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THE CRITICAL PERIOD AND THE LEXICON: INVESTIGATING INVARIANCE AFTER ACQUISITION IN A COMPUTATIONAL MODEL OF LANGUAGE CHANGE

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Abstract: This study explores Kauhanen's (2017) model of language change, specifically, his implementation of a critical period. Kauhanen models the spread of linguistic variants in a network of speakers to determine whether a model of neutral change (drift) can produce S-curves. Neutral change/drift is language change that occurs exclusively due to the relative frequency of variants a speaker is exposed to and a small probability of innovation/mutation (Kauhanen 2017). Kauhanen deems a strict critical period parameter essential for his model's S-curve production. This speaker invariance after acquisition appears to limit his model's applicability to later-life change. Both drift and S-curve production are possible in lexical change, a domain in which later-life plasticity is expected. I explore Kauhanen's critical period via a partial replication of his model. I use this to implement, remove, and alter this critical period to determine whether his results can be reproduced under these conditions. My results show Kauhanen's S-curves can be reproduced in my partial (static) replication of his model, provided that his strict critical period is implemented. This suggests Kauhanen's model would not produce S-curves in the absence of this critical period. Thus, it appears his model would not be applicable to later-life change, and specifically, to change in the domain of the lexicon. It additionally suggests his model can be simplified and produce the same results. I also find that drift can produce S-curves in a static model, contradicting the observations of previous research. This investigation is carried out with the broader aim to explore the extent to which a model of this nature can be applicable to all domains of language change.

Keywords: critical period, S-curves, drift, language change, language model, linguistic variants, lexicon, lexical change

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The critical period and the lexicon: Investigating invariance after acquisition in a computational model of language change

1. Introduction

This study begins to investigate whether a computational model can be applicable to all domains of language change. This is undertaken via an exploration of one aspect of Kauhanen's (2017) model of *neutral change* which appears to limit its applicability – a critical period. Kauhanen defines neutral change as the adoption of one of multiple linguistic variants by speakers based on the relative frequency of variants in their neighbourhoods and a small probability of speaker innovation/mutation (Kauhanen 2017:329). A speaker's neighbourhood comprises all other speakers they are directly linked to in the network. In neutral change, there is no differential weighting or bias towards any of the variants (cf. Blythe & Croft 2012), nor prestige associated with any of the speakers in the social network (cf. Fagyal et al. 2010). Kauhanen's concept of neutral change is analogous to definitions of *drift* in the literature, as will be discussed in Chapter 2.

Kauhanen's critical period is strict in the sense that speakers are invariant after the "point of acquisition" (Kauhanen 2017: 334). I investigate the implications of Kauhanen's critical period via a partial replication of his model, of which three versions are produced. Speakers in each version have different degrees of plasticity in variant acquisition, i.e., ability to change variants throughout the simulation. I primarily consider my results in the context of lexical change, a domain to which I suggest his S-curve-producing model not to be applicable, due to the critical period. Later-life change in the lexicon is expected – the vocabulary can develop significantly throughout the lifespan as new words are acquired or learnt during adulthood (Meyerhoff 2006:140). In comparison, later-life change is suggested to be less common and less significant in other domains such as syntax and phonology (Meyerhoff 2006:140).

Kauhanen's model explores the parameters required for his model to produce S-curves, or what he terms "well-behaved" change. This is an idealised language change trajectory (Fagyal et al. 2010:2) against which Kauhanen evaluates his model. This study explores one parameter he deems essential for S-curve production: the critical period. Kauhanen does not explore the effects and implications of this assumed critical period, beyond stating that future research should investigate relaxing this assumption (Kauhanen 2017:335). This is what forms the basis of this research. Language change models aim to further our understanding of the foundations and implications of theories of language change (Baker 2008:289; Fagyal et al. 2010). This study aims to test the results and applicability of an existing model, to investigate the implications of specific modelling decisions, and more broadly, the extent to which models can be applicable to all domains of language change.

