**Associating the origin and spread of sound change using agent-based modelling applied to /s/-retraction in English.**

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Research on sound change has often been pursued from two separate perspectives: its origin which is concerned with the types of phonetic variation that are most likely to turn into sound change (Beddor, 2009; Ohala, 2012; Solé, 2014); and its spread around a community which in some models of sound change is based on imitating social factors that are prestigious or markers of leadership (Fagyal et al, 2010; Garrett & Johnson, 2013). The type of model to be presented in this talk is at the boundary between the two and has its origins in the principle of communication density (Bloomfield, 1933; Labov, 2001; Stanford & Kenny, 2013; Trudgill, 2008).

The computational-cognitive architecture used in the present study to simulate the principle of communication density is one in which, as in episodic models of speech (Pierrehumbert, 2003a, 2006), there is a stochastic association between categories (both phonological units and words) and speech signals and in which the stochastic associations can be updated by feedback from signals to categories (Blevins & Wedel, 2009; Wedel, 2007). This architecture tests the idea that sound change sometimes, but only rarely, emerges when the incremental updating of the phonetic variation through usage in the community causes a reorganisation in the relationship between phonological categories and signals.

The more specific hypotheses to be tested are concerned with /s/-retraction in clusters containing a rhotic (e.g. from /s/ to /ʃ/ in 'street') that has been found in some varieties of English (Kraljic et al, 2008; Rutter, 2011) and that is analysed here for Australian English. An acoustic and perceptual study in Stevens & Harrington (2016), found evidence for /s/-retraction in particular in /str/ and to a lesser extent in /spr, skr/-initial clusters. With the exception of 2-3 speakers, /str/ was nevertheless generally much closer acoustically and perceptually to /s/ (*seem*) than to /ʃ/ (*sheep*) for these Australian speakers.

The purpose of the present study was to simulate the propagation of this phonetic variation using an agent-based computational model. An /s/→/ʃ/ change was predicted to occur because of an asymmetry in which /s/ is oriented in an acoustic space towards /ʃ/ to a greater extent than in the other direction. From this perspective, there should be a greater probability of some outlying tokens of /ʃ/ being absorbed into the /s/ space than the other way round which would cause /s/ to shift incrementally towards /ʃ/ (see also Harrington & Schiel, in press for /u/-fronting; Pierrehumbert, 2001 for domain-final stop devoicing).

An agent-based model was used for the simulation in which each agent stored (i) word labels from 41 separate word items containing target /s, str, ʃ/ and (ii) up to 10 repetitions per item of parameterised speech signals between the acoustic onset and offset of the target sibilant. The parameterisations were the mean, $k_0$, and curvature, $k_2$, calculated with the discrete cosine transformation (Harrington et al, 2008) of the first spectral moment. These parameters were chosen because they were found to distinguish optimally between /s, ʃ/. The data were taken from the 20 (9 male, 11 female) speakers in Stevens & Harrington (2016). There was one agent per speaker. There were 9 monosyllabic word items with the target sibilant in word-initial position.

For the remaining items, the target sibilant was word-medial between rhythmically weak (*w*) and strong (*s*) syllables in *w_w* (e.g. '*poli**c**y*, '*chemi**s**try*, '*poli**sh**ing*), *w_s* (e.g. *a*'***ss**embly*, *de*'***s**troy*, *ma*'*c**h**ine*) and *s_w* (e.g. '*po**ss**ible*, *ca*'*ta**s**trophe*, '*pa**ss**ionate*) contexts.

Sibilants for each agent were initially grouped into two phonological classes /s/ that included all /s, str/ words and /ʃ/. Given the evidence that phonological categorisation is sub-phonemic (e.g. Pierrehumbert, 2003b; Reinisch & Mitterer, 2016), we applied a *k*-means clustering algorithm (Hartigan & Wong, 1979) to the $k_0 \times k_2$ parameter space to split any phonological class into two. Splitting occurred only if the probability of category membership of the data points to the two new classes was significantly greater than to the single class. The reverse of this procedure was applied to merge pairs of categories if the probability of class membership to the merged single category was greater than or equal to the separate categories. Split and merge were iteratively applied to each agent's phonological classes until there was no further change to the derived sub-phonemic classes. In this way, words were initialised with slightly different mappings from words to sub-phonemic classes for each agent.

The simulation consisted of randomly chosen agent-pairs, one of which was the agent-talker and the other the agent-listener. A word was randomly chosen from the agent-talker's lexicon. The agent-talker produced a word by sampling from a Gaussian distribution calculated over the $k_0 \times k_2$ signal space associated with the word class. The agent-listener absorbed the produced signal into memory, but only if it was probabilistically within the 95% confidence interval of whichever sub-phonemic class that the perceived word was associated with. Whenever a listener absorbed a signal into memory (i) memory decay was implemented to discard the oldest signal from the same word class and (ii) the split and merge algorithms were re-applied, thereby potentially causing a slight reorganisation of the relationship between words and sub-phonemic classes. Within any one simulation, pairwise interactions were continued (typically up to $n$ = 60,000) until there was no further significant change in the population's sub-phonemic classes and signals. The simulations were repeated separately 100 times (thus 100 simulations × 60,000 interactions).

There were four hypotheses. (1) Some agents will merge the phonological classes /str/ and /ʃ/ (2) /str/ will shift acoustically towards /ʃ/. (3) (1, 2) will apply predominantly to sibilants in the *w_w* stress pattern, given that the speakers on which these agents were based typically had a lower spectral centre of gravity of /s/ in this context (4) (1, 2) will apply to a greater extent to male speakers, given the findings in Stevens & Harrington (2016) that listeners tended to perceive /ʃ/ in /str/ clusters to a greater extent in male speakers.

The results showed that there was no evidence for (3, 4). Within any simulation, there was some evidence for (1) but very little for (2). A categorical re-allocation of /str/ to either /s/ or /ʃ/ without any acoustic change may be typical of the initial stages of sound change in which there is category instability but without there necessarily being any change to speech production (Ohala, 2012). There was, however, evidence for (1, 2) in typically 5/100 simulations. Thus the typical state in this computational model is one of phonetic variation with no change. But in around 5% of cases, the inherent randomness in both the choice of agents that talk to each other and selection of words could cause changes in the expected direction of (1, 2).

To a certain extent, the model shows phonetic variation to be the norm and sound change to be exceptional. We are currently exploring which parameter settings are most likely to precipitate change. To do so, we are varying: speaker-agents and word-items; the characteristics of the split-and-merge algorithms; and the criteria for absorbing (or not) perceived items into memory.

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