Published in final edited form as:
*J Phon*. 2010 October ; 38(4): 640–653. doi:10.1016/j.wocn.2010.09.005.

# Language context elicits native-like stop voicing in early bilinguals' productions in both L1 and L2

**Mark Antoniou**[a,*], **Catherine T. Best**[a,b], **Michael D. Tyler**[a,c], and **Christian Kroos**[a]

Mark Antoniou: m.antoniou@uws.edu.au; Catherine T. Best: c.best@uws.edu.au; Michael D. Tyler: m.tyler@uws.edu.au; Christian Kroos: c.kroos@uws.edu.au

[a]MARCS Auditory Laboratories, Building 5, Bankstown Campus, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 1797, Australia

[b]Haskins Laboratories, 300 George Street, Suite 900, New Haven, CT 06511, USA

[c]School of Psychology, University of Western Sydney, Locked Bag 1797, Penrith South DC, NSW 1797, Australia

## Abstract

The way that bilinguals produce phones in each of their languages provides a window into the nature of the bilingual phonological space. For stop consonants, if early sequential bilinguals, whose languages differ in voice onset time (VOT) distinctions, produce native-like VOTs in each of their languages, it would imply that they have developed separate first and second language phones, that is, language-specific phonetic realisations for stop-voicing distinctions. Given the ambiguous phonological status of Greek voiced stops, which has been debated but not investigated experimentally, Greek-English bilinguals can offer a unique perspective on this issue. We first recorded the speech of Greek and Australian-English monolinguals to observe native VOTs in each language for /p, t, b, d/ in word-initial and word-medial (post-vocalic and post-nasal) positions. We then recorded fluent, early Greek–Australian-English bilinguals in either a Greek or English language context; all communication occurred in only one language. The bilinguals in the Greek context were indistinguishable from the Greek monolinguals, whereas the bilinguals in the English context matched the VOTs of the Australian-English monolinguals in initial position, but showed some modest differences from them in the phonetically more complex medial positions. We interpret these results as evidence that bilingual speakers possess phonetic categories for voiced versus voiceless stops that are specific to each language, but are influenced by positional context differently in their second than in their first language.

## 1. Introduction

Fluent bilingual speakers are faced with the challenge of accommodating two languages, at all levels of linguistic structure. Research has attempted to determine whether bilinguals integrate or keep their languages separate. Our research focus is on how they accommodate two phonological systems, specifically, how they produce consonants used by both languages, but with systematically different phonetic specifications for each. Evidence is mixed as to whether bilinguals develop separate phonetic categories for second language phones or if a single set of merged categories (e.g., Flege, 1991; Kang & Guion, 2006) is used for both the first language (L1) and second language (L2). When bilinguals produce monolingual-like speech, it has been generally taken as evidence that they have developed



*Corresponding author. Tel.: +61297726560; fax: +61297726326.

separate language-specific phonetic categories and that the L1 and L2 do not influence one another. If compromise (in between) values are produced, on the other hand, it has been argued that they have a single set of merged categories. In the present report, we attempt to disentangle these two issues by using a careful manipulation of language mode in two subgroups of matched bilinguals, we uncover evidence that, in fact, bilinguals can produce monolingual-like phonetic values in both languages in most phonetic contexts, yet show evidence of interlanguage interaction in certain other contexts, indicating that the truth lies somewhere in between phonetic merger between the L1–L2 and completely independent systems for each language. In our research, we follow the definition of bilingualism as the regular frequent use of two languages. It is important to note that bilingual speakers rarely possess an equal command of their languages (Grosjean, 1998). The present study focused specifically on L2-dominant bilinguals, a group that has received little systematic research attention but that, importantly, allows us to address the theoretical controversy from a novel and informative perspective.

According to the Speech Learning Model, or SLM (Flege, 1995, 1999, 2003; Flege, Schirru, & MacKay, 2003), bilinguals cannot fully separate their L1 and L2 phonetic subsystems as they exist in a common phonetic space, and so will necessarily influence one another. SLM predicts that the greater the perceived phonetic dissimilarity of an L2 phone from any L1 phoneme, the more likely it is that a new L2 category will be formed. This will deflect away nearby L1 categories, so as to maintain phonetic contrast between the L1 and L2, resulting in inauthentic production of both the L1 and L2. If a new category is not formed, the L2 phone will merge with the L1 category, combining properties of the L1 and L2 phones, also resulting in accented production of the L2, and causing L1 production to become more L2-like. However, more recently, Flege and colleagues have proposed that those bilinguals who are dominant in their L2 may be less likely to show L1–L2 interference (Flege, MacKay, & Piske, 2002). We note that if L2-dominant early bilinguals suppress the influence of the L1 system, the prior version of SLM would need to be modified.

Other researchers have instead proposed that a bilingual's speech is not fixed, but is sensitive to the language context. According to the language mode framework (Grosjean, 2001), bilinguals move along a monolingual-bilingual continuum, varying the levels of activation of each language. Bilinguals may be in monolingual mode (in which the other language is deactivated, although never completely) when interacting with a monolingual speaker of one of their languages, or in a bilingual mode (where both languages are activated, and mixing may occur) when interacting with a bilingual speaker of the same languages. Language mode has not often been acknowledged in studies of bilingual speech production, which have usually not noted the language context of the experimental situation (Kang & Guion, 2006; Mack, 1989; MacKay, Flege, Piske, & Schirru, 2001; Sebastian-Galles, Echeverria, & Bosch, 2005). Similarly, language mode has not been addressed by theories of nonnative or second language speech production (e.g., SLM). Nevertheless, it is possible to extrapolate from the language mode framework (Grosjean, 2001) to speech production. Specifically, we propose that bilinguals are most likely to produce monolingual-like speech when in a monolingual mode. That is, bilinguals should adapt their language output to suit the situational language context, to maximise communicative efficacy, and this should affect speech production as well as higher levels of language, akin to the way a monolingual speaker switches between speech registers or styles (see Giles, Coupland, & Coupland, 1991).

Some speech production studies of bilingual language use have indeed attempted to induce a monolingual language mode under experimental conditions, by presenting instructions and materials in only one language with the aim of activating that language, and inhibiting the other (Caramazza, Yeni-Komshian, Zurif, & Carbone, 1973; Flege & Eefting, 1987;

Grosjean & Miller, 1994; Hazan & Boulakia, 1993; Magloire & Green, 1999; Sundara, Polka, & Baum, 2006). Language mode has most commonly been manipulated when investigating languages that differ in stop-voicing distinctions, as this allows for objectively defined and well-established acoustic comparisons between the speech of bilingual and monolingual speakers. Voice onset time (VOT) is one such measure, defined as the timing between the release of a stop closure and the onset of vocal-fold vibration (Lisker & Abramson, 1964). It distinguishes voiced from voiceless stops (e.g., /p/ vs. /b/), and provides a common basis for describing cross-language differences in the phonetic realisation of stop-voicing. The task faced by bilinguals whose languages differ in VOT settings is that they must somehow deal with these language-specific VOT settings for stop-voicing contrasts in each of their languages. Language-specific phonetic categories have been proposed for perception (Best & Tyler, 2007). Here, we extend that concept to speech production. We argue that if bilinguals in each monolingual mode produce VOTs equivalent to those of monolingual speakers in each language, this can be interpreted as evidence of separate L1 and L2 *phonetic categories* (e.g., [p] versus [p▯] realisations for the phoneme /p/). However, we note that separate phonetic settings would not necessarily preclude the possibility that *phonological* elements and contrasts may nonetheless be shared between the two languages (e.g., /b/-/p/ is a phonological contrast in both languages).

Evidence thus far is mixed, however, as to whether bilingual speakers can produce VOTs equivalent to those of monolinguals in each of their languages. When languages differ in VOT settings, bilingual speakers have been reported either to fail to match the VOTs of monolingual speakers of one or both languages (Flege & Eefting, 1987; Fowler, Sramko, Ostry, Rowland, & Hallé, 2008; Sundara et al., 2006), or to match the VOTs of monolinguals in both languages (Kang & Guion, 2006). Indeed, Magloire and Green (1999) reported that for English and Spanish /b, p/, bilinguals produced VOTs like monolinguals of each of their languages at not only normal, but also at fast and very fast speaking rates. As a result of these conflicting findings, the degree to which bilinguals shift their VOT values when speaking in their different languages remains unresolved.

Bilingual speakers differ in their patterns of language acquisition and language use, which also corresponds to differences in their speech production (Flege et al., 2003; Guion, Flege, & Loftin, 2000; Hazan & Boulakia, 1993). Factors that have varied in previous studies of bilinguals (e.g., age of acquisition, language dominance, ratio of L1/L2 use, accented input) may have contributed to the varying results. Care must be taken to recruit bilinguals who do not differ in their pattern of language acquisition, language dominance, language use (including the social contexts in which each language is used) and level of fluency in each language.

The present report examines the production of bilabial and coronal stops by Greek–English bilinguals. Greek–English early bilinguals in Australia are an ideal group for adherence to our strict selection criteria as they have acquired Greek from birth (from their native-speaking migrant parents and grandparents), and have become dominant in their L2, English, as spoken in a specific dialectal form, Sydney-regional Australian, which they also acquired from native speakers from an early age. Australian English is a nonrhotic dialect of English, spoken as a first language by most native-born Australians, and acquired as an L2 by Australian-born early bilinguals of migrant communities. As with most English dialects, Australian English voiceless stops have long-lag aspirated VOT in word-initial position, for example, PUSH [p$^{h}$ʊʃ], TIN [t$^{h}$ɪn] (Cox & Palethorpe, 2007), whereas voiced stops typically have short-lag-unaspirated VOT in word-initial position, with /b/ and /d/ realised as [p] and [t], e.g., BACK [pæk˺], DIG [tɪg] (Cox & Palethorpe, 2007). The VOTs of medial stops vary based on stress position. Medial stops occurring in stressed syllables have more extreme VOTs (voiced=larger voicing lead, voiceless=longer lag VOT) than those in unstressed syllables.

Standard Modern Greek is spoken by most native-born Greeks as well as in Greek migrant communities, such as those in Australia. Greek voiceless stops are produced with short-lag unaspirated VOT (Fourakis, 1986; Kollia, 1993). The phonological status of the voiceless stops /p, t, k/ is widely accepted. However, over the past 50 years, one of the most passionately debated aspects of Greek phonology has been the phonological status of Greek voiced stops, that is, whether voiced stops are (a) single segments that stand in minimal contrast with voiceless stops, or (b) sequences of nasal+voiceless stop (Arvaniti, 1999, 2007; Arvaniti & Joseph, 2000, 2004; Holton, Mackridge, & Philippaki-Warburton, 1997; Joseph & Philippaki-Warburton, 1987; Koutsoudas & Koutsoudas, 1962; Newton, 1972; Pagoni-Tetlow, 1993, 1994; Viechnicki, 1996).

Orthographically, Greek voiced stops are represented by digraphs, for example, [b] = μπ (mp in Roman alphabet script); [d] = ντ (nt); [g]=γκ or γγ. In Standard Modern Greek, word-initial voiced stops are prevoiced [b, d, g] (Botinis, Fourakis, & Prinou, 2000). There is greater variation in the production of Greek stops in medial position, as the nasal preceding the stop may or may not be realised (Arvaniti & Joseph, 2000). There is evidence from other languages that voiced stops, but not voiceless stops, may have nasal onsets (J. J. Ohala & M. Ohala, 1993), and that the presence of the epenthetic nasal sets the stage for sound change, that is, listeners may reinterpret the phonetically predictable event as a distinctive phonological event (M. Ohala & J. J. Ohala, 1991). It has been suggested that Greek is presently undergoing such a sound change, as the nasalisation is disappearing from the speech of young Athenians (Arvaniti & Joseph, 2000). We will offer some evidence that this sound change has already occurred.