This study explores the effects of implementing, removing, and adapting Kauhanen's notion of a critical period in a partial replication of his model, with the aim to investigate the effects of this on his own model's applicability. I refer to my model as a partial replication because Kauhanen's rewiring parameter could not be replicated due to constraints of time and computational power. I consequently explore Kauhanen's critical period via a static version of his model. Thus, I am concurrently testing the observation that drift cannot produce S-curves in a static population (e.g., Kauhanen 2017; Fagyal et al. 2010; Blythe & Croft 2012). Kauhanen's critical period is explored via three model versions:

- *Fixed speakers:* speakers may change variants exactly once during the simulation. Speakers have zero plasticity after initial acquisition. This is to test the effects of implementing Kauhanen's critical period.

- *Variable speakers:* speakers have no critical period, i.e., can change variants any number of times throughout the simulation, according only to the frequency of variants in their neighbourhood and the probability of innovation/mutation. This is to test the effects of removing Kauhanen's critical period.

- *Alternative critical period:* speakers have greater plasticity after initial acquisition. Speakers have the potential to change variants 50 times before their critical period closes. This is to test the effects of altering Kauhanen's critical period.

The questions investigated in this study are:

1. What are the implications of Kauhanen's assumption of a critical period on the applicability of his model, and specifically its applicability to the lexicon?

2. What are the effects of implementing, removing, and altering this assumption on a static version of his model?

In Chapter 2 I present the background for this research. Section 2.1 provides an overview of S-curves in language change literature, including the domains in which they have been observed. Additionally, it discusses their use as a model of change; Kauhanen's motivation to determine the parameters necessary for his model to produce S-curves. I find that S-curves can be observed in the domain of lexical change. In section 2.2 I provide background on drift (Kauhanen's neutral change) in cultural evolution and language. I find that drift has been posited as a driver of lexical change. In section 2.3 I consider the critical period of language acquisition. I explore cases of change observed post-adolescence, i.e., after the closure of the critical period. These include examples from the domain of the lexicon, to which I expect Kauhanen's model not to be applicable.

In Chapter 3 I introduce the ODD protocol (Grimm et al. 2006, 2010) as a systematic means to describe a computational model, enabling it to be understood and reproduced. I attempt to interpret and present Kauhanen's model using this protocol. In Chapter 4 I motivate and present my model using the ODD protocol, facilitating its comparison with that of Kauhanen. Chapter 5 consists of the simulation results. I find that S-curves (Kauhanen's well-behavedness) can be reproduced in a static version of the model, provided that his strict critical period is implemented, i.e., speakers cannot change variants after the point of acquisition. Population-wide change is only observed in 5% of simulation runs when the critical period is removed and does not follow an S-curve trajectory. No population-wide change occurs where the critical period is altered to allow for some degree of later-life plasticity. Thus, it appears the S-curve production of Kauhanen's model is dependent on the strict critical period.

In Chapter 6 I consider my results in the context of the literature. I discuss how the results suggest his critical period does limit his model to specific types of language change; change that occurs before the closure of the critical period. Thus, Kauhanen's model appears not to be applicable to instances of later-life change. These include the specific phonological and syntactic cases discussed, and, more significantly, change in the domain of the lexicon. I explore the cause of the difference between the S-curve production of my static model and the contrasting results of Kauhanen (2017), Fagyal et al. (2010), and Blythe and Croft (2012).

I consider questions that arise, such as whether one model can account for change in the lexicon as well as other domains. Additionally, I suggest Kauhanen’s model presentation limits its reproducibility. I motivate the standardisation of model description via Grimm et al.’s (2006, 2010) ODD protocol to facilitate replication and further research. This leads on to the discussion of the limitations of this study and suggestions for future work.

