting that at least some

listeners were also sensitive to category goodness. The regression curves estimated by the quadratic term regression model are overlaid on the histograms and schematically show the average response characteristics of the group in each of the two sessions.

The panels in the second and third columns of Figure 2 plot the average rating values as a function of VOT and f_0 , respectively. It can be observed that perception of the contrast between /t/ and /d/ was much more strongly influenced by VOT than by f_0 in both sessions. The stimuli were more likely to be judged as more /t/-like as VOT values increased (second column), whereas the ratings did not change dramatically as f_0 values changed (third column). Based on visual inspection, an effect of the f_0 cue was observed primarily for stimuli in the ambiguous VOT (19ms VOT and 28ms) conditions. In these conditions, stimuli were judged as more /t/-like as f_0 values increased. These observations were confirmed by the results of the mixed-effects regressions. The regression model included VOT, f_0 , and the interaction of VOT and f_0 as fixed effects and allowed the slopes of VOT and f_0 to vary at the individual subject level. When this complex model was compared to a simpler regression model where the interaction of VOT and f_0 was *not* included, the results of the deviance test (first session: $\chi^2 = 13.7$, $df=1$, $p<0.001$; second session: $\chi^2 = 6.03$, $df=1$, $p<0.05$), indicated that adding the interaction term significantly improved model fit for the data from both sessions. In the complex model where VOT, f_0 , and the interaction of VOT and f_0 were the explanatory variables and the measurement units were normalized, both VOT and f_0 were significant predictors of listener response patterns in the two sessions. The effect of VOT was greater than that of f_0 , as indicated by its larger coefficient in both sessions (first session: $\beta_{\text{vot}}=0.85$ [S.E=0.048; $t=17.5$] vs. $\beta_{f_0}=0.20$ [S.E=0.029; $t=7.15$]; second session: $\beta_{\text{vot}}=0.85$ [S.E = 0.043; $t = 19.6$] vs. $\beta_{f_0}=0.14$ [S.E = 0.017; $t = 8.3$]). This result confirmed listeners' greater sensitivity to VOT than to f_0 in differentiating the contrast between /t/ and /d/ on the VAS task.

The listeners' responses to each stimulus item (that is, to each combination of VOT and f_0) are shown in the rightmost column of Figure 2, which was inspired by Escudero and Boersma (2004). The /d/-likeness of the listener's perception, based on the pixel numbers of actual clicks, is indicated by the size and the degree of darkness of each stimulus' symbol; the larger and darker the symbol, the more /d/-like the listener's perception of the stimulus. It can be observed that the symbols have darker colors for the shorter VOT values, indicating that subjects on average were strongly influenced by VOT in perceiving /d/ vs. /t/. This dark color is clearly in contrast with the lighter colors for the longer VOT values. By contrast, the size-and-darkness pattern was similar for the cells at the top of each panel (higher f_0 stimuli) as compared to those at the bottom of the panel (lower f_0 stimuli), indicating that the listeners, as a group, were not greatly influenced by f_0 . The effect of f_0 appeared to be conditioned by the VOT values of the stimuli. While the size-and-darkness pattern rarely changed within the same VOT conditions, the symbols gradually became smaller and lighter as f_0 values increased in the mid-range of VOT values (19ms and 28ms), namely in the ambiguous VOT conditions.

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These group results were consistent with previous research (e.g., Abramson & Lisker, 1985; Gordon et al., 1993; Whalen et al., 1993). However, we also observed that there were clear differences across participants in gradiency of response, as evidenced by differences in the histograms of click locations (leftmost column of Figure 3). Figure 2 shows histograms and regression curves estimated from each session of the VAS task for three selected participants who represented three different response patterns. Some listeners (e.g., ID21110 in the top panel) judged the stimuli categorically, choosing responses mostly at the two endpoints of /t/ and /d/. By contrast, other listeners (e.g., ID21101 in the bottom panel) judged the stimuli in a

much more gradient manner, choosing responses across the entire VAS scale. There was also an intermediate pattern (neither clearly gradient nor clearly categorical) illustrated by the participant in the middle panel. The individual listeners' gradiency of response was quantified in terms of the slope coefficient of the quadratic term of the regression model (Section 2.4.1). As illustrated in the leftmost column panels of Figure 3, the quadratic term estimated by the regression model yielded a relatively steep concave curve for the categorical listener ($\beta[\text{quadratic term}] = 0.00078$ for the first session; 0.0007 for the second) and a relatively shallow concave curve for the gradient listener ($\beta[\text{quadratic term}] = 0.00018$ for the first session; 0.00030 for the second). Importantly, these response patterns for individual listeners were consistent across the two test sessions, although the exact value of the gradiency measure varied from one session to another. A correlation test showed a significant positive correlation in individuals' gradiency of response (quadratic slope coefficients) between the two sessions ($r = .48$, $df = 29$, $p < .01$).