Just two previous studies have compared the VOT production of Greek–English bilinguals to that of monolingual speakers, although neither manipulated language mode. In one, late Greek–English bilinguals were found to produce Greek (L1) word-initial /p, t, k/ with VOTs that were longer than those produced by Greek monolinguals (Efstathopoulou, 2006). However, the bilinguals differed in their ages at when L2 learning had commenced, making it difficult to determine the contribution of age of acquisition to L1 accentedness. In the other study, Beach, Burnham, and Kitamura (2001) found that Greek–English bilinguals produced monolingual-like VOTs for English /p/, but not English /b/, which they produced with voicing lead. However, the bilinguals also varied widely in language dominance and patterns of language acquisition; two of the participants were simultaneous bilinguals (from birth) while the others had acquired their languages sequentially by the age of five. To overcome the limitations of these past studies, we manipulated language mode, employed strict selection criteria, and compared the bilinguals to monolingual speakers of both languages.

Language mode was manipulated between groups. It was predicted that the two groups of bilinguals would produce different language-specific VOTs: Voiceless stops will be produced with long-lag VOT in English mode and short-lag VOT in Greek mode, whereas voiced stops would be produced with short-lag VOT in English mode and voicing lead in Greek mode.

To understand the effects of language mode on stop-voicing production by Greek–English bilinguals, we must first examine the productions by monolingual speakers of both languages (in Experiments 1a, 2a, 3a). The results from the monolinguals will inform our predictions and interpretation of results for the bilinguals (in Experiments 1b, 2b, 3b). In addition, the phonetic details of the medial context effects are markedly different in English and Greek. Therefore, we will first examine the production of initial stops in Experiment series 1, before investigating VOT under two different stress conditions in the phonetically more complex medial positions in Experiment series 2 (post-vocalic context) and Experiment series 3 (post-nasal context).

## 2. Experiment 1a: Greek and English monolinguals' production of /pa, ta, ba, da/

We recorded the productions of bilabial and coronal stops in syllable-initial position by Australian and Greek monolingual speakers. Bilabial and coronal stops were investigated because English and Greek differ in the place of articulation between the coronal stops (English=alveolar, Greek=dental), but not for the bilabials, and place of articulation is known to systematically affect VOT (Klatt, 1975). Given these place differences, we would expect a larger VOT difference between bilabials and coronals in English than Greek.

Examining stops in initial position also allows for comparison with previous VOT studies. The phonetic properties of the voicing distinction in each language are most clear-cut in initial position, according to descriptions in the literature. Greek monolinguals were expected to produce the voiced stops with voicing lead, and voiceless stops with short-lag VOT. English monolinguals were expected to produce voiced stops with very short-lag VOT and voiceless stops with long-lag VOT.

### 2.1. Method

**2.1.1. Participants—**Eight English monolingual speakers ($M_{AGE}$=24.5 years; four males and four females) and eight Greek monolingual speakers ($M_{AGE}$=22.1 years; four males and four females) were recorded. The English monolinguals were students at the University of Western Sydney and participated in exchange for course credit. The Greeks were students at the University of Athens and participated as part of their coursework. In Greece, nearly all students have some knowledge of English from school. To the extent that they had heard English spoken, it was mostly Greek-accented, with modest exposure to British and/or American varieties, but not to Australian English.

**2.1.2. Stimuli—**Participants produced the stop consonants /p, t, b, d/ in word-initial CV context /pa, ta, ba, da/. Stops were produced preceding an /a/, because low vowels are associated with lower velum positions than high vowels (which may promote the appearance of a nasal). Target syllables were embedded in carrier phrases in each language that were selected to provide preceding and following vowel contexts as similar as possible across languages — *say* CV *again* (English condition) and *λέει* CV *άλλο* [lei CV alo] (Greek condition).

**2.1.3. Procedure—**Speakers produced targets in carrier sentences that were presented on a computer monitor in quasi-random order. To minimise contrastive hyperarticulation, stop-voicing minimal pairs that share the same place of articulation were not presented in consecutive trials (e.g., pa vs. ba). Stimulus presentation was controlled by Opa 1.0 stimulus presentation software developed at MARCS Auditory Laboratories for this purpose. Trials containing coughs, stutters or speech errors were rejected during the recording session. Replacements were recorded later in the session, such that four correct utterances were recorded for each target. Note that individual sentences from Experiments 1–3 were presented randomly, onscreen, in one large recording session.

Speech was recorded digitally to computer (16 bit, 44.1 kHz) using a Shure SM10A headset cardioid microphone and an EDIROL UA-25 USB audio interface. The English monolinguals were recorded in the anechoic chamber at MARCS Auditory Laboratories (Xu, Buchholz, & Fricke, 2005). The Greek monolinguals were recorded in a quiet room at the linguistics laboratory at the National and Kapodistrian University of Athens.

The target utterances (pseudo-words) were segmented from the speech recordings and labeled using Praat (Boersma & Weenink, 2001) acoustic analysis software. Markers were placed at the beginning of the closure phase of the stop, at the moment of consonantal release, and at the end of the burst at the onset of the vowel. The following criteria were used for measuring VOT: If voicing was absent immediately before the release burst, the stop was considered voiceless and positive VOT was reported, whereas if voicing was present immediately before the release, the stop was considered prevoiced and negative VOT was reported (see illustrative oscillograms and spectrograms of Greek voiceless and voiced stops in Figs. 1 and 2).

### 2.2. Results

The English monolinguals produced voiced stops with voicing onset that coincided with the release (very slight prevoicing for /b/; very short lag VOT for /d/), and voiceless stops /p, t/ with long-lag VOT. Greek speakers substantially prevoiced their voiced stops /b, d/, and produced the voiceless stops with short-lag VOTs that were slightly longer (more positive), but less variable (narrower distribution), than the voiced stop VOTs of the Australians. Mean VOTs and standard deviations are shown in Table 1.

A 2 × (2 × 2) Analysis of Variance (ANOVA) on VOT was conducted, with *language* as the between-subjects factor, and *voicing* and *place* as within-subjects factors. A significant main effect of language, $F(1, 14)=118.6$, $p<.001$, revealed that the grand mean VOT of the Greek stops was significantly smaller than the corresponding mean for English stops (Greek voiced stops were more prevoiced: $M_{\mathrm{GREEK}}= -128.5$ ms; $M_{\mathrm{ENGLISH}}=2.0$ ms; and Greek voiceless stops had shorter lag: $M_{\mathrm{GREEK}}=15.9$ ms; $M_{\mathrm{ENGLISH}}=80.0$ ms). There was also a significant main effect of voicing, $F(1, 14)=313.7$, $p<.001$, confirming that voiced stops were produced with more voicing lead than voiceless stops, across both languages ($M_{\mathrm{VOICED}}= -63.2$ ms; $M_{\mathrm{VOICELESS}}=48.0$ ms). The significant Language × Voicing interaction, $F(1, 14)=28.064$, $p=.001$, revealed that the difference in VOT between voiced and voiceless stops was greater in Greek than in English ($M_{\mathrm{GREEK}}=144.4$ ms; $M_{\mathrm{ENGLISH}}=77.9$ ms). All other main effects and interactions were non-significant.

### 2.3. Discussion

The English voiced stops were produced with very short-lag VOT, and voiceless stops had long-lag VOT, consistent with previous findings on Australian English (Cox & Palethorpe, 2007). Greek voiced stops were strongly prevoiced, in clear contrast to the voiceless stops, which were produced with short-lag VOT, compatible with previous reports of voicing values of Greek stops (Botinis et al., 2000; Fourakis, 1986). The Greek voiced stops were not preceded by nasalisation, consistent with reports that the nasal is disappearing in the speech of Athenian speakers (Arvaniti & Joseph, 2000).

The present findings appear consistent with an argument that Greek voiced stops warrant phonological status as singleton segments. However, given the stimulus set and restricted context in which target syllables were produced, further study is required examining other contexts. Further, despite the stark difference in VOT, we cannot yet rule out the alternative explanation that the underlying nasal has been neutralised to prevoicing in initial-position Greek voiced stops (Experiments 2–3 will address this issue for medial stop contexts).

The patterns of VOT production in Greek and English set up a very interesting scenario for Greek–English bilingual speakers. Given the observed VOT differences between Greek and

English, the question we asked next was whether bilingual speakers would shift their productions of VOT in each language mode, to reproduce the language-specific differences between voiced and voiceless stops. If bilinguals have separate phonetic categories for each language, they should produce monolingual-like VOTs in each language, whereas if they produce compromise VOTs that fail to match those of monolinguals in one or both languages, this would indicate that they have merged L1–L2 categories.

## 3. Experiment 1b: Greek and English bilinguals' production of /pa, ta, ba, da/

Experiment 1b investigated the production of word-initial voiced and voiceless bilabial and coronal stops by Greek–English early bilinguals. The two groups of bilinguals were recorded in different language modes, manipulated to activate only one of the bilinguals' languages to provide the optimal conditions for them to produce monolingual-like VOTs. Strict selection criteria were employed to ensure that any differences observed between the bilingual groups were solely due to the manipulation of language mode.

Based on the findings of Experiment 1a, if bilinguals have developed separate phonetic categories for voiced and voiceless stops in each of their languages, then the difference in VOT between the voiced and voiceless stops in Greek should be greater than the difference in VOT in English stops.

### 3.1. Method

**3.1.1. Participants—**Two groups of eight bilinguals (English mode $M_{age}$=30.7 years; Greek mode $M_{age}$=25.0 years; four males and females per group) were recruited from the Greek-Australian community in Sydney. All bilinguals came from the same population, and strict criteria were employed to ensure that they did not differ in their pattern of language acquisition, dominance or use. They were born in Sydney, Australia, had been exposed to Greek since birth, later learned and became fluent in English (by the age of six), and were dominant in English, their L2 (see Table 2 for mean self-ratings). All continued to use both Greek and English in some social situations in their everyday lives. They received $20 for their participation.

**3.1.2. Stimuli—**The same stimuli were used as in Experiment 1a.

**3.1.3. Procedure—**All contact, instructions, forms, carrier phrases and feedback occurred in only one language for each bilingual participant. Additionally, when participants conversed with the experimenter prior to recording, care was taken to avoid topics that would likely activate the bilingual's other language. For example, bilinguals in English mode were usually asked about their work, Australian news headlines and current events, whereas those in Greek mode were asked about their family, culture, church and trips to Greece.

As in Experiment 1a, speakers produced targets in carrier sentences in quasi-random order. Four correct utterances of each target were recorded. The Greek–English bilingual participants were recorded in the anechoic chamber at MARCS Laboratories.

### 3.2. Results

The bilinguals in English mode, similarly to the English monolinguals, slightly prevoiced English /b/ and produced English /d/ with short-lag VOT. They produced the English voiceless stops /p, t/ with long-lag VOT. The bilinguals in Greek mode, like the Greek monolinguals, produced Greek /b, d/ with substantial voicing lead, and /p, t/ with short-lag VOT (see Table 3).