Chapter 7 consists of my conclusions. Based on my results, I suggest Kauhanen’s critical period limits his model’s applicability to instances of later-life change in multiple domains, and specifically, to the domain of the lexicon. I conclude that Kauhanen’s S-curve-producing drift can be replicated in a partial (static) version of his model, provided that his critical period is implemented. Thus, it appears drift can be observed in a static network model. This study raises questions about how later-life change could be modelled and invites further exploration into whether the lexicon can be accounted for in a model applicable to change in other domains.

2. Background

2.1 S-curves in language change research

The aim of Kauhanen's model is to determine whether S-curves, what he terms "well-behavedness", can be observed in cases of neutral change (i.e., drift, see section 2.2). The s-shaped trajectory of change has been observed in various domains of science and language and, thus is seen as a template for the diffusion of innovation (Rogers 1983, in Chambers 2013:312; Nevalainen 2015). This includes the process of language change (e.g., Fagyal et al. 2010; Nevalainen 2015); this trajectory has been detected in many cases of grammatical and lexical change (Fagyal et al. 2010:2). Kauhanen (2017:332) states that the S-curve is seen as a "basic desideratum" of language change models; hence, his aim to uncover the parameters necessary for his model to produce S-curves. The S-curve model is used as a means of evaluating computational models of change because it exhibits the idealised trajectory of variant frequency over time, with the cumulative adoption of a new variant forming a smooth s-shaped curve. This trajectory is as follows[1]: a new variant emerges in a language community, initially used only by a few members. Initial adoption by others is slow, propagated by interaction with speakers approximately reproducing what they hear (Denison 2003:58). If the variant survives this first phase, there is a subsequent period of comparatively rapid spread throughout the population as further members encounter and reproduce the variant. Once the majority have the variant, the rate of change decreases again as there are few members left to adopt it. Fagyal et al. (2010:2) discuss the S-curve in terms of three phases; innovation, selection and propagation, and establishment/fixation.

Blythe and Croft (2012) define S-curves as the absence of "large fluctuations" and "a tendency for [a] trend to reverse one or more times" (Blythe & Croft 2012:285). They posit these large fluctuations and trend reversals to be characteristic of neutral change. Thus, they reject neutral change as a means to produce S-curves (Blythe & Croft 2012:285), as concluded also by Ke et al. (2008) and Fagyal et al. (2010). This is one of the motivations for Kauhanen's model; to determine whether S-curves can be generated by neutral change.

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[1] – based on the description by Fagyal et al. (2010)

In a survey of existing language change research, Blythe and Croft (2012:279) present 22 documented examples of change that follow a full S-curve trajectory. This means an uninterrupted S-curve, featuring all three phrases outlined by Fagyal et al. (2010); innovation, selection and propagation, and establishment/fixation. The examples presented (Blythe & Croft 2012:279) include changes in the domains of syntax (e.g., Kroch 1989), phonology (e.g., Chambers & Trudgill 1998), and the lexicon (e.g., Chambers 2002). Regarding change in the lexicon, Chambers (2002) observes an s-shaped trajectory of change in the lexical terms used for "sofa" in Canadian English, specifically in the Golden Horseshoe region in Southern Ontario. The term "couch" gradually replaced "chesterfield" in this community, with the rate of change corresponding to an S-curve; initially slow, then rapidly increasing, then decreasing again once "couch" had become an established term. This demonstrates competition between an existing and an incoming lexical variant, following an S-curve trajectory. Fagyal et al. (2010) state that the variants modelled in their agent-based model of language change could be lexical items and would follow the same S-curve trajectory observed for change in other domains (Fagyal et al. 2010:1). They suggest the variants could be competing lexical items to express the French *voiture* (car); "véhicule", "bagnole", "char", and "tacot" (Fagyal et al. 2018:8). These examples demonstrate that S-curves can be seen or expected in some instances of lexical change. Thus, we would expect Kauhanen's S-curve-producing model to be applicable to some instances of change in this domain.