Note to Publisher: Insert Figure 3 about here

The other three columns in Figure 3 display the VAS responses of the first session as a function of the two acoustic cues for these same three speakers. Similar to the group results, perception of the contrast between /t/ and /d/ was more strongly influenced by VOT than by f_0 for all three of these listeners. The three plots in the second column of Figure 3 (one for each speaker) show a strong relationship between VOT and the ratings; stimuli with longer VOT values were consistently rated as more /t/-like. In contrast, the three plots in the third column show that stimuli with higher f_0 were not consistently rated as more /t/-like. Linear regressions with VOT, f_0 and the interaction of the two as predictors, which were performed separately for the three subjects, indicated that VOT was a significant predictor ($p < .0001$) of VAS responses for all three listeners in both VAS sessions but f_0 was not consistently significant across listeners and the interaction of VOT and f_0 was not significant across listeners in either session. The f_0 coefficients for the responses of the participant shown in the top panel [ID21110] did not reach a significance level of $p < .05$ in either session [first session: $\beta_{f_0} = 0.16$ ($p = .074$); second session: $\beta_{f_0} = 0.13$ ($p = 0.198$)] and those for the responses of the participant shown in the middle panel [ID11106] were significant in only one session [first session: $\beta_{f_0} = 0.13$ ($p = .072$); second session: $\beta_{f_0} = 0.20$ ($p < .01$)]. The f_0 coefficients for the responses of the participant shown in the bottom panel [ID21101] were significant in both sessions [first session: $\beta_{f_0} = 0.16$ ($p < .05$); second session: $\beta_{f_0} = 0.17$ ($p < .005$)]. When the measurement units were standardized, the regression models showed that VOT was a more effective variable than f_0 in explaining the response variable; consistently for the three speakers, the coefficients of VOT were greater than those of f_0 : First session: [ID21110] $\beta_{\text{vot}} = 1.24$ vs. $\beta_{f_0} = 0.16$; [ID11106] $\beta_{\text{vot}} = 1.18$ vs. $\beta_{f_0} = 0.13$; [ID21101] $\beta_{\text{vot}} = 0.82$ vs. $\beta_{f_0} = 0.16$; second session: [ID21110] $\beta_{\text{vot}} = 0.13$ vs. $\beta_{f_0} = 1.18$; [ID11106] $\beta_{\text{vot}} = 1.07$ vs. $\beta_{f_0} = 0.20$; [ID21101] $\beta_{\text{vot}} = 0.79$ vs. $\beta_{f_0} = 0.17$.

The listeners' responses to each stimulus item in a $\text{VOT} \times f_0$ space are presented in the panels in the rightmost column of Figure 3. As in Figure 2, the /d/-likeness of the listener's perception is indicated by the size and the degree of darkness of each stimulus' symbol. It can be observed that the symbols in all three panels have darker colors for the shorter VOT values, indicating that all three subjects were strongly influenced by VOT in perceiving /d/ vs. /t/. The difference among these three listeners was that the dots for the categorical listener (top panel) become smaller and darker rather abruptly between 19ms VOT and 28ms VOT, whereas those of the gradient listener (bottom panel) become smaller and darker gradually as VOT values increase. If the size-and-darkness pattern is similar for the cells at the top of each panel (higher f_0 stimuli) as compared to those at the bottom of the panel (lower f_0 stimuli), then this indicates that the listener is not influenced by f_0 . It can be observed that the size and darkness patterns of the symbols for the categorical listener in the top panel differed slightly from those of the gradient

listener in the bottom panel. For the categorical listener, the size and darkness of the symbols varied very little between the top and bottom halves of the panel. By contrast, the plot for the gradient listener appeared to have some variation in the size and darkness of the symbols as the stimuli varied along the f_0 dimension, suggesting that this listener was sensitive to f_0 as well as to VOT when differentiating /t/ and /d/.

Finally, we used correlation analysis to examine the relation between gradiency of response and sensitivity to VOT and f_0 on the VAS task. Sensitivity to the acoustic cue was represented by the subject-level VOT and f_0 coefficients from the regression model separately constructed for each individual listener where VOT and f_0 were independent variables (Morrison & Kondurova, 2009). With respect to the VOT cue, listeners' coefficients were meaningfully correlated with their gradiency measure in both sessions (first session: $r = 0.88$, $p < .0001$; second session: $r = 0.704$, $p < .0001$). This positive correlation coefficient indicated that the more categorical listeners (larger quadratic slope) also tended to be more sensitive to VOT. The VOT coefficients between the two sessions were also significantly correlated ($r = 0.674$, $p < .0001$), suggesting a systematic sensitivity to VOT within listeners.