A 2 × (2 × 2) ANOVA was conducted on the VOT data, of the same design as in Experiment 1a. A significant effect of language mode, $F(1, 14)=132.3$, $p<.001$, revealed that bilinguals produced shorter VOTs in Greek than in English mode ($M_{GRMODE}= -53.1$ ms; $M_{ENMODE}=42.2$ ms). As expected, a significant main effect of voicing, $F(1, 14)=460.8$, $p<.001$, revealed that voiceless stops had longer mean lag than voiced stops in both language modes ($M_{VOICED}= -59.8$ ms; $M_{VOICELESS}=48.9$ ms). More importantly, a significant Language Mode × Voicing interaction, $F(1, 14)=24.4$, $p<.001$, showed that the difference in VOT between voiced and voiceless stops was greater in Greek than in English ($M_{GRMODE}=133.8$ ms; $M_{ENMODE}=83.7$ ms). As is shown in Fig. 3, and supported by additional ANOVAs (described next), these findings are consistent with the performance of both the Greek and the English monolingual speakers observed in Experiment 1a. A significant main effect of place, $F(1, 14)=6.7$, $p=.021$, indicated that bilabial voiced stops had greater prevoicing, and bilabial voiceless stops had shorter lag, than the corresponding coronals ($M_{BILABIALS}= -9.4$ ms; $M_{CORONALS}= -1.5$ ms). The significant Language Mode × Place interaction, $F(1, 14)=7.9$, $p=.014$, indicated that this difference was greater in English than in Greek ($M_{GRMODE}=0.7$ ms; $M_{ENMODE}=16.6$ ms).

Having established that the bilinguals did in fact switch language mode, and given the similarity of the bilinguals' VOTs to those of the monolinguals' (Fig. 3), we ran two additional 2 × (2 × 2) ANOVAs, with a between-subjects factor of lingualism (monolingual vs. bilingual) and within-subjects factors of voicing and place, to determine whether the bilinguals in Greek mode differed from the Greek monolinguals, and whether the bilinguals in English mode differed from the English monolinguals.

For Greek, there was no significant main effect of lingualism, nor were there any significant interactions involving lingualism (see Table 4). This indicates that the bilinguals did not differ from the monolinguals in their Greek word-initial VOTs ($M_{GREEK}= -56.3$ ms; $M_{GRMODE}= -53.1$ ms). The significant main effect of voicing showed that the monolinguals and the bilinguals taken together produced Greek voiced stops that were significantly more prevoiced than the Greek voiceless stops ($M_{VOICED}= -124.2$ ms; $M_{VOICELESS}=14.9$ ms).

For English, akin to what was observed for Greek, there was no significant main effect of lingualism, nor were there any significant interactions involving lingualism (see Table 5). The bilinguals did not differ from the monolinguals for their VOTs in English ($M_{ENGLISH}=41.0$ ms; $M_{ENMODE}=42.2$ ms). The significant main effect of voicing showed that the monolinguals and the bilinguals produced English voiceless stops with longer lag VOT than the voiced stops ($M_{VOICED}=1.2$ ms; $M_{VOICELESS}=82.0$ ms). The significant main effect of place confirmed that, unlike the findings for Greek, English bilabial stops were produced with different VOTs (voiced: more voicing lead; voiceless: shorter lag VOT) than English coronal stops ($M_{BILABIAL}=35.6$ ms; $M_{CORONAL}=47.6$ ms).

### 3.3. Discussion

The results of the present study show a striking effect of the manipulation of language mode. Bilinguals in Greek mode produced VOTs that were clearly distinct from those of the bilinguals in English mode. In fact, they produced a pattern of results that is comparable to that of the monolingual Greek speakers.

Greek–English bilinguals in Greek mode produced VOTs for word-initial /b, d/ that were significantly more prevoiced than, and /p, t/ that were significantly shorter than those produced in English mode. These findings mirror those obtained from the comparison of monolingual speakers of Greek and English in Experiment 1a. Importantly, the difference in VOT between voiced and voiceless stops was greater for bilinguals in Greek mode than it was for bilinguals in English mode, which also mirrors Experiment 1a. Moreover, the bilinguals in each language mode did not differ from the corresponding monolinguals in either language.

Both groups of bilinguals produced the difference in VOT for bilabial versus coronal place. There have been reported correlations between place and magnitude of VOT, which has been reported to be longer the more posterior the consonant constriction is. Interestingly, the bilinguals' VOT differences between labials and coronals were greater for English, which has an alveolar place, than for Greek, which has a more anterior dental place, that is, the English coronal is spatially farther from the bilabial. The bilinguals in English mode showed this place difference in VOT even though the English monolinguals did not. One possible explanation for this might be that bilinguals maintain a difference between the VOT settings of English and Greek by dissimilating their English and Greek categories (Flege, 1995), slightly exaggerating the place difference.

The results of Experiment 1b have important implications for theories of phonetic and phonological organisation in bilinguals. It is not the case that bilinguals are sensitive to a VOT distinction in only one language, and are simply producing voiced and voiceless stops in the other language by maintaining this distinction with, perhaps, just a shift of the paired categories along the VOT continuum. For the two languages, the voiced and voiceless categories are not equally spaced along the VOT dimension. We reported in Experiment 1a that the difference in VOT between voiced and voiceless stops is greater in Greek than in English. The bilingual speakers, in Experiment 1b, successfully produced this difference dependent on language mode.

The present findings are consistent with previous work that has demonstrated that bilinguals produce VOTs in both languages that mirror those of monolingual speakers if the manipulation of the language of presentation is pervasive and convincing (Magloire & Green, 1999), although here we have extended previous findings by demonstrating that bilinguals match the VOTs of monolinguals for both bilabial and coronal stops, even when the coronals have a place difference between the languages (English=alveolar, Greek=dental). With particular respect to Greek–English bilinguals in English mode, our findings are consistent with those of Beach et al. (2001) who reported that bilinguals produced monolingual-like VOTs for the English voiceless stop /p/. However, our bilinguals did not prevoice their English voiced stops /b, d/ as they had in the Beach et al. (2001) study. We speculate that this is because we used stricter selection criteria (L2-dominant, early, fluent bilinguals) and unlike Beach et al., we used a convincing language mode manipulation that placed our bilinguals in a monolingual-English mode.

Our findings support the existence of language-specific phonetic categories, that is, Greek versus English-specific variants of /p, t, b, d/ for the bilingual groups, as outlined by PAM-L2 (Best & Tyler, 2007) for perception, but shown here for production. This assertion is based on the observation that the bilinguals produced clearly distinct VOT values, remarkably close to those of their monolingual counterparts. Importantly, the bilinguals' productions of voiced and voiceless stops in Greek and English were more native-like than would be required for mere intelligibility in both languages. That is, there is no obvious communicative pressure for bilingual speakers to produce their stops with such native accuracy in each language. The bilinguals' categories have not deflected away (or dissimilated) to maintain L1–L2 phonetic contrast as the SLM would predict. The bilinguals have instead preserved the overlapping VOTs of the Greek voiceless and English voiced stops.

Our findings are compatible with Flege et al.'s (2002) prediction that L2-dominant bilinguals are likely to show diminished L1–L2 interference. Indeed, our bilingual participants show no apparent interference: each language mode group produced VOTs that were statistically indistinguishable from monolinguals for initial stops occurring in monosyllables. These findings would be strengthened by comparison with L1-dominant bilinguals. Unfortunately, such a population is unlikely to exist for Greek and English, in either Greece or any English-speaking country. However, research on bilingual speakers of other languages may address the underlying issues well enough, as it has already been demonstrated with other groups that L1-dominant bilinguals typically show traces of their L1 on production of stop voicing in the L2 (e.g., Caramazza et al., 1973; Williams, 1977).

Given the phonetic differences between initial and medial stop-voicing in both English and Greek, and the implication that medial stops reflect more complex contextual influences than initials because they have both a following phonetic context (like initials) and a preceding phonetic context within the same word, we turned next to examine monolinguals' and bilinguals' production of stop-voicing in medial position within disyllabic targets. Prior bilingual speech research has focused almost exclusively on initial stops, thus little is know in any case about their productions of medial stops. In addition, the ambiguous status of Greek voiced stops is more evident in medial position, where the voiced stops can be prenasalised. It remains unclear, then, whether bilinguals match the VOTs of monolingual speakers in the phonetically more complex, medial environments. Therefore, it is critical to examine the phonetic characteristics of the voicing distinction in post-vocalic contexts (Experiments 2a, b), as well as post-nasal contexts (Experiments 3a, b).

## 4. Experiment 2a: Greek and English monolinguals' production of /p, t, b, d/ in medial post-vocalic contexts

The VOTs of English medial stops vary based on stress position. English medial voiceless stops are aspirated in stress-initial syllable position (e.g., SUPPORT [sɐˈp$^{h}$oːt], FACTORIAL [ˌfækˈt$^{h}$oːɾ$^{j}$əɫ]; Cox & Palethorpe, 2007). At the beginning of an unstressed syllable, however, voiceless stops usually have shorter VOTs and are unaspirated or very weakly aspirated (e.g., BEEPER [ˈbiːpə, LOOKING [ˈlƱkɪŋ]). In intervocalic, stress-initial position, voiced stops are realised as fully voiced (e.g., ABORT [ɐˈboːt˺], ADORE [ɐˈdoː]; Cox & Palethorpe, 2007). Thus, in general, English VOT values become more extreme (voiced: more negative VOT values, voiceless: more positive values) in stress-initial position (Klatt, 1976).

The phonetic realisation of Greek voiced stops in word-medial position, on the other hand, is the source of much debate (Arvaniti, 1999, 2007; Arvaniti & Joseph, 2000, 2004; Malikouti-Drachman, 1993; Newton, 1961; Viechnicki, 1996). The debate concerns the role of the nasal preceding the stop. As in word-initial position, Greek medial-position voiceless stops are produced with short-lag VOT. Voiced stops are produced with voicing lead, but in traditional accounts are said to be prenasalised [$^{m}$b, $^{n}$d, $^{n}$g] (Newton, 1972). However, when variations in dialect, idiolect, rate of speech, and social register are taken into account, the variation in pronunciation is considerable. For example, the word άντρας MAN would be pronounced with a full nasal preceding the stop, as [ˈandras] in the Peloponnese, but without any nasal as [ˈadras] in Crete, and as prenasalised [ˈa$^{n}$dras] in Athens, although the nasal is disappearing in the speech of young Athenians (Arvaniti & Joseph, 2000). There have been reports that manipulating stress does not result in VOT changes in Greek, as it does in English (Fourakis, 1986). In addition to the unclear role of nasalisation in Greek medial voiced stops, competing findings also suggest that the effects of stress on word-medial Greek stop voicing is not yet fully understood (Arvaniti, 2000; Kollia, 1993).

Before examining the bilinguals' production of VOT in word-medial context it was again necessary to conduct a systematic study of the production of monolingual speakers of each language. In order to control for speaker variation in production of Greek medial stops, we specifically instructed whether speakers would produce Greek stops with or without realising the nasal (Experiment 2: non-nasal stops, Experiment 3: post-nasal stops). If Greek voiced stops are phonologically contrastive with voiceless stops, we would expect to see VOT differences in both stress positions and both instruction contexts. We expected, of course, to replicate prior reports of stress position effects on voicing in the English stops.

## 4.1. Method

The same two groups of monolingual speakers were recorded as in Experiment 1a. Participants produced the stops in word-medial disyllabic context with stress occurring on either the first syllable ˈVCV /ˈapa, ˈata, ˈaba, ˈada/ or on the second syllable VˈCV /aˈpa, aˈta, aˈba, aˈda/. As in Experiment 1a, targets were embedded in carrier phrases in each language. The recordings were made during the same session as in Experiment 1a.