In summary, Kauhanen's aims to uncover the parameters necessary to produce S-curves in his model of neutral change are due to the widespread view of S-curves as a realistic trajectory of language change. S-curves have been observed in various domains, including the lexicon. This is noteworthy; this study investigates the applicability of Kauhanen's model to later-life change. The lexicon is a domain I suggest his model will not be applicable to, as will be explored in section 2.3. However, the observation that S-curves can be seen in lexical change suggests Kauhanen's S-curve-producing model should be applicable to change in the lexical domain.

2.2 Drift in cultural evolution and language

Drift is defined by Newberry et al. (2017:223) as "randomness in the set of forms that each speaker happens to encounter and reproduce". This definition corresponds to Kauhanen's neutral change. Kauhanen assimilates his definition to the following mechanisms identified by Blythe and Croft (2012:273-277), summarised as “neutral evolution, which is random, frequency-driven drift” and “neutral interactor selection, in which speaker-speaker interaction frequencies play a role” (Kauhanen 2017:332). Newberry et al.’s (2017) definition of drift encompasses both mechanisms; randomness in the variants encountered and reproduced is generated by stochasticity in speaker-speaker interactions and “random fluctuations in [variant] frequencies in a finite population” (Blythe & Croft 2012:275). Thus, Kauhanen’s neutral change is essentially drift.

Kimura (1983, in Clark 2020:11) states that there is always an effect of random processes during evolutionary change. Drift has been explored as a model of cultural evolution, to understand which cultural elements, including aspects of language (Trott & Bergen 2022), can be explained (or are better explained) by this process. Drift has been considered in cases where some cultural elements/variants become highly popular while others appear to die out, without there being any advantage to one element/variant over another. This contrasts with selection towards specific elements/variants, which appear to have some social or functional advantage (e.g., Trott & Bergen 2022). Hahn and Bentley (2003) demonstrate that a model of drift can account for the patterns observed in the frequency distribution of baby names in the United States over time. Specifically, drift can explain the maintenance of the power law distribution of baby names over the 100 years investigated (Hahn & Bentley 2003:120); many names appear at a low frequency and very few appear at a high frequency. This power law distribution is maintained despite changes in frequencies of certain names. The baby names are functionally equivalent – there is no need for bias towards particular names to explain this pattern. Rather, it can be due to proportional sampling (Hahn & Bentley 2003:123), i.e., due to drift. Similarly, Bentley’s (2008) analysis of keyword frequencies in academic writing posited drift as the driver of this specific type of lexical change in certain academic fields. The lexical items are not necessarily synonymous terms in direct competition, so this is not the nature of change Kauhanen models. However, this is significant because Bentley (2008) demonstrates that lexical items may be randomly copied without any associated bias or prestige.

Various studies suggest drift can be the driving force of instances of language change (e.g., Clark 2020; Ventura et al. 2022; Newberry et al. 2017). The importance of considering drift in language change is summarised by Karjus et al. (2020:18); there is no need to theorise about other possible causes of language change if drift cannot be ruled out. Similarly, Kauhanen states that neutral change, i.e., drift, may provide an explanation for instances of change that have received “rather ad hoc solutions” in previous literature (Kauhanen 2017:329). The role of drift in language change has often been overlooked and underappreciated (Kauhanen 2017; Newberry et al. 2017). Blythe (2012) suggests drift cannot be ruled out as a cause for certain phonetic changes, e.g., the convergence of speakers on one of multiple competing vowels (Blythe 2012:10-11; see also Labov 2001). It is also evidenced in syntactic change (e.g., Clark 2020; Ventura et al. 2022; Newberry et al. 2017; Blythe 2012). The competing variants in drift could be different means of conveying a particular syntactic function, e.g., the future tense (Blythe 2012:5). Additionally, Blythe suggests the variants could be synonyms of a particular word (Blythe 2012:5), implicating that drift can drive some instances of lexical change. This has been investigated elsewhere; Reali and Griffiths (2010) claim drift can account for change in the lexical domain, analogising words to alleles in genetic drift. It is worth noting, however, that Reali and Griffiths’ (2010) speakers are biased towards regularisation. This means they have a bias towards reducing the amount of (here, lexical) variation in their learning and production (Saldana et al. 2021). Thus, their definition of drift is not equivalent to Kauhanen’s neutrality, as their model involves an inherent bias. However, it has been suggested by Ventura et al. (2022) that drift itself is sufficient to explain patterns of lexical regularisation. Their results suggest drift could be a “major driver” of regularisation and of language change in general (Ventura et al. 2022:15). Again, this suggests a role of drift in the domain of the lexicon, and specifically in lexical regularisation.