However, the relationship between the gradiency measure and sensitivity to f_0 was not systematic in the analysis of the VAS response patterns. The correlations between individuals' f_0 coefficients and their gradiency were not statistically significant in the analyses of either session (first session: $r = 0.224$, $p = .232$; second session: $r = 0.177$, $p = .348$). The f_0 coefficients across the two sessions were also not correlated ($r = -0.117$, $p = .536$). That is, the responses from the off-line VAS task failed to exhibit a systematic variability of f_0 use in differentiating between voiced and voiceless stop consonants. We further investigated the relationship between gradiency in speech perception on the VAS task and listeners' sensitivity to the secondary cue of f_0 by examining listeners' response on the AEM task, an on-line task.

3.2 AEM task

Figure 4 shows the change in the estimated logit values of looking to /d/ over time as a function of different VOT and f_0 conditions for the AEM task in the first session (see Appendix A and B for the figure and the model summary table based on the second session). This figure plots the estimated slopes from the mixed-effects models in six selected acoustic conditions. Table 1 presents the parameter estimations of the regression models associated with the three top panels of Figure 4: the shortest (9ms), mid-level (19ms) and longest (59ms) VOT conditions. Similarly, Table 2 shows the parameter estimations of the regression models associated with the three bottom panels of Figure 4: the lowest (98Hz), mid-level (114Hz), and highest (130Hz) f_0 conditions. The patterns from the AEM task were mostly similar to the results for the VAS task in that they also showed that listeners were much more sensitive to changes in VOT than to changes in f_0 . Across the different f_0 conditions (bottom panels), stimuli with shorter VOT values consistently resulted in more looks to /d/ in each temporal bin than stimuli with longer VOT values. As summarized in Table 2, there were significant effects of the linear term between the 9ms (reference category) and 59ms VOT conditions across the three f_0 models: The coefficients of the 59ms VOT condition relative to the 9ms VOT condition (Linear slope [9ms:59ms] in Table 2), were consistently negative and statistically significant at the level of $p < 0.05$, indicating that the curves were shallower for the 59ms VOT condition. It can also be noted in Table 1 that the regression models for the 9ms VOT and 59ms VOT conditions did not show significant coefficients of the linear slope interaction between the reference f_0 (98Hz) and either of the other two f_0 conditions (Linear slope [98Hz:114Hz] and [98Hz:130Hz] in Table 1), confirming that VOT values were the primary influence in determining looks to /d/ for the listeners.

While the slope differences of different f_0 conditions were quite small in the shortest (9ms) and the longest VOT (59ms) conditions of Figure 4 due to ceiling or floor effects, we identified one VOT condition in which listeners' sensitivity to f_0 was relatively clear. In an ambiguous VOT

condition (19ms, shown in the top center panel), listeners looked more to /d/ over time as f_0 decreased. That is, listeners attended to the f_0 cue to voicing when the VOT cue was ambiguous. The slope for the highest f_0 condition (130 Hz) in the 19ms VOT condition model was shallower than that of the mid-level f_0 (114 Hz) and that of the lowest f_0 (98 Hz). Table 1 shows that in the 19ms VOT condition, the linear slope coefficient of the highest f_0 relative to the lowest f_0 was significant ($\beta = -4.19$, $SE = 1.381$, $p < 0.005$), indicating that listeners looked less to /d/ in the higher f_0 condition relative to the lower f_0 condition when the VOT was ambiguous.

Note to Publisher: Insert Figure 4 about here

Note to Publisher: Insert Table 1 about here

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We were interested in whether there was a relationship between the gradiency measure in the VAS task (slope coefficient from the quadratic term) and the measures of sensitivity to f_0 in the AEM task. For this analysis, we examined individual listeners' response patterns in the AEM task in the conflicting vs. cooperating cue combinations of the highest and the lowest f_0 conditions and in the ambiguous VOT conditions. Figure 5 presents individuals' curves as well as the average fit from the model in the conflicting cue condition (130Hz f_0 and 9ms VOT) and the cooperating cue condition (130Hz f_0 and 59ms VOT) associated with the highest f_0 in each of the two sessions. Figure 6 presents the patterns in another conflicting cue condition (98Hz f_0 and 59ms VOT) and cooperating cue condition (98Hz f_0 and 9ms VOT) associated with the lowest f_0 in each of the two sessions. Figure 7 shows the ambiguous VOT conditions (19ms and 28ms VOTs combined) paired with the two f_0 conditions (98Hz and 130Hz).

The left panels of Figure 5 display the trajectories estimated from the regression models in the highest f_0 condition. It can be observed that the slopes are generally steeper for the shorter VOT condition, but there is much individual variability in the conflicting cue condition. This individual variability in the trajectories was not completely random: a similar pattern appeared in the two AEM sessions, and individual listeners patterned consistently in these two sessions in that the linear slope coefficients of the 9ms VOT condition were significantly correlated between the two sessions [$r = 0.416$, $p = 0.021$].