## 4.2. Results

VOTs for the English and Greek monolingual groups are displayed in Table 6. Overall, the English monolinguals slightly prevoiced medial /b, d/, and produced medial /p, t/ with long-lag VOT. The Greek monolinguals produced /b, d/ with prevoicing and /p, t/ with short-lag VOT.

A 2 × (2 × 2 × 2) ANOVA was conducted with voicing, place and stress as within-subjects factors. A significant main effect of language, $F(1, 14)=124.8$, $p<.001$, illustrated that the two languages differed in their word-medial VOT settings ($M_{\text{GREEK}}= -52.8$ ms; $M_{\text{ENGLISH}}=29.1$ ms). A significant Language × Stress interaction, $F(1, 14)=12.5$, $p=.003$, revealed that the difference between stressed and unstressed syllables was greater in English than in Greek ($M_{\text{GREEK}}=6.5$ ms; $M_{\text{ENGLISH}}=11.6$ ms). A significant main effect of voicing, $F(1, 14)=378.4$, $p<.001$, confirmed the expected differences between voiced and voiceless stops across both languages ($M_{\text{VOICED}}= -67.4$ ms; $M_{\text{VOICELESS}}=43.7$ ms). A Language × Voicing interaction, $F(1, 14)=378.4$, $p<.001$, revealed that the differences between voiced and voiceless stops were greater in Greek than in English ($M_{\text{GREEK}}=138.4$ ms; $M_{\text{ENGLISH}}=83.9$ ms). The significant Voicing × Place interaction, $F(1, 14)=8.6$, $p=.011$, and higher order three-way interaction of Language × Voicing × Place revealed that the VOT difference between coronal voiced and voiceless stops was larger than that for bilabial stops, and more so in English than in Greek, $F(1, 14)=17.4$, $p=.001$.

## 4.3. Discussion

As in Experiment 1a, the Greek voiced stops had very long voicing lead, whereas the voiceless stops were produced with short-lag VOT. Stress did not result in a significant change in the VOT of Greek stops, consistent with previous research (Fourakis, 1986). No acoustic evidence was found that the Greek speakers nasalised their voiced stops in medial position under this instruction condition.

Consistent with previous reports (Cox & Palethorpe, 2007), English voiceless stops were produced with long-lag VOT, and the length of the lag was exaggerated when the stop was in a stressed syllable. The English voiced stops were produced with slight prevoicing, with the exception of the English coronal voiced stop in unstressed position (ˈada), which was more prevoiced than the other English voiced stops. We observed more prevoicing when English voiced stops occurred in unstressed syllables, unlike what has previously been reported for English voiced stops (Klatt, 1976).

The VOTs of the Greek and English stops were affected differently when the stress was manipulated, in that the Greek stops did not show as much change in stressed versus unstressed syllables. These language-specific VOT differences pose a tougher challenge for our bilingual speakers than those observed in initial-position. It remains to be seen if even highly fluent bilinguals will produce language-specific word-medial differences that vary in their pattern of VOT as a function of stress (Greek: unaffected by stress, English: affected by stress), while also maintaining the language-specific VOT differences for voiced and voiceless stops.

The present findings are compatible with the view that Greek voiced stops warrant phonological status. As was reported in Experiment 1a, the VOTs of the Greek voiced and voiceless stops were markedly different and did not overlap. Voiced stops were produced with voicing lead, without prenasalisation.

## 5. Experiment 2b: Greek and English bilinguals' production of /p, t, b, d/ in medial post-vocalic contexts

The pattern of VOT production in stressed versus unstressed word-medial oral stops by Greek and English is more complicated than that observed in Experiment 1a. Given the observed differences between Greek and English medial stop voicing, to assess whether bilingual speakers switch language modes fully in production of stop voicing it is necessary to test whether word-medial VOTs are produced that differ in each language, akin to monolingual speakers.

To our knowledge, this is the first systematic investigation of the effect of language mode on the production of medial stop consonants by bilinguals. Thus, we expected each language mode group to show the same pattern of results observed in Experiment 2a for the corresponding monolinguals, compatible with the theoretical underpinnings of Grosjean's (2001) language mode framework.

### 5.1. Method

The same two groups of bilinguals that were recruited for Experiment 1b participated in this experiment. The stimuli used were identical to those used in Experiment 2a. The procedure used was identical to that in Experiment 1b.

### 5.2. Results

As expected, the bilinguals in English mode produced English voiced stops with voicing lead, and English voiceless stops with long-lag VOT. The bilinguals in Greek mode produced the Greek voiced stops with very long voicing lead, and the voiceless stops with short-lag VOT (see Table 7).

A 2 × (2 × 2 × 2) ANOVA was conducted with voicing, place and stress pattern as within-subjects factors. The significant main effect of language mode revealed that our manipulation of language context was effective in getting our bilingual speakers to produce VOTs that were significantly different in Greek and English, $F(1, 14)=48.8$, $p<.001$. A significant interaction of Language Mode × Stress, $F(1, 14)=11.9$, $p=.004$, revealed that stress had the opposite effect on VOTs in Greek than in English ($M_{GRMODE}= -11.1$ ms; $M_{ENMODE}=11.6$ ms). The significant main effect of voicing, $F(1, 14)=309.5$, $p<.001$, confirmed the expected difference in VOT between voiced and voiceless stops across languages ($M_{VOICED}= -60.6$ ms; $M_{VOICELESS}=42.4$ ms). A significant main effect of place, $F(1, 14)=12.0$, $p=.004$, showed that the mean VOT between bilabial and coronal stops differed in both language modes ($M_{BILABIALS}= -11.4$ ms; $M_{CORONALS}= -6.9$ ms). A significant interaction of Voicing × Place, $F(1, 14)=7.1$, $p=.018$, revealed that, across both language modes, the VOT difference between voiced and voiceless stops was greater for coronals than bilabials ($M_{BILABIALS}=99.6$ ms; $M_{CORONALS}=106.4$ ms).

As shown in Fig. 4, the bilinguals produced VOTs similar to those of the monolinguals in Experiment 2a. However, it appears that some differences from monolinguals emerged, particularly in the production of the English voiced bilabial stop /b/. In order to determine whether the bilinguals differed from the monolinguals in their VOTs for the medial oral stops, two additional 2 × (2 × 2 × 2) ANOVAs were conducted.

For Greek, as shown in Table 8, there was no significant main effect of lingualism, nor were there any significant interactions involving lingualism. This indicates that the bilinguals in Greek mode did not differ from the corresponding monolinguals in their VOTs for Greek stops in medial position ($M_{GREEK}= -52.8$ ms; $M_{GRMODE}= -47.3$ ms). The significant main effect of voicing confirmed that the monolinguals and the bilinguals produced Greek voiced stops that were significantly more prevoiced than the Greek voiceless stops, which had short-lag VOT ($M_{VOICED}= -115.2$ ms; $M_{VOICELESS}=15.1$ ms). The significant main effect of place showed that, across both groups, the VOTs of Greek bilabial stops were shorter (voiced: more prevoiced; voiceless: shorter lag) than those of the Greek coronal stops ($M_{BILABIALS}= -53.5$ ms; $M_{CORONALS}= -46.6$ ms). The significant main effect of stress showed that stops occurring in stressed syllables had different VOTs than stops in unstressed position. The significant Voicing × Stress interaction indicates that Greek voiced stops occurring in stressed syllables were produced with more voicing lead, whereas voiceless stops were unaffected by stress (voiced stops: $M_{STRESSED}= -123.2$ ms; $M_{UNSTRESSED}= -107.2$ ms; voiceless stops: $M_{STRESSED}=14.3$ ms; $M_{UNSTRESSED}=15.8$ ms).

For English, as shown in Table 9, there was no significant main effect of lingualism. However, there were significant Lingualism × Voicing, Lingualism × Place, and Lingualism × Voicing × Place interactions. These showed that the bilinguals in English mode differed from the monolinguals, particularly in the prevoicing of the voiced bilabials (voiced bilabials: $M_{ENGLISH}= -5.1$ ms; $M_{ENMODE}= -40.0$ ms; voiced coronals: $M_{ENGLISH}= -20.6$ ms; $M_{ENMODE}= -19.4$ ms; voiceless bilabials: $M_{ENGLISH}=63.8$ ms; $M_{ENMODE}=70.6$ms; voiceless coronals: $M_{ENGLISH}=78.3$ms; $M_{ENMODE}=80.0$ms). The significant main effect of stress showed that when English stops occurred in stressed syllables, both groups' voiced stops had shorter voicing lead, and voiceless stops had longer lag VOT ($M_{STRESSED}=31.8$ms; $M_{UNSTRESSED}=20.1$ms).

### 5.3. Discussion

The bilinguals in Greek mode and those in English mode produced clearly different VOT values for voiced and voiceless stops. Both groups exhibited language-specific differences, akin to those of the monolinguals in Experiment 2a. Like the English monolinguals, the English mode bilinguals also produced English voiceless stops with long-lag VOT and this was more extreme in stressed syllables. However, the bilinguals produced English voiced bilabial stops in medial position with longer voicing lead than the English monolinguals. As predicted, bilinguals in Greek mode produced Greek voiced stops with voicing lead and voiceless stops with short-lag VOT. Their VOT productions did not differ from those of the Greek monolinguals for stops produced in medial context.

It was demonstrated once again that Greek voiced and voiceless stops have clearly distinct VOT values for both the monolingual speakers (in Experiment 2a) and the bilingual Greek mode speakers. These findings are also compatible with the argument that Greek voiced stops warrant phonological status. However, as in Experiment series 1, and despite no observable nasalisation for the Greek voiced stops, we cannot rule out the possibility that an underlying nasal is present that has been reduced to prevoicing.

Given the variability in the realisation of the nasal within medial stops in Modern Greek, we instructed our speakers to produce oral stops. Next, it is necessary to examine the production of Greek nasal+stop sequences in order to determine whether VOT differences between Greek voiced and voiceless stops persist even when the nasal is overtly realised.

## 6. Experiment 3a: Greek and English monolinguals' production of /p, t, b, d/ in medial post-nasal contexts

This experiment set investigated the production of Greek and English monolinguals' productions of voicing in word-medial stops when preceded by a nasal. We refer to these VNCV sequences as nasal+stop. The reason for instructing each speaker to realise the nasal preceding the stop was to control interspeaker variability; unless specifically instructed to do otherwise, in some Greek words, some speakers realise the nasal, while others do not. Combined with the production of oral stops in Experiment series 2, these findings will inform our predictions for the performance of bilinguals in Experiment 3b. Nasal+stop sequences are phonotactically legal in English, so English monolinguals were included in the analyses to (a) compare their productions to those of the Greek monolinguals and (b) inform our hypotheses for the Greek–English bilinguals in English mode in Experiment 3b.

If Greek voiced stops are not phonologically contrastive with voiceless stops as segments, but are instead sequences of nasal+voiceless stop, then we would not expect any differences between the voiced and voiceless stops in post-nasal contexts (e.g., amba vs. ampa). However, if Greek monolinguals produce Greek voiceless stops with short-lag VOT, whereas Greek voiced stops are prevoiced, *even when preceded by a nasal*, this would lend support to the view that Greek voiced stops are truly contrastive with voiceless stops. Due to the production of the nasal preceding the voiced stop, we would expect that the voicing lead would be shorter than that observed in the voiced stops preceded by a vowel in Experiment 2a. This is because voiced stop prevoicing is shorter when preceded by a nasal. For example, in English, when a voiced stop is preceded by a nasal, the VOT should be multiplied by 0.8, to take into account the duration lost to the nasal (Klatt, 1975). Although reduced, we would still expect that the Greek voiced stops to be prevoiced, despite the nasal. The effects of stress on VOT production in Greek VNCV sequences was unknown; no prior research has addressed this question. However, based on the findings in Experiment 2a, we predicted that Greek stop voicing would be relatively unaffected by stress.