Dircks and Stoness’ (1999) *naming game* agent-based model also suggests drift is possible in the domain of the lexicon. In their model, a speaker and hearer are stochastically selected from a population. The speaker names and signals (by virtually pointing) to a chosen object. The hearer interprets this information, and if the speaker and hearer agree on this object reference the interaction succeeds. If not, the hearer may adapt their variant according to that of the speaker. There appears to be no bias towards any particular variant. Dircks and Stoness (1999) found the majority of the population converged on a particular variant in a significant proportion of population runs, including where this model was tested with a static population. This contradicts the findings of Kauhanen (2017), Fagyal et al. (2010), and Blythe and Croft (2012), who conclude drift is not possible in a static network model. Dircks and Stoness’ (1999) study is a further example suggesting drift as a driver of lexical change.

In summary, it is suggested the role of drift should be considered in all instances of language change (e.g., Karjus et al. 2020). Kauhanen (2017) explores drift as he considers its role and implications to be overlooked. Drift is considered applicable to change in various cultural and linguistic domains, including the domain of the lexicon. This suggests Kauhanen's (2017) model of neutral change (drift) should be applicable to lexical change.

2.3 The critical period

Speakers in Kauhanen's (2017) model are completely invariant after a critical period. Upon acquiring a linguistic variant, this becomes fixed, i.e., can no longer change. He states that this is not unrealistic for categorical or near-categorical features (Kauhanen 2017:334). This strict critical period does not correspond with Meyerhoff's (2006) definition, based on Lenneberg (1967); a period during which "language learning seems to be easiest" (Meyerhoff 2006:133). According to Meyerhoff (2006:133), this period is childhood and, in some cases, early adolescence. This definition accounts for later-life (i.e., post-critical period) change, suggesting it is possible but not as easy as change before the closure of the critical window. In this section, I explore examples from previous research in which speakers have demonstrated some level of plasticity post-adolescence, i.e., later-life change.

Sankoff and Blondeau's (2007) study of the pronunciation of /r/ in Montréal French showed 2 out of 12 categorical/near-categorical users of [r], i.e., almost 17% of the group, shifting to 65-66% use of [R]. These post-adolescent speakers, aged 24 and 45, demonstrate significant later-life change despite their previously categorical/near-categorical use of [r] (Sankoff & Blondeau 2007:527). Of the 22 participants who could have changed to the innovative [R] variant, 41% showed significant later-life change in /r/ production (Sankoff & Blondeau 2007:573), demonstrating some degree of plasticity later in life. Seven speakers shifted from variable to categorical/near-categorical [R]. Their results suggested the majority of [R] users changed their production after initial first language acquisition, i.e., after the critical period (Sankoff & Blondeau 2007:583). Thus, Sankoff and Blondeau's (2007) study suggests categoricity is somewhat nuanced. Although less than 20% of the speakers beginning with categorical/near categorical [r] changed their variant usage, this remains a significant observation, in which their variant use shifted "dramatically" (Sankoff & Blondeau 2007:576) post-adolescence. This demonstrates, firstly, that change is possible where the use of features was previously categorical/near-categorical, and secondly, that speakers vary in whether their use of the same feature is categorical or variable. This is something Kauhanen's model does not capture.