The right panels of Figure 5 plot the linear slope coefficient differences between the 9ms VOT and 59ms VOT conditions calculated from the random effects at the subject-by-condition level (that is, the random effects coefficient of the 59ms VOT condition was subtracted from that of the 9ms VOT condition, see Section 2.4.2) as a function of the gradiency measure from the VAS task (see Section 2.4.1). There was a significant positive correlation between the two dimensions (first session: $r = 0.369$, $p = 0.049$; second session: $r = 0.398$, $p = 0.029$). That is, the more gradient listeners tended to have smaller linear slope differences between the two VOT conditions while the more categorical listeners had larger linear slope differences between the two conditions. This pattern suggests that there was a greater influence of the f_0 cue on voicing perception for gradient listeners. This result provides some evidence that individual differences in gradiency of perception on the VAS task were related to individual differences in sensitivity to f_0 on the AEM task.

Figure 6 shows the trajectories estimated from the regression models in the lowest f_0 condition (left panels). Similar to Figure 5 of the highest f_0 condition, the linear slopes were, on average, steeper for the 9ms VOT condition than the 59ms VOT condition. The variability observed in the individuals' slopes was not random in that the individuals' linear slope coefficients of the 9ms VOT were correlated between the two AEM sessions [$r = 0.377$, $p = 0.039$]. Unlike the patterns in the highest f_0 condition, however, the individual variability in the responses on the AEM task, represented by the linear slope coefficient differences between the 9ms VOT and 59ms VOT conditions, were not significantly correlated with the gradiency measure from the VAS task (Figure 6, right panels). While a visual inspection indicates an overall trend that more gradient listeners tended to have smaller slope differences between the two VOT conditions, the correlation coefficients were not statistically significant [first session: $r = 0.215$, $p = 0.251$; second session: $r = 0.258$, $p = 0.167$].

To summarize, we found that there was a significant relation between gradiency and slope coefficient differences in the set of conflicting-cooperating cue conditions associated with the highest f_0 but not in the other set associated with the lowest f_0 . We speculate that the choice of "looks to /d/" as the dependent variable may be related to these inconsistent results. Given the dependent variable, the highest f_0 with longer VOT cooperates for a percept of /t/ (where individual slopes are likely to be bounded at the floor), whereas the lowest f_0 with shorter VOT cooperates for a percept of /d/. That is, it may be that this asymmetry might weaken the usefulness of the lowest f_0 as an experimental condition examining how the conflicting f_0 information affected individual listeners' perception of the stops with a reference to their perception in the cooperating f_0 information.

The results for the two stimulus conditions with ambiguous VOTs were similar to the results for the highest f_0 condition. The left panels in Figure 7 present the trajectories based on the regression model estimations in the ambiguous VOT conditions (19ms and 28ms VOTs). While the linear slope differences between the higher f_0 and lower f_0 conditions are subtle based on the average model fits (thick lines), it can be observed that there was considerable variability in the subject-level curves. This individual variability was systematic and consistent within subjects across the multiple sessions; there was a significant correlation of the slope coefficients from the 98Hz f_0 condition between the two AEM sessions [$r = 0.374$, $p = 0.041$].² Furthermore, individual differences in the AEM task were correlated with individual differences in the gradiency measure from the VAS task. The right panels in Figure 7 show the slope coefficient differences between the two f_0 conditions (98Hz and 130Hz) estimated from the random effect plotted against the gradiency measure from the VAS tasks. Overall, there was a negative relationship between these two measures. Individuals who showed a more gradient response pattern on the VAS task had a greater linear slope differences between the two f_0 conditions. Conversely, individuals who exhibited a more categorical response pattern on the VAS task had smaller linear slope differences between the two different f_0 conditions. However, the correlation between the two measures was only significant for the responses from the second test session [first session: $r = 0.008$, $p = 0.96$; second session: $r = -0.395$, $p = 0.030$]. Consistent with the pattern in the conflicting f_0 cue condition illustrated in Figure 5 (right panels), this result suggests that there was a greater effect of the f_0 cue on voicing perception for

² It should be noted that the correlations between our working measures of f_0 sensitivity (i.e., coefficient differences between shortest and longest VOTs at highest f_0) and of f_0 effect size (i.e., coefficient differences between lowest f_0 and highest f_0 at the ambiguous VOT) were not significantly correlated across the two test sessions. It is difficult to know how to interpret these findings, as researchers rarely examine consistency in eye gaze patterns across two test sessions and there are many differences between sessions, beginning with calibration. However, it is also important to note that although the difference scores were not correlated across the two test sessions, the linear slope coefficients themselves were. These slope coefficients came from the conditions where the slopes could potentially be steepest, thus allowing more room for individual variation.

the more gradient listeners as compared to the less gradient listeners. However, this result is quite tentative, given that it was significant only for the second test session.