### 6.1. Method

The same English and Greek monolingual speakers were recorded as in Experiments 1a and 2a. Participants produced the nasal+stop consonants /mp, nt, mb, nd/ word-medially in stressed (VˈNCV) /aˈmpa, aˈnta, aˈmba, aˈnda/ and unstressed syllables (ˈVNCV) /ˈampa, ˈanta, ˈamba, ˈanda/. Greek nasal+stop sequences were elicited by inserting a second nasal following the first vowel (e.g., a άμ-μπα [ˈamba] vs. *άμ-πα*), [ˈampa] and training participants on producing overt nasalisation, before the recording began. None found the request difficult to understand or produce. The recording procedure was identical to that in Experiments 1a and 2a.

Separating the nasal and stop was difficult. Nasals are produced with closure of the oral cavity, open velum and radiation through the nasal cavity. They are characterised by the presence of the *nasal formant* (a high-intensity low-frequency F1), another peak around 1000 Hz, and antiresonances that dampen the higher frequencies (Stevens, 1999). We separated the nasal and the stop at the point where sudden energy loss occurred in the

NIH-PA Author Manuscript

NIH-PA Author Manuscript

frequency components above approximately 250 Hz, caused by the closure of the velum to produce the oral stop, and measured the prevoicing from that point up to the release burst (see Fig. 5).

### 6.2. Results

The English monolinguals produced the word-medial nasal+voiced stops with lead VOT, with the exception of the voiced coronal stop in stressed position (aˈnda) which had zero VOT. English voiceless stops were produced with long-lag VOT. The Greek monolinguals produced voiced stops with voicing lead and voiceless stops with short-lag VOT (see Table 10).

A 2 × (2 × 2 × 2) ANOVA was conducted with voicing, place and stress pattern as within-subjects factors. A significant main effect of language, $F(1, 14)=12.0$, $p<.001$, confirmed the expected language-specific differences in mean VOT ($M_{GREEK}= -22.1$ ms; $M_{ENGLISH}=29.2$ ms). Greek stops were produced with shorter mean VOTs (voiced stops: longer lead VOT; voiceless stops: shorter lag VOT) than English stops. A significant main effect of voicing, $F(1, 14)=474.9$, $p<.001$, indicated that voiced and voiceless stops differed in VOT across both languages ($M_{VOICED}= -36.2$ ms; $M_{VOICELESS}=43.2$ ms). A significant main effect of place, $F(1, 14)=5.1$, $p=.040$, showed a difference in mean VOT for bilabial and coronal stops across both languages, specifically that bilabial voiced stops were more prevoiced and bilabial voiceless stops had shorter lag VOT than coronals ($M_{BILABIALS}=1.2$ ms; $M_{CORONALS}=5.8$ ms). The significant Language × Stress interaction, $F(1, 14)=8.4$, $p=.012$, indicated that the difference in VOT between stops in stressed versus unstressed position was greater in English than it was in Greek ($M_{GREEK}=5.9$ ms; $M_{ENGLISH}=13.4$ ms). A significant three-way Voicing × Place × Stress interaction revealed that the VOTs of voiced bilabial stops were more affected by the stress difference than the coronals, across both languages, $F(1, 14)=5.5$, $p=.034$.

For both groups, VOTs of voiced stops were shortened by the preceding nasal, whereas voiceless stops were unaffected, when compared to productions in the medial VCV contexts. To take account for the duration taken up by the nasal, the VOTs of the voiced stops produced by English monolinguals in medial VCV context would need to be multiplied by 0.9, and for Greeks by 0.5 (English monolinguals: $M_{VCV}= -12.9$ ms; $M_{VNCV}= -11.9$ ms; Greek monolinguals: $M_{VCV}= -122.0$ ms; $M_{VNCV}= -60.4$ ms).

### 6.3. Discussion

In accordance with the results of Experiment 2a, the English voiced stops were produced with slight prevoicing, with the exception of the coronal voiced stop occurring in an unstressed syllable (ˈanda), which was again produced with more voicing lead than the other English voiced stops. English voiceless stops were produced with long-lag VOT, and the length of the lag was exaggerated when the stop was in a stressed syllable (at least for voiceless bilabials).

The Greek and English VOTs were both affected by stress position. Unlike in the post-vocalic (VCV) contexts of Experiment 2a, it appears that stress did affect the lead VOT of Greek bilabial voiced stops in word-medial post-nasal position. This finding supports Kollia’s (1993) account that Greek VOTs are affected by stress position. Concerning the phonological debate of Greek stop-voicing distinctions, if voiced stops are simply sequences of nasal+voiceless stop, then the VOTs of the nasal+voiceless stops here (e.g., ampa) should have been identical to the medial voiced stops from Experiment 2a (e.g., aba), or if the nasal is realised, identical to the nasal+voiced stops (e.g., amba). Given that the Greek nasal +voiceless stops clearly differed in their VOTs from the voiced stops, this suggests that voiced stops are not sequences of nasal and voiceless stop. The findings indicate that Greek voiced stops should be considered as phonological singleton segments, contrasting with voiceless stops before which a nasal (as a separate segment) may or may not be realised.

Based on these observed differences, we are now in a position to test whether bilingual speakers produce word-medial VOTs that are consistent with monolingual speakers of each of their languages. The difference between the Greek and English voiced stops was smaller here than in Experiment 2a. This is presumably because of the lowering of the velum during vocal fold vibration, the realisation of the nasal that shortens the voicing lead of the Greek voiced stops. Given this smaller difference between Greek and English stops, bilingual speakers may not keep their VOTs for voiced stops as distinct in each language mode in a VNCV context. If bilinguals have developed separate phonetic categories for Greek and English voiced stops, however, they should still produce distinct VOTs for voiced and voiceless stops in Greek and English, even in this nasal context.

## 7. Experiment 3b: Greek and English bilinguals' production of /p, t, b, d/ in medial post-nasal contexts

Based on the findings in Experiment 3a, we hypothesised that bilinguals would produce different VOTs for English and Greek that are consistent with the stress pattern differences between the two monolingual groups. However, the degree with which their productions in each language would differ was not easily predictable.

Recall that the realisation of the nasal before word-medial voiced stops is disappearing in Standard Modern Greek, the dialect spoken by our Athenian monolinguals (Arvaniti & Joseph, 2000). No such reports have examined the Greek spoken in Australia, which is likely to have diverged phonetically over time from its origin (see Appel & Muysken, 1987). Therefore, despite our explicit instructions to produce a nasal preceding the stop, it is plausible that our bilingual speakers would not produce a pattern of VOT production that resembles that of current Athenian Greek monolingual speakers in VNCV context. However, if by instructing the bilinguals to produce a nasal preceding the stop we effectively controlled for dialect variation, and if bilinguals have separate categories for Greek and English stops, we would expect that the bilinguals would produce monolingual-like VOTs in both languages.

### 7.1. Method

The same two groups of bilinguals that were recruited for Experiments 1b and 2b participated. The stimuli were identical to those in Experiment 3a. The procedure was identical to Experiments 1b and 2b.

### 7.2. Results

The bilinguals in English mode produced English voiced stops that were prevoiced, with the exception of /aˈnda/ which had near zero VOT. The English voiceless stops were produced with long-lag VOT. The bilinguals in Greek mode produced the Greek voiced stops with voicing lead, and the voiceless stops with short-lag VOT (see Table 11).

A 2 × (2 × 2 × 2) ANOVA was conducted with voicing, place and stress pattern as within-subjects factors. A significant main effect of language mode, $F(1, 14)=63.0$, $p<.001$, demonstrated that our manipulation was once again effective in getting bilinguals to switch their VOT settings when speaking in Greek and English ($M_{GRMODE}= -22.1$ ms; $M_{ENMODE}=30.1$ ms). A significant main effect of voicing, $F(1, 14)=947.8$, $p<.001$, illustrated that the VOT of voiced and voiceless stops differed in both language modes

($M_{VOICED}$= −37.5 ms; $M_{VOICELESS}$=45.5 ms). A significant Language Mode × Voicing interaction, $F(1, 14)$=16.1, $p$=.001, revealed that the difference in VOT between voiced and voiceless stops was greater in English than in Greek ($M_{GRMODE}$=72.2 ms; $M_{ENMODE}$=93.9 ms). A significant main effect of place, $F(1, 14)$=10.2, $p$=.007, revealed that there was a significant difference in VOT for bilabial and coronal stops in both language modes ($M_{BILABIALS}$= −0.1 ms; $M_{CORONALS}$=8.1 ms). A significant Language Mode × Stress interaction, $F(1, 14)$=21.4, $p$<.001, and the higher order Language Mode × Voicing × Stress interaction, $F(1, 14)$=5.5, $p$=.034, revealed that the VOT difference between stops in stressed and unstressed syllables differed for Greek and English ($M_{GRMODE}$=7.9 ms; $M_{ENMODE}$=10.3 ms). Greek voiced stops were produced with longer voicing lead in stressed position, whereas English voiced stops were produced with longer voicing lead in unstressed position. Also, Greek voiceless stops were produced with longer lag in unstressed position, whereas English voiceless stops were produced with longer lag in stressed position.

For both groups of bilinguals, the VOTs of voiced stops were shortened by the preceding nasal, whereas voiceless stops were unaffected, when compared to productions in the medial VCV contexts. To take account for the duration taken up by the nasal, the VOTs of the voiced stops produced by the English mode bilinguals in medial VCV context would need to be multiplied by 0.6, and for the Greek mode bilinguals by 0.5 (English mode: $M_{VCV}$= −29.7 ms; $M_{VNCV}$= −16.9 ms; Greek mode: $M_{VCV}$= −108.3 ms; $M_{VNCV}$= −58.2 ms).

As shown in Fig. 6, the bilinguals in both language modes produced VOTs in word-medial nasal context similar to those of monolingual speakers. In order to determine whether the bilinguals differed from the monolinguals in their VOTs for the medial oral stops, two additional 2 × (2 × 2 × 2) ANOVAs were conducted.

For Greek, as shown in Table 12, there was no significant main effect of lingualism, nor were there any significant interactions involving lingualism. This indicates that the bilinguals in Greek mode did not differ reliably from the monolinguals in their VOTs for Greek nasal+stops in medial position ($M_{GREEK}$= −22.1 ms; $M_{GRMODE}$= −22.1 ms). The significant main effect of voicing confirmed that the monolinguals and the bilinguals produced Greek voiced stops that were significantly more prevoiced than the Greek voiceless stops, produced with short lag ($M_{VOICED}$= −59.3 ms; $M_{VOICELESS}$=15.1 ms). The significant main effect of place showed that the VOTs of Greek bilabial stops were shorter (voiced: longer prevoicing; voiceless: shorter lag) than those of the Greek coronal stops ($M_{BILABIALS}$= −24.6 ms; $M_{CORONALS}$= −19.6 ms). The significant main effect of stress showed that stops in stressed position had different VOTs than stops in unstressed position ($M_{STRESSED}$= −25.5 ms; $M_{UNSTRESSED}$= −18.7 ms). More specifically, the significant Voicing × Stress interaction revealed that voiced stops occurring in stressed position were produced with more voicing lead, whereas voiceless stops were unaffected by stress (voiced stops: $M_{STRESSED}$= −65.6 ms; $M_{UNSTRESSED}$= −53.0 ms; voiceless stops: $M_{STRESSED}$=14.5 ms; $M_{UNSTRESSED}$=15.7 ms).