A similar change is observed in the syntactic domain of Montréal French. Wagner and Sankoff (2011) demonstrate a shift in the use of the inflected future (IF) versus the periphrastic future (PF) by individuals between 1971 and 1984. They observed a decrease in the number of categorical users of the PF (Wagner & Sankoff 2011:298). IF use increased in speakers who already had the variant, but additionally, those who did not have it initially appeared to add it to their grammar after 1971 (Wagner & Sankoff 2011:298). Again, this demonstrates a change post-critical period and a change in speaker categoricity over time.

Further examples include Queen Elizabeth II's vowel production from the 1950s to the 1980s (Harrington et al. 2000), and Noam Chomsky's vowel production between 1970 and 2009 (Kwon 2018). Both demonstrate later-life change, with their vowel positions moving in the direction of their communities' vowel production. The Queen's vowels shifted in formant position and average position towards those of the standard southern-British accent (Harrington et al. 2000). Chomsky's vowels significantly shifted, quantitatively and qualitatively, towards the vowel positions common in the Boston accent, where Chomsky moved aged 27 (Kwon 2018).

These above examples of phonological and syntactic later-life change are all of a similar nature. They appear to take place in the direction of the community; either following patterns of community-wide change (Sankoff & Blondeau 2007; Wagner & Sankoff 2011; Harrington et al. 2000), or in Chomsky's case, towards the language use of a dialect group he moved into (Kwon 2018). This nature of change is termed "lifespan change" by Sankoff (2005). In the case of phonology, lifespan change is restricted to following the direction of the community and may be otherwise constrained (Meyerhoff 2006:144). Speakers cannot "radically" change their syntactic or phonological systems later in life (Meyerhoff 2006:245).

Developmental plasticity in the lexicon differs from other domains. The vocabulary can be updated easily during adulthood as speakers learn or acquire more words (Meyerhoff 2006:140). Sankoff's (2005) lifespan change is "well-attested" in the lexicon (Meyerhoff 2006:144). For example, Bloom and Markson (1998) observe adults performing equally as well as children in a task involving learning artificial names for objects. This suggests a difference between adult capacities for vocabulary learning compared to that of syntax and morphology (Bloom & Markson 1998:68-69), with adults being less successful at the latter than children. The difference in post-critical period development between the lexicon and other domains of language is evident in the case of Genie, a child deprived of language input who had not acquired a first language by the age of 13. When she began to be taught English, Genie showed comparatively “rapid and extensive” lexical development (Curtiss 1981:20), with more limited acquisition of syntax, morphology (Curtiss 1981:21), and phonology (Curtiss 1977).

With regard to categoricity, Fagyal et al. (2010) suggest their agent-based model of language change (in which speakers are categorical, as in Kauhanen’s model) would be more appropriate for “*categorical* adoptions of new words and expressions” (Fagyal et al. 2010:17, emphasis added), as opposed to phonological change. Their model does not involve any notion of a critical period, and yet they state it to be more appropriate to categorical lexical change. Thus, it appears categorical/near-categorical features do not necessarily have a strict critical period (cf. Kauhanen 2017:334).

In summary, I find various cases of later-life change that appear not to correspond with Kauhanen’s assumption of a strict critical period, including with regard to his speaker categoricity. Notably, lifespan change in the lexical domain is well-attested (e.g., Meyerhoff 2006), and can be categorical (e.g., Fagyal et al. 2010). Kauhanen’s model of categorical/near-categorical features should, therefore, be applicable to lexical change. However, it appears his strict critical period may prevent this.

3. Kauhanen's model and the ODD protocol

3.1 The ODD protocol

The ODD (Overview, Design concepts, and Details) protocol (Grimm et al. 2006, 2010) is a format for explicitly describing an individual-based or agent-based model, such as that of Kauhanen (2017). It aims to standardise this procedure, rendering models more understandable and reproducible (Grimm et al. 2010). Kauhanen's (2017) model is not explained using a standardised protocol, nor does he present it using explicit subsections of this nature. Thus, one of the first steps in this study is attempting to interpret and present his model using the ODD protocol. In Chapter 4, my model is presented in the same format, to render clear the differences between the two and ensure the reproducibility of my model.