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3.3 Relationship between individual differences in executive function and speech perception patterns

We used partial correlations to examine whether any of the different measures of executive function were related to the measure of gradiency from the VAS task (slope coefficients of the quadratic regression models) or to the measure of sensitivity to $f0$ from the AEM task (linear slope differences between models for the 9 ms and 59 ms VOT conditions in the highest $f0$ condition and linear slope differences between models for the 98Hz and 130Hz $f0$ conditions in the ambiguous VOT condition). Tables 3 and 4 summarize the outputs of the partial correlation (two conditions: one, non-verbal IQ only partialled out and two, both non-verbal IQ and the other executive function measure partialled out).

The correlation tests with the gradiency measure were performed in two ways: (a) the gradiency measure was based on responses from all stimulus conditions, and (b) the gradiency measure was based on responses only from the ambiguous VOT conditions (19ms and 28ms VOTs). The output presented in Tables 3(a) shows that, after applying the Bonferroni adjustment to the p -value for multiple comparisons, the gradiency measure based on responses from all stimulus conditions was not consistently correlated with our measure of attention switching, response time on the Trail Making Task (TMT) for both of the two partial correlation tests: a significant correlation was only found between TMT and gradiency measured in the first session when IQ was partialled out. The partial correlation test with the other executive function test also yielded coefficients not reaching significance level ($p < .0125$) in either session. Our measure of inhibition (response time on the Color-Word Naming task (CW)) was not correlated with the gradiency measure for either the first or the second test session for the partial correlation tests.

The results were similar when the gradiency measure was computed only over the responses from the ambiguous VOT conditions (Table 3b). TMT scores were not significantly correlated with the gradiency measure in either of the two partial correlation tests. Again, there was no significant correlation between our measure of inhibition and the gradiency measure. These results suggest that gradiency of speech perception and sensitivity to $f0$ were not related to higher level cognitive processing, at least for the measures assessed in this study.

Similarly, the measure of sensitivity to $f0$ from AEM task was not correlated with any of the executive function scores in any of the partial correlation tests. As presented in Tables 4, there were no significant correlations between this slope measure and the executive function measures, regardless of whether sensitivity to $f0$ was measured in the ambiguous VOT stimulus condition or in the highest or lowest $f0$ condition for either of the two AEM sessions. At least for the measures assessed in this study, we did not find evidence that sensitivity to $f0$ in the AEM task was related to cognitive processing.

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4.0 Discussion

The current study examined whether individual differences in how gradient listeners were in their perception of a stop voicing contrast was systematically related to differences in their sensitivity to a secondary acoustic cue. While the visual analogue scaling (VAS) task is designed to elicit attention to within-category differences, we found that there were large individual differences in performance on this task; response patterns for some listeners were much more gradient than response patterns for other listeners. A unique feature of this study was that we tried to quantify gradiency of performance on the VAS task. Using this measure, we were able to show that the gradiency of listeners' response patterns was consistent across two test sessions separated in time by about a week. This result suggests that gradiency of performance on the VAS task was not simply a task strategy that a listener adopts on a particular day, but was somehow associated with an individual listener's consistent pattern of speech perception. This finding is consistent with previous research that individual differences in speech are consistent within individual listeners (e.g., Idemaru & Holt, 2011; Schertz et al., 2015).

Evidence for a relation between individual differences in gradiency of performance on the VAS task and their use of a secondary acoustic cue was somewhat weaker. Listeners with a more categorical response pattern on the VAS task were more sensitive to VOT on this task than listeners with a more gradient response pattern. However, gradiency of response on the VAS task was not associated with greater sensitivity to f_0 on this task. Listeners with a more gradient response patterns on the VAS task tended to be more sensitive to f_0 on an online eye-tracking task, although this result was not observed across all possible conditions. Kapnoula and colleagues have found more robust support for the claim that more gradient listeners are more sensitive to the secondary cue on f_0 in a study that related gradiency of response on a VAS task to use of f_0 on a 2AFC task (Kapnoula, Winn, Kong, Edwards, & McMurray, 2016). Such a finding is consistent with observations in previous research that there are individual differences in perceptual cue weighting patterns (Haggard et al., 1970; Stevens & Klatt, 1994; Walley & Carrell, 1983; Whalen et al., 1993; Idemaru et al., 2012; Toscano et al., 2010). The current finding further supports the claim of Hazan and Rosen (1991) that individual differences in cue integration strategies are systematic. Hazan and Rosen (1991) found larger individual differences in reduced-cue conditions relative to full-cue conditions. Similarly, the current study found significant correlations between individual differences in gradiency of perception and sensitivity to f_0 in conflicting f_0 cue conditions and in ambiguous VOT stimulus conditions. As noted above, these results are compatible with the proposal of Francis et al. (2008) for the *dynamic redistribution of attention*, although Francis and colleagues did not predict that there might be individual differences in whether attention would be dynamically redistributed. (See also Gordon et al., 1993 for the influence of a distractor task on attention to primary and secondary acoustic cues in speech perception.) Francis and colleagues hypothesized that attention to individual cues is reallocated dynamically by accommodating the usefulness of each cue to the specific listening condition. Under excellent listening conditions, listeners focus on primary acoustic cues to differentiate speech sounds. However, under more difficult listening conditions, such as listening to speech in noise or listening when attention is limited or when conflicting or ambiguous cues are present, listeners will also rely on secondary cues. The current study did not vary the demands of the overall listening conditions, but it was more difficult to differentiate between /t/ and /d/ in some of the stimulus conditions (e.g., in the competing cues condition or the ambiguous VOT conditions). We found that it was in these less