For English, as shown in Table 13, there was no significant main effect of lingualism. However, there was a significant three-way Lingualism × Voicing × Place interaction. This showed that the bilinguals in English mode produced longer prevoicing of the voiced bilabial, but not coronal, voiced stops, and produced longer lag for the voiceless stops than did the monolinguals (voiced bilabials: $M_{ENGLISH}$= −12.1 ms; $M_{ENMODE}$= −24.2 ms; voiced coronals: $M_{ENGLISH}$= −11.6 ms; $M_{ENMODE}$= −9.5 ms; voiceless bilabials: $M_{ENGLISH}$=65.5 ms; $M_{ENMODE}$=73.8 ms; voiceless coronals: $M_{ENGLISH}$=75.0 ms; $M_{ENMODE}$=80.3 ms). The significant main effect of stress showed that English stops differed in their VOT according to stress context ($M_{STRESSED}$=35.6 ms; $M_{UNSTRESSED}$=30.1 ms). The significant main effect of place showed that there was a significant difference in VOT for the English bilabial and coronal stops, specifically that the bilabial voiced stops were more prevoiced, and coronal voiceless stops had longer lag VOT ($M_{BILABIALS}$=69.6 ms; $M_{CORONALS}$=77.7 ms).

### 7.3. Discussion

Once again, the results demonstrate that the bilinguals in each language mode produced different VOTs for their voiced versus voiceless stops. As predicted, bilinguals in Greek mode produced Greek voiced stops with voicing lead and voiceless stops with short-lag VOT. Like the Greek monolinguals in Experiment 3a, the bilinguals produced shorter voicing lead for the Greek voiced stops than the medial stops in Experiment series 2.

The bilinguals in English mode produced English voiced stops with voicing lead, with the exception of /aˈnda/ which had near zero VOT. This pattern of VOT production differs from that of the English monolinguals reported in Experiment 3a, but is consistent with the bilinguals' initial-position prevoicing reported by Beach et al. (2001). Speech production studies often report that bilinguals with L1s that use prevoicing for voiced stops will also prevoice English (L2) voiced stops. Such findings are interpreted as L1 interference on production of the L2. The bilinguals here produced English voiceless stops with long-lag VOT and this was, as predicted, more extreme in stressed syllables.

It appears that the bilinguals have separate phonetic categories for Greek and English voiced stops. However, given that they acquired English years after learning Greek it is likely that their English categories *in this segmentally complex context* were influenced by their knowledge of Greek (their L1), and that this persisted, despite their L2-dominance later in life.

## 8. General discussion

The series of experiments presented in this paper have demonstrated that fluent early Greek–English bilinguals matched the VOTs of syllable-initial stops produced by monolingual speakers of Greek and English. Bilinguals produced distinct initial-position VOTs for voiced and voiceless stops in both languages, preserving the larger VOT difference in Greek, observed from the monolinguals. They also produced distinct VOTs for the medial stops, even when the stop was preceded by nasal. The bilinguals' VOT productions in each language were very accurate, that is similar to the monolinguals', more so than would be required for mere intelligibility. Therefore, their accuracy cannot be attributed to communicative pressure. The bilinguals in Greek mode were indistinguishable from the Greek monolinguals. The bilinguals in English mode showed some L1 interference on the L2 for some of the English medial stops.

These findings have implications for SLM. SLM cannot account for the native-like productions of our bilingual speakers. They showed no influence of the L2 when producing the L1, and their initial-position productions of the L2 were free of L1 interference. This is, nonetheless, consistent with Flege et al.'s (2002) later prediction that L2-dominant bilinguals are less likely to show L1–L2 interference. However, the few interference effects that we observed were of the L1 on the L2 (not of the L2 on the L1). Thus, even L2-dominant bilinguals are not entirely immune to L1 interference on the L2. In addition, the findings may be interpreted as evidence for the existence of language-specific phonetic categories, that is, Greek versus English variants of /p, t, b, d/, compatible with those posited by PAM-L2 for perception (Best & Tyler, 2007).

The data provide support for the view that the bilinguals' categories from both languages exist in one phonological space. Even L2-dominant bilinguals, despite their fluency, showed (albeit minimal) L1–L2 interference effects. Interestingly, it was in the bilinguals' dominant language, English (L2), that we observed effects from the L1 (non-English-like prevoicing in some medial contexts). Such observed differences between the bilinguals in English mode and the English monolinguals cannot be attributed to accented L2 input, differences in the setting where L2 learning took place, or regional variations due to dialect. The bilinguals were recruited from the same population as the English monolinguals and any difference in English VOTs must be due to interference from the bilinguals' L1. We have demonstrated that this occurs even when the situational language context is carefully controlled. Therefore, even though we argue that the bilinguals have developed separate phonetic categories for the L2, there is interaction between the L1 and L2. Future studies should assess whether L2-dominant bilinguals exhibit L1–L2 influence in speech perception analogous to what we have reported here for speech production.

Given the contextually constrained differences from monolinguals in the bilinguals' dominant language (English), it seems remarkable that the bilinguals approached the VOTs of the Greek native speakers with such accuracy across the various contexts. Despite years of dominance in the L2 (English), the VOTs of the bilinguals in Greek mode were indistinguishable from those of the Greek natives, even in the phonetically more complex medial contexts. These findings suggest that despite their L2-dominance, these fluent early bilinguals suppressed L2 influence on the L1, but failed to completely suppress the L1 influence on the L2 in the more complex phonotactic context with and without preceding nasals.

Although not the central aim of this paper, the present results are compatible with the view that Greek voiced stops are singleton segments that stand in minimal contrast to the voiceless stops. Greek monolinguals and Greek–English bilinguals produced VOTs that were significantly different for voiced and voiceless stops in word-initial and word-medial positions, even when the stops were preceded by a nasal. Future research should investigate other vowel and post-nasal contexts. In addition, perception of Greek voiced versus voiceless stops in a variety of contexts must be examined to determine whether Greek listeners perceive voiced and voiceless stops as distinct categories.

We have demonstrated that bilingual speakers are sensitive to the language context, and produce native-like stop-voicing in the L1 and L2. In speech production, L2-dominant bilinguals largely, though not perfectly, suppress L1–L2 interference. This does not mean that bilinguals keep their languages completely separate, as the modest L1–L2 interference effects on the L2 productions in the phonetically more complex medial positions demonstrates that bilinguals must integrate the L1 and L2 into a common phonological space. Future research will examine whether placing the bilinguals in the opposite language mode and asking that they rapidly switch languages to produce the same targets as they did here will result in language-relevant shifts in VOT within-subjects (see Sancier & Fowler, 1997), consistent with those observed between-subjects in the present series of studies.

## Acknowledgments

This research was supported by a UWS Postgraduate Research Award, MARCS Auditory Laboratories Fieldwork Travel grant, and NIH grant DC000403 (PI: C.T. Best). We offer our sincere thanks to Professor Antonis Botinis (Linguistics, University of Athens) for his generous assistance in the recruitment of Greek native speakers and provision of quiet recording space at the University.

## References

Appel, R.; Muysken, P. Language contact and bilingualism. Baltimore: Edward Arnold; 1987.

Arvaniti, A. Greek voiced stops: Prosody, syllabification, underlying representations or selection of the optimal?. Proceedings of the 3rd international linguistics conference for the Greek language; Athens. Ellinika Grammata; 1999. p. 383-390.

Arvaniti A. The phonetics of stress in Greek. Journal of Greek Linguistics. 2000; 1:9–39.

Arvaniti A. Greek phonetics: The state of the art. Journal of Greek Linguistics. 2007; 8:97–208.

Arvaniti A, Joseph BD. Variation in voiced stop prenasalization in Greek. Glossologia. 2000; 11–12:131–166.

Arvaniti A, Joseph BD. Early modern Greek /b d g/: Evidence from Rebetika and Folk Songs. Journal of Modern Greek Studies. 2004; 22:73–94.

Beach EF, Burnham D, Kitamura C. Bilingualism and the relationship between perception and production: Greek/English bilinguals and Thai bilabial stops. International Journal of Bilingualism. 2001; 5:221–235.

Best, CT.; Tyler, MD. Nonnative and second-language speech perception: Commonalities and complementarities. In: Bohn, O.; Munro, MJ., editors. Language experience in second language speech learning: In honor of James Emil Flege. Amsterdam: John Benjamins Publishing Company; 2007. p. 13-34.

Boersma P, Weenink D. Praat, a system for doing phonetics by computer. Glot International. 2001; 5:341–345.

Botinis A, Fourakis M, Prinou I. Acoustic structure of the Greek stop consonants. Glossologia. 2000; 11–12:167–200.

Caramazza A, Yeni-Komshian GH, Zurif EB, Carbone E. The acquisition of a new phonological contrast: The case of stop consonants in French-English bilinguals. Journal of the Acoustical Society of America. 1973; 54:421–428. [PubMed: 4759015]

Cox F, Palethorpe S. Australian English. Journal of the International Phonetic Association. 2007; 37:341–350.

Efstathopoulou, N. ITRW on Experimental Linguistics. ISCA; 2006. The influence of second language learning on speech production by Greek/English bilinguals: The case of VOT; p. 77-88.

Flege JE. Age of learning affects the authenticity of voice-onset time (VOT) in stop consonants produced in a second language. Journal of the Acoustical Society of America. 1991; 89:395–411. [PubMed: 2002177]

Flege, JE. Second language speech learning: Theory, findings, and problems. In: Strange, W., editor. Speech perception and linguistic experience: Issues in cross-language research. Baltimore: York Press; 1995. p. 233-277.

Flege, JE. Age of learning and second language speech. In: Birdsong, D., editor. Second language acquisition and the critical period hypothesis. New Jersey: Lawrence Erlbaum; 1999. p. 101-131.

Flege, JE. Assessing constraints on second-language segmental production and perception. In: Schiller, NO.; Meyer, AS., editors. Phonetics and phonology in language comprehension and production: Differences and similarities, Phonology & phonetics. Berlin: Walter de Gruyter; 2003. p. 319-355.

Flege JE, Eefting W. Production and perception of English stops by native Spanish speakers. Journal of Phonetics. 1987; 15:67–83.

Flege JE, MacKay IRA, Piske T. Assessing bilingual dominance. Applied Psycholinguistics. 2002; 23:567–598.

Flege JE, Schirru C, Mackay IRA. Interaction between the native and second language phonetic subsystems. Speech Communication. 2003; 40:467–491.

Fourakis M. An acoustic study of the effects of tempo and stress on segmental intervals in modern Greek. Phonetica. 1986; 43:172–188. [PubMed: 3797481]

Fowler CA, Sramko V, Ostry DJ, Rowland SA, Hallé PA. Cross language phonetic influences on the speech of French–English bilinguals. Journal of Phonetics. 2008; 36:649–663. [PubMed: 19802325]

Giles, H.; Coupland, N.; Coupland, J. Accommodation theory: Communication, context, and consequence. In: Giles, H.; Coupland, J.; Coupland, N., editors. Contexts of accommodation: Developments in applied sociolinguistics. Cambridge: Cambridge University Press; 1991. p. 1-68.

Grosjean F. Studying bilinguals: Methodological and conceptual issues. Bilingualism: Language and Cognition. 1998; 1:131–149.