ideal stimulus conditions that individual differences in attention to sub-phonemic acoustic details were observed.

Why was it the case that gradient listeners, rather than categorical listeners, were more flexible in utilizing redundant cues in difficult listening conditions, although this relationship was not robustly observed in all of the conditions we examined? It has been assumed in the literature with disordered populations such as children with dyslexia (e.g., Hazan & Barrett, 2000, Joanisse, Manis, Keating, & Seidenberg, 2000; Werker & Tees, 1987) that a categorical response pattern is preferable to a gradient response pattern and that individuals with a gradient response pattern have less robust phonological representations. By contrast, we found that individuals with a gradient response pattern on the VAS task were most able to attend to the secondary cue of *f0* on the AEM task in a challenging listening condition. With respect to this seemingly contradictory result, we point out that the VAS task – unlike the two-alternative forced choice (2AFC) paradigm of the classic categorical perception paradigm – is *designed* to elicit a gradient response pattern. We would argue that the “best” performers on the VAS task were those with a gradient response pattern and so it is not surprising that these listeners were also the most attentive to secondary cues in challenging listening conditions on the AEM task. Because speech cues are probabilistic and fine-grained subphonemic detail influences lexical processing (e.g., Clayards et al., 2008; McMurray et al., 2007), there are several advantages to a gradient response pattern. Everyday, non-laboratory listening situations are often quite noisy. There may be background noise or there may be interruptions to the signal (a door slam, a siren, etc.) and these results in perturbations to the speech signal. Fortunately, speech has redundant cues – if a durational cue such as VOT is obscured, another cue such as *f0* is still present. In these everyday listening situations, if individuals who have a more gradient response strategy are more likely to attend to multiple cues, then these listeners may have an advantage in word and sentence recognition. This suggests that a gradient response pattern may be preferable in real-life listening contexts.

In explaining individual differences in speech perception, we had hypothesized that gradiency of performance on the VAS task would be related to general cognitive control. We tested this hypothesis by correlating our measure of gradiency with performance on measures of inhibition and task shifting. We found little support for this claim and Kapnoula et al. (2016) also did not find consistent relationships between gradiency on a VAS task and measures of executive function. Furthermore, it should be noted that both the trail-making task and the color-word naming task are linguistic tasks of shifting and inhibition and our dependent variables are also linguistic as they both involve speech perception. It is possible that even the weak relationship between shifting and gradiency that was present might not have been observed if we had used a non-linguistic measure of task shifting.

There are a number of reasons that we did not observe stronger or more consistent correlations between the executive function measures and the speech perception measures. It may be that our target population – normal hearing monolingual speakers – produced too narrow range of variability to statistically test the relationship. Also, it is possible that the individual differences observed here are related to other aspects of cognitive control, such as working memory, which was not examined in the current study. Another limitation of the current study was the relatively small number of stimuli (90) in each session. A larger number of stimuli might have resulted in a more robust measure of gradiency for the VAS task and stronger correlations with the executive function measures. These are topics for future research.

Finally, the results of this study suggest some implications for L2 acquisition. We hypothesize that individuals with a more gradient response strategy in L1 speech perception will be better at learning a second language phonology relative to individuals with a more categorical response strategy in L1. It has been proposed that learning new cue weighting strategies is a crucial part of second language learning (Holt & Lotto, 2006; Iverson et al., 2003, 2005; Escudero, Bendersa & Lipski, 2009; Flege, Bohn, & Jang, 1997; Schertz et al., 2015; 2016; Silbert et al.,

2015) as well as first language acquisition (Nitttrouer 1992; 2002; Nitttrouer & Miller, 1997; Hazan & Barret, 2000; Li, 2012; Walley & Carrel, 1983). Besides a group-level perceptual advantage or deficit of phonological structure between L1 and L2 (Best, 1995; Best & Tyler, 2007; Flege, 2005; Chang & Mishler, 2012), we suspect that individuals who attend more to secondary cues in order to supplement less informative primary cues in their first language are more attentive to how cue weighting differs in their second language and may be more successful L2 learners.