Grosjean, F. The bilingual's language modes. In: Nicol, J., editor. One mind, two languages: Bilingual language processing. Oxford: Blackwell Publishing; 2001. p. 1-22.

Grosjean F, Miller JL. Going in and out of languages: An example of bilingual flexibility. Psychological Science. 1994; 5:201–209.

Guion SG, Flege JE, Loftin JD. The effect of L1 use on pronunciation in Quichua-Spanish bilinguals. Journal of Phonetics. 2000; 28:27–42.

Hazan VL, Boulakia G. Perception and production of a voicing contrast by French–English bilinguals. Language and Speech. 1993; 36:17–38.

Holton, D.; Mackridge, P.; Philippaki-Warburton, I. Greek: A comprehensive grammar of the modern language. London: Routledge; 1997.

Joseph, BD.; Philippaki-Warburton, I. Modern Greek. London: Croom Helm; 1987.

Kang K, Guion SG. Phonological systems in bilinguals: Age of learning effects on the stop consonant systems of Korean-English bilinguals. Journal of the Acoustical Society of America. 2006; 119:1672–1683. [PubMed: 16583911]

Klatt DH. Voice onset time, frication, and aspiration in word-initial consonant clusters. Journal of Speech, Language and Hearing Research. 1975; 18:686–706.

Klatt DH. Linguistic uses of segmental duration in English: Acoustic and perceptual evidence. Journal of the Acoustical Society of America. 1976; 59:1208–1221. [PubMed: 956516]

Kollia HB. Segmental duration changes due to variations in stress, vowel, place of articulation, and voicing of stop consonants in Greek. Journal of the Acoustical Society of America. 1993; 93:2298.

Koutsoudas A, Koutsoudas O. A contrastive analysis of the segmental phonemes of Greek and English. Language Learning. 1962; 12:211–230.

Lisker L, Abramson AS. A cross-linguistic study of voicing in initial stops: Acoustical measurements. Word. 1964; 20:384–422.

Mack M. Consonant and vowel perception and production: Early English–French bilinguals and English monolinguals. Perception & Psychophysics. 1989; 46:187–200. [PubMed: 2762107]

MacKay IRA, Flege JE, Piske T, Schirru C. Category restructuring during second-language speech acquisition. Journal of the Acoustical Society of America. 2001; 110:516–528. [PubMed: 11508976]

Magloire J, Green KP. A cross-language comparison of speaking rate effects on the production of voice onset time in English and Spanish. Phonetica. 1999; 56:158–185.

Malikouti-Drachman, A. New approaches to some problems of Greek phonology. In: Philippaki-Warburton, I.; Nicolaidis, K.; Sifianou, M., editors. Themes in Greek linguistics. Amsterdam: John Benjamins Publishing Company; 1993. p. 33-44.

Newton BE. The rephonemization of modern Greek. Lingua. 1961; 10:275–284.

Newton, BE. The generative interpretation of dialect: A study of modern Greek phonology. London: Cambridge University Press; 1972.

Ohala, JJ.; Ohala, M. The phonetics of nasal phonology: Theorems and data. In: Huffman, M.; Krakow, R., editors. Nasals, nasalization, and the velum. San Diego, CA: Academic Press; 1993. p. 225-249.

Ohala M, Ohala JJ. Nasal epenthesis in Hindi. Phonetica. 1991; 48:207–220.

Pagoni-Tetlow S. Modern Greek prenasalisation. Studies in Greek Linguistics. 1993; 14:355–369.

Pagoni-Tetlow, S. Themes in Greek linguistics: Papers from the first international conference on Greek linguistics, Reading, September 1993. Amsterdam: John Benjamins Publishing Company; 1994. Government and element-licensing: The Modern Greek evidence; p. 209-216.

Sancier ML, Fowler CA. Gestural drift in a Bilingual speaker of Brazilian Portuguese and English. Journal of Phonetics. 1997; 25:421–436.

Sebastian-Galles N, Echeverria S, Bosch L. The influence of initial exposure on lexical representation: Comparing early and simultaneous bilinguals. Journal of Memory and Language. 2005; 52:240–255.

Stevens, KN. Acoustic phonetics. Cambridge, MA: MIT Press; 1999.

Sundara M, Polka L, Baum S. Production of coronal stops by simultaneous bilingual adults. Bilingualism: Language and Cognition. 2006; 9:97–114.

Viechnicki P. The problem of voiced stops in modern Greek: A non-linear approach. Studies in Greek Linguistics. 1996; 16:59–70.

Williams L. The perception of stop consonant voicing by Spanish–English bilinguals. Perception & Psychophysics. 1977; 21:289–297.

Xu J, Buchholz JM, Fricke FR. Flat-walled multilayered anechoic linings: Optimization and application. Journal of the Acoustical Society of America. 2005; 118:3104–3109.

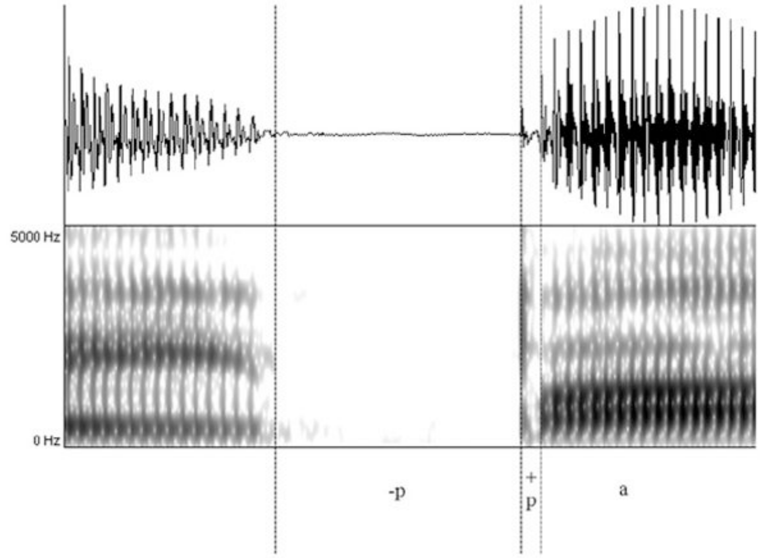


**Fig. 1.**
Positive VOT reported, denoted by +p.

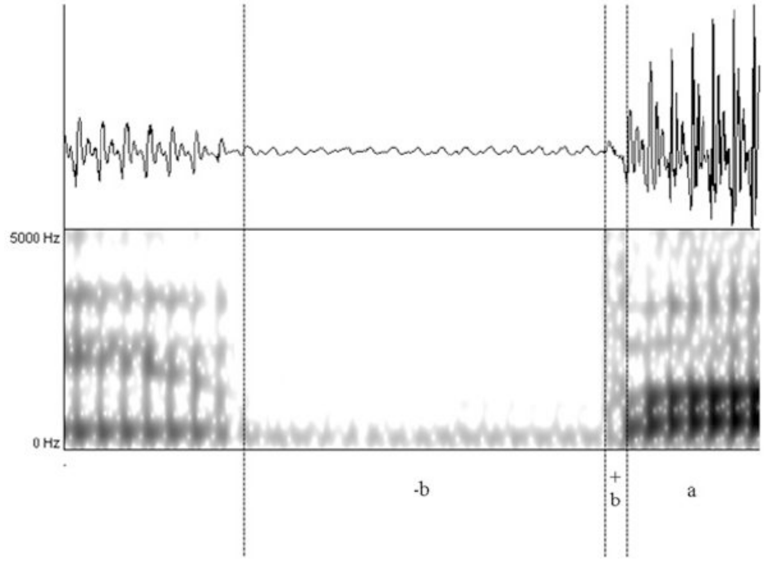


**Fig. 2.**
Negative VOT reported, denoted by −b.

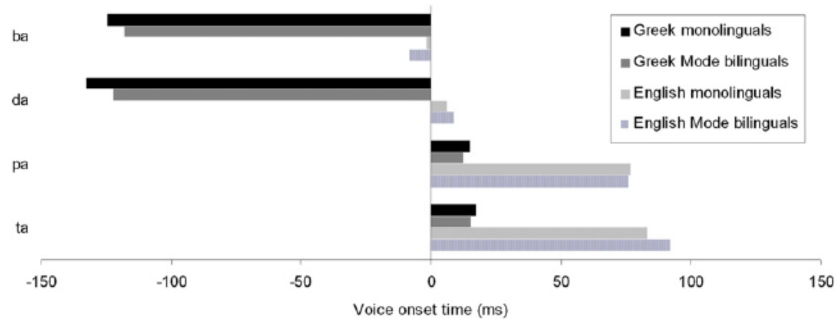


**Fig. 3.**

Greek and English word-initial mean VOTs produced by Greek and English monolinguals and bilinguals in Greek and English language modes.

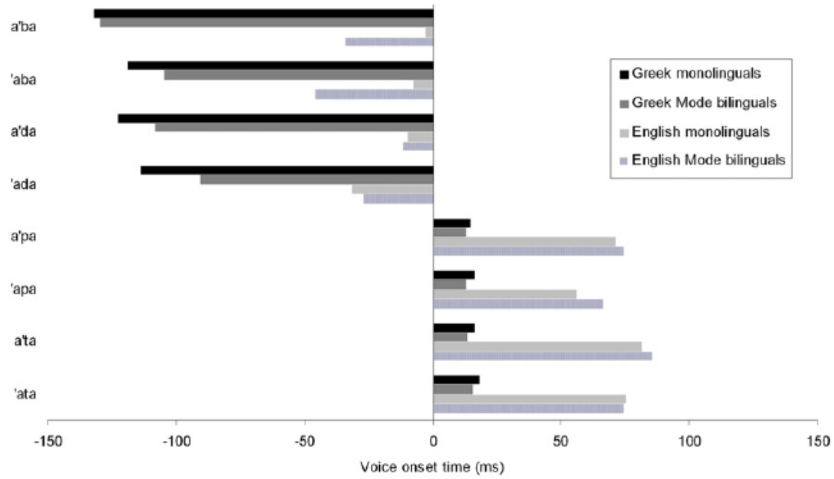


**Fig. 4.**

Mean VOTs of Greek and English word-medial oral stops produced by Greek and English monolinguals and bilinguals in Greek and English language modes.