5.0 Conclusions

This study showed that some individuals were consistently more gradient than others in their differentiating between voiced and voiceless stop consonants on a VAS task. We also found that individuals with a more gradient response pattern also tended to be more attentive to *f₀*, a secondary cue to voicing. We speculate that a gradient response pattern in normal adults may be optimal in everyday listening contexts in a noisy environment.

Acknowledgements

This work was supported by NIDCD grant R01 02932 and NSF grant BCS-0729140 to Jan Edwards and by NICHD P30 HD03352 grant to the Waisman Center. We thank all listeners who participated in this study. We are grateful to Mary E. Beckman, Elisabeth Bownik, Alia Dayne, Matt Goupell, Margarita Kaushanskaya, Benjamin Munson, Ryan Sovinski, and Jeewon Yoo for their help on many aspects of this study.

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Table 1 *Parameter estimations of the mixed effects time-series regression models in three different VOT conditions (9ms, 19ms and 59ms). The lowest f0 value (98 Hz) was the reference condition of the model. Bold indicates coefficients with p-values that were less than 0.05 and italic indicates coefficients with p-values that were less than 0.1.*

	9ms VOT		19ms VOT		59ms VOT	
	Estimate	SE	Estimate	SE	Estimate	SE
Intercept (98 Hz, reference f0)	-0.857	0.187	-1.208	0.182	-2.746	0.119
Linear slope (98 Hz)	14.701	1.125	11.409	1.273	-0.242	0.775
Quadratic slope (98 Hz)	-0.066	0.476	0.159	0.431	0.372	0.26
Cubic slope (98 Hz)	-2.058	0.305	-1.164	0.265	-0.158	0.167
Intercept (98Hz: 114Hz)	-0.212	0.16	-0.361	0.182	0.194	0.147
Intercept (98Hz: 130Hz)	-0.235	0.159	-0.703	0.181	0.024	0.148
Linear slope (98Hz: 114Hz)	-0.069	1.231	-1.933	1.395	-0.141	1.02
Linear slope (98Hz: 130Hz)	-1.635	1.227	-4.197	1.381	<i>1.929</i>	1.031
Quadratic slope (98Hz: 114Hz)	-2.031	0.673	1.192	0.566	-1.136	0.343
Quadratic slope (98Hz: 130Hz)	0.143	0.671	-2.438	0.539	-1.302	0.369
Cubic slope (98Hz: 114Hz)	0.94	0.424	-0.985	0.341	0.473	0.226
Cubic slope (98Hz: 130Hz)	-0.183	0.418	0.928	0.323	-0.462	0.234

Table 2 *Parameter estimations of the mixed effects time-series regression models in three different f0 conditions (98Hz, 114Hz and 130Hz). The shortest VOT condition (9ms) was the reference condition of the model. Bold indicates coefficients with p-values that were less than 0.05 and italic indicates coefficients with p-values that were less than 0.1.*

	98 Hz f0		114 Hz f0		130 Hz f0	
	Estimate	SE	Estimate	SE	Estimate	SE
Intercept (9ms, reference VOT)	-0.858	0.158	-1.066	0.185	-1.094	0.153
Linear slope (9ms)	14.742	1.139	14.638	1.113	13.115	0.989
Quadratic slope (9ms)	-0.067	0.398	-2.055	0.418	0.071	0.376
Cubic slope (9ms)	-2.055	0.255	-1.14	0.259	-2.224	0.227
Intercept (9ms: 19ms)	-0.35	0.187	-0.503	0.197	-0.817	0.175
Intercept (9ms: 59ms)	-1.886	0.189	-1.475	0.199	-1.629	0.179
Linear slope (9ms: 19ms)	-3.327	1.435	-5.153	1.383	-5.898	1.35
Linear slope (9ms: 59ms)	-14.996	1.462	-15.108	1.407	-11.401	1.407
Quadratic slope (9ms: 19ms)	0.229	0.556	3.418	0.542	-2.35	0.466
Quadratic slope (9ms: 59ms)	0.444	0.631	1.339	0.61	-1.028	0.602
Cubic slope (9ms: 19ms)	0.885	0.349	-1.013	0.329	1.989	0.277
Cubic slope (9ms: 59ms)	1.902	0.406	1.446	0.396	1.626	0.372

Table 3 *Output of the partial correlation tests between with each cognitive measure and the gradiency of response from the VAS task measured in two specific stimulus conditions: (a) all conditions and (b) ambiguous VOT conditions only. Results shown separately for data from the first and second sessions. Bold indicates $p < .0125$. [TMT: Trail Making Task, CW: Color-Word Naming test, IQ: non-verbal IQ test]*

correlation between gradiency & controlled covariates			first session		second session	
			r	p	r	p
(a) Gradiency measured in the all VOT conditions						
TMT	CW	IQ	-0.379	0.036	-0.289	0.123
TMT	IQ		-0.477	0.004	-0.344	0.056
CW	TMT	IQ	0.025	0.901	0.052	0.786
CW	IQ		-0.314	0.085	-0.201	0.283
(b) Gradiency measured in the ambiguous VOT conditions						
TMT	CW	IQ	-0.411	0.021	-0.423	0.017
TMT	IQ		-0.420	0.015	-0.363	0.042
CW	TMT	IQ	0.160	0.406	0.247	0.191
CW	IQ		-0.185	0.326	-0.084	0.660