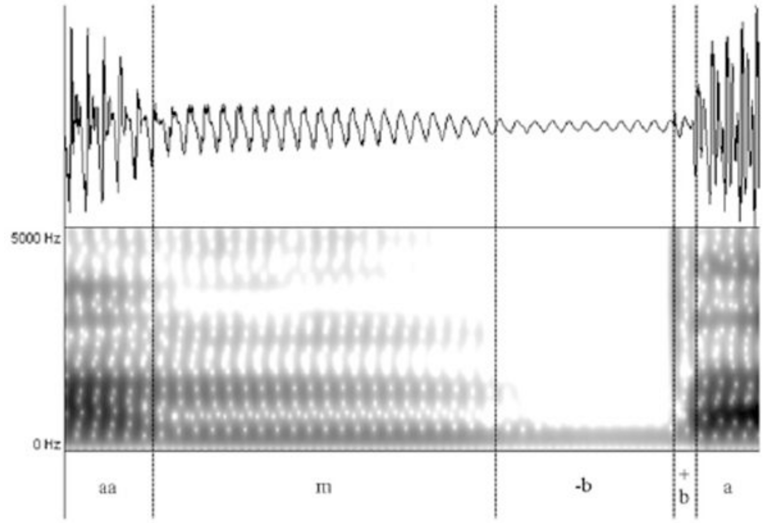


**Fig. 5.**
Segmenting the nasal (m) and prevoicing (−b) of the Greek nasal + voiced stop [ˈamba].

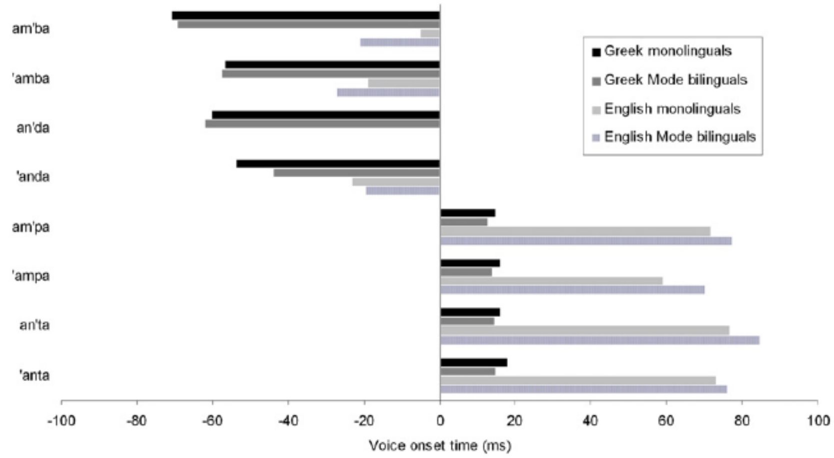


**Fig. 6.**

Mean VOTs of Greek and English word-medial nasal stops produced by Greek and English monolinguals and bilinguals in Greek and English language modes.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

**Table 1**

Mean VOTs produced by English and Greek monolingual speakers in word-initial position (ms). Standard deviations are also presented.

| **Language** | **ba** | | **da** | | **pa** | | **ta** | |
|---|---|---|---|---|---|---|---|---|
| | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| English | **−2.0** | 32.5 | **6.1** | 27.5 | **76.7** | 17.3 | **83.2** | 10.7 |
| Greek | **−124.3** | 40.8 | **−132.7** | 20.0 | **14.8** | 3.9 | **17.0** | 4.2 |

**Table 2**

Bilinguals' age of acquisition and mean self-ratings (1=very little; 5=very well) of their mastery of Greek (L1) and English (L2).

| Language mode | Age learned | | Self-rating (1–5) | |
|---|---|---|---|---|
| | Greek | English | Greek | English |
| English | 0.0 | 3.6 | 3.5 | 5.0 |
| Greek | 0.0 | 3.4 | 4.0 | 5.0 |

**Table 3**

Mean VOTs produced by Greek–English bilingual speakers in word-initial position (ms). Standard deviations are also presented.

| Language mode | ba | | da | | pa | | ta | |
|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| English | **−8.4** | 23.6 | **9.0** | 21.1 | **76.2** | 19.3 | **92.0** | 19.9 |
| Greek | **−117.9** | 27.1 | **−122.1** | 30.3 | **12.3** | 2.4 | **15.3** | 6.5 |

**Table 4**

Monolinguals' and bilinguals' productions of Greek word-initial stop-voicing distinctions. Asterisk indicates significance.

| Effect | *F*(1,14) | *p* |
|---|---|---|
| Lingualism | 0.2 | .662 |
| Voicing | 396.7* | <.001 |
| Lingualism × Voicing | 0.6 | .451 |
| Place | 0.3 | .593 |
| Lingualism × Place | 0.2 | .662 |
| Voicing × Place | 2.3 | .152 |
| Lingualism Voicing × Place | 0.1 | .756 |

**Table 5**

Monolinguals' and bilinguals' productions of English word-initial stop-voicing distinctions. Asterisk indicates significance.

| Effect | *F*(1,14) | *p* |
|---|---|---|
| Lingualism | 0.0 | – |
| Voicing | 401.2* | <.001 |
| Lingualism × Voicing | 0.5 | .491 |
| Place | 17.7* | .001 |
| Lingualism × Place | 2.7 | .123 |
| Voicing × Place | 0.2 | .662 |
| Lingualism × Voicing × Place | 0.0 | – |

NIH-PA Author Manuscript
NIH-PA Author Manuscript

## Table 6

Mean VOTs produced by English and Greek monolingual speakers in stressed and unstressed word-medial positions. Standard deviations are also presented.

| Language | aˈba | | ˈaba | | aˈda | | ˈada | | aˈpa | | ˈapa | | aˈta | | ˈata | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| English | **−2.7** | 35.1 | **−9.9** | 14.3 | **−9.9** | 41.4 | **−31.2** | 30.7 | **71.5** | 14.3 | **56.1** | 15.2 | **81.4** | 14.0 | **75.2** | 7.7 |
| Greek | **−131.9** | 16.8 | **−119.0** | 20.0 | **−122.9** | 20.0 | **−114.0** | 27.9 | **14.5** | 3.4 | **16.5** | 4.2 | **16.3** | 5.6 | **18.3** | 5.8 |

NIH-PA Author Manuscript
NIH-PA Author Manuscript



**Table 7**

Mean VOTs produced by Greek–English bilingual speakers in stressed and unstressed word-medial position (ms). Standard deviations are also presented.

| Language mode | aˈba | | ˈaba | | aˈda | | ˈada | | aˈpa | | ˈapa | | aˈta | | ˈata | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| English | **−34.0** | 53.4 | **−46.1** | 54.7 | **−11.8** | 41.1 | **−27.1** | 41.5 | **74.5** | 12.3 | **66.7** | 19.6 | **85.5** | 17.5 | **74.5** | 22.3 |
| Greek | **−129.7** | 19.5 | **−104.8** | 21.7 | **−108.3** | 19.2 | **−90.8** | 12.8 | **13.1** | 2.6 | **13.1** | 4.7 | **13.4** | 4.9 | **15.5** | 5.9 |

**Table 8**

Monolinguals' and bilinguals' productions of Greek word-medial oral stop-voicing distinctions. Asterisk indicates significance.

| Effect | *F*(1,14) | *p* |
|---|---|---|
| Lingualism | 2.3 | .152 |
| Voicing | 750.4* | <.001 |
| Lingualism × Voicing | 2.9 | .111 |
| Place | 14.2* | .002 |
| Lingualism × Place | 1.2 | .292 |
| Stress | 17.3* | .001 |
| Lingualism × Stress | 1.2 | .292 |
| Voicing × Place | 6.5* | .023 |
| Lingualism × Voicing × Place | 1.8 | .201 |
| Voicing × Stress | 14.7* | .002 |
| Lingualism × Voicing × Stress | 2.2 | .160 |
| Place × Stress | 1.2 | .292 |
| Lingualism × Place × Stress | 0.0 | – |
| Voicing × Place × Stress | 2.8 | .116 |
| Lingualism × Voicing × Place × Stress | 0.5 | .491 |

## Table 9

Monolinguals’ and bilinguals’ productions of English word-medial oral stop-voicing distinctions. Asterisk indicates significance.

| Effect | $F(1,14)$ | $p$ |
|---|---|---|
| Lingualism | 0.3 | .593 |
| Voicing | 172.5* | <.001 |
| Lingualism × Voicing | 2.1 | .169 |
| Place | 4.2 | .060 |
| Lingualism × Place | 4.7* | .048 |
| Stress | 10.6* | .006 |
| Lingualism × Stress | 0.0 | – |
| Voicing × Place | 3.3 | .091 |
| Lingualism × Voicing × Place | 15.9* | .001 |
| Voicing × Stress | 0.2 | .662 |
| Lingualism × Voicing × Stress | 0.0 | – |
| Place × Stress | 0.7 | .417 |
| Lingualism × Place × Stress | 0.0 | – |
| Voicing × Place × Stress | 2.3 | .152 |
| Lingualism × Voicing × Place × Stress | 2.3 | .152 |

## Table 10

Mean VOTs for nasal stops produced by English and Greek monolingual speakers in stressed and unstressed word-medial positions. Standard deviations are also presented.

| Language | aˈmba | | ˈamba | | aˈnda | | ˈanda | | aˈmpa | | ˈampa | | aˈnta | | ˈanta | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| English | **−5.1** | 26.8 | **−19.1** | 21.3 | **0.0** | 24.0 | **−23.3** | 14.7 | **71.9** | 18.5 | **59.1** | 13.0 | **76.7** | 19.9 | **73.3** | 10.9 |
| Greek | **−71.8** | 24.5 | **−56.8** | 13.1 | **−62.3** | 22.1 | **−53.5** | 18.3 | **14.8** | 4.0 | **16.0** | 4.3 | **16.1** | 5.6 | **18.0** | 6.2 |

## Table 11

Mean VOTs for prenasalised stops produced by Greek–English bilingual speakers in stressed and unstressed word-medial positions. Standard deviations are also presented.

| **Language mode** | **aˈmba** | | **ˈamba** | | **aˈnda** | | **ˈanda** | | **aˈmpa** | | **ˈampa** | | **aˈnta** | | **ˈanta** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** | ***M*** | ***SD*** |
| English | **−21.2** | 31.1 | **−27.2** | 22.5 | **0.5** | 22.8 | **−19.5** | 22.7 | **77.2** | 17.0 | **70.4** | 16.1 | **84.6** | 18.0 | **76.0** | 21.3 |
| Greek | **−69.3** | 18.7 | **−57.5** | 8.0 | **−62.1** | 21.7 | **−43.9** | 13.8 | **12.7** | 2.9 | **14.0** | 5.2 | **14.5** | 6.2 | **14.8** | 5.7 |

NIH-PA Author Manuscript

NIH-PA Author Manuscript

**Table 12**

Monolinguals' and bilinguals' productions of Greek word-medial nasal stop-voicing distinctions. Asterisk indicates significance.

| Effect | *F*(1,14) | *p* |
|---|---|---|
| Lingualism | 0.0 | – |
| Voicing | 600.9* | <.001 |
| Lingualism × Voicing | 0.5 | .491 |
| Place | 5.4* | .036 |
| Lingualism × Place | 0.1 | .756 |
| Stress | 9.4* | .008 |
| Lingualism × Stress | 0.2 | .662 |
| Voicing × Place | 2.7 | .123 |
| Lingualism × Voicing × Place | 0.2 | .662 |
| Voicing × Stress | 7.2* | .018 |
| Lingualism × Voicing × Stress | 0.4 | .537 |
| Place × Stress | 0.0 | – |
| Lingualism × Place × Stress | 1.3 | .273 |
| Voicing × Place × Stress | 0.0 | – |
| Lingualism × Voicing × Place × Stress | 2.4 | .144 |

## Table 13

Monolinguals' and bilinguals' productions of English word-medial nasal stop-voicing distinctions. Asterisk indicates significance.

| **Effect** | ***F*(1,14)** | ***P*** |
|---|---|---|
| Lingualism | 0.0 | – |
| Voicing | 683.7* | <.001 |
| Lingualism × Voicing | 3.1 | .100 |
| Place | 9.9* | .007 |
| Lingualism × Place | 1.3 | .273 |
| Stress | 14.4* | .002 |
| Lingualism × Stress | 0.2 | .662 |
| Voicing × Place | 0.0 | – |
| Lingualism × Voicing × Place | 5.4* | .036 |
| Voicing × Stress | 2.2 | .160 |
| Lingualism × Voicing × Stress | 0.2 | .662 |
| Place × Stress | 0.7 | .417 |
| Lingualism × Place × Stress | 0.8 | .386 |
| Voicing × Place × Stress | 3.8 | .072 |
| Lingualism × Voicing × Place × Stress | 0.2 | .662 |