Table 4 Output of the partial correlation tests between each cognitive measure and the f_0 sensitivity measure from the AEM task assessed in the two specific acoustic conditions: (a) highest f_0 , (b) lowest f_0 and (c) ambiguous VOT conditions. Results shown separately for data from the first and second sessions. [TMT: Trail Making Test, CW: Color-word naming test, IQ: non-verbal IQ test]

correlation between f0 sensitivity &			first session		second session	
controlled covariates			r	p	r	p
(a) Linear slope differences between 9ms and 59ms VOT in the highest f0 condition						
TMT	CW	IQ	0.069	0.723	0.072	0.712
TMT	IQ		-0.165	0.384	0.025	0.893
CW	TMT	IQ	-0.271	0.150	-0.077	0.691
CW	IQ		-0.307	0.092	-0.038	0.842
(b) Linear slope differences between 9ms and 59ms VOT in the lowest f0 condition						
TMT	CW	IQ	-0.145	0.453	0.14	0.446
TMT	IQ		0.034	0.856	0.301	0.100
CW	TMT	IQ	0.242	0.202	0.115	0.552
CW	IQ		0.199	0.290	0.287	0.118
(c) Linear slope differences between 98Hz and 130Hz f0 in the ambiguous VOT condition						
TMT	CW	IQ	-0.085	0.660	-0.167	0.385
TMT	IQ		0.036	0.851	0.025	0.895
CW	TMT	IQ	0.160	0.406	0.263	0.162
CW	IQ		0.140	0.459	0.208	0.268

Figure1

Path associated with the 'doggie' picture: /d/

Path associated with the 'taco' picture: /t/

Figure2

Figure3

Figure4

Figure 5

Figure6

Figure7

FIGURE CAPTION

Figure 1

Illustration of the Y-shape pipe used in the anticipatory eye movement task.

Figure 2

The leftmost column shows histograms of click locations of all listeners' responses with regression curves of quadratic terms overlaid on top. The two center columns show the logit-transformed click-location values averaged across listeners as a function of VOT (second column) and f_0 (third column). The rightmost column shows all subjects' responses to each stimulus category in a $VOT \times f_0$ space; the darkness/size of the symbol is a function of how /d/-like the stimulus was rated (the larger and the darker the dot, the more /d/-like). The responses from the first session are presented in the top panels and those from the second in the bottom panels.

Figure 3

Examples of three different response patterns for the VAS task: categorical (top), intermediate (middle), and gradient (bottom) from the first session. The leftmost column plots histograms of click locations with the quadratic curves overlaid based on the regression models. The logit-transformed click-location values in pixels averaged within subject are shown as a function of VOT (second column) and f_0 (third column). The rightmost column plots individual subject responses to each stimulus category in a $VOT \times f_0$ space; the darkness/size of the symbol is a function of how d-like the stimulus was rated (the larger and the darker the dot, the more /d/-like).

Figure 4

Logit values of estimated linear slopes of looking to /d/ over time (temporal bins) in the AEM task (first session response only). The top row shows three VOT conditions in the three separate plots, with three line-types to indicate three different f_0 conditions in each plot. The bottom row shows three f_0 conditions in the three separate plots, with three line-types to indicate three different VOT conditions in each plot.

Figure 5

The left panels show individual subject model fits for two of the time-series mixed effects regression models (9ms and 59ms VOT in the highest f_0 condition [130Hz]). Each curve indicates the model fit of an individual listener. The right panels show the difference between the slopes for these two curves plotted as a function of the gradiency measure for each participant. Responses from the two test sessions are presented separately on the top (first session) and bottom (second session) rows.

Figure 6

The left panels show individual subject model fits for two of the time-series mixed effects regression models (9ms and 59ms VOT in the lowest f_0 condition [98Hz]). Each curve indicates the model fit of an individual listener. The right panels show the difference between the slopes for these two curves plotted as a function of the gradiency measure for each participant. Responses from the two test sessions are presented separately on the top (first session) and bottom (second session) rows.

Figure 7

The left panels show individual subject model fits for two of the time-series mixed effects regression models (98Hz and 130Hz f_0 s in the ambiguous VOT conditions [19ms and 28ms VOTs]). Each curve indicates the model fit of an individual listener. The right panels show the difference between the slopes for these two curves plotted as a function of the gradiency measure for each participant. The two test sessions are presented separately in top (first session) and bottom (second session) rows.