Following the structure of the ODD protocol, section 3.2 presents the purpose of Kauhanen's model. Section 3.3 presents the entities, state variables, and scales involved. Section 3.4 consists of the process overview and scheduling. Section 3.5 describes the initial state of the model. Section 3.6 presents any external input to the model. Section 3.7 explains each of the submodels identified in section 3.4.

3.2 Purpose

Kauhanen's (2017) model aims to explore the possibility of well-behaved neutral change. Neutral change is defined as the adoption of one of multiple linguistic variants by speakers based on the relative frequency of variants in their neighbourhoods, with the other contributing factor being a small probability of speaker innovation/mutation (Kauhanen 2017:329-330). Kauhanen's neutral change is essentially drift, as explained in section 2.2. Kauhanen's "well-behavedness" is a quantification of S-curve production, which he measures using three criteria: dominance, shifting, and monotonicity. Due to the scope of this study, these will each be defined below using his qualitative descriptions (Kauhanen 2017:336). For their formal definitions, see Kauhanen (2017:353-356).

1) Dominance: the population reaches a state in which most or all speakers use one variant, i.e., one variant is (nearly) dominant.

2) Shifting: the population shifts from a state in which one variant is dominant to a state in which another is dominant.

3) Monotonicity: the manner by which shifting occurs, with the new variant's frequency increasing "along smooth propagation curves" (Kauhanen 2017:336).

Kauhanen defines well-behavedness as the satisfaction of these criteria. Values for each are produced per simulation and combined to produce an overall well-behavedness score (Kauhanen 2017:341-342). The purpose of this quantification is to create a standard, enabling model evaluation against "real life change trajectories" (Kauhanen 2017:335), i.e., S-curves[2].

3.3 Entities, State Variables, and Scales

3.3.1 Entities

The entities of Kauhanen's model represent individual speakers. In his simulations, $N = 100$, where N is the number of speakers.

3.3.2 State variables

Using Kauhanen's notation, there are C competing variants in the model, where C can be arbitrarily large (Kauhanen 2017:333). Speakers are categorical; they have one of C possible variants at any time (Kauhanen 2017:333). Speakers are invariant after "the point of acquisition" (Kauhanen 2017:334), i.e., the point at which their variant is determined. This is the point at which they are added to the population – the connections they receive via the rewiring parameter determine the speakers (and, therefore, the variants) they are exposed to. This process is explained in section 3.7.3. Speaker invariance is described as a critical period, after which speakers' variants cannot change.

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[2] However, to my knowledge, his *well-behavedness* has not been adopted by other researchers in the field. Thus, this study will discuss change in terms of S-curves and monotonicity as opposed to well-behavedness.

3.3.3 Scales

Kauhanen’s simulations have a temporal scale, defined in terms of iterations. His simulations are run for 5×10^4 iterations after a period of calibration, where the simulation is run for $100N = 10^4$ iterations to determine the initial shape of the network (Kauhanen 2017:340). This is achieved via his rewiring parameter.

3.4 Process overview and scheduling

Below is an overview of the process, split into submodels, i.e., steps of Kauhanen’s model that I have identified. Each step is defined in section 3.7, Submodels.

1. Set up
    - 1.1 Initiate network
    - 1.2 Calibrate

2. Simulate
    - 2.1 Rewire
    - 2.2 Set variant
    - 2.3 Report

3. Repeat (2) for 5×10^4 iterations

3.5 Initialisation

Kauhanen’s model is initialised with one variant having a relative frequency of 1, i.e., having “strict dominance” (Kauhanen 2017:340). Thus, all speakers are initialised with the same one of *C* possible variants.

3.6 Input

To my knowledge, data is not input into his model from external sources[3].

3.7 Submodels

Here, the submodels from section 3.4 are outlined:

3.7.1 Initiate network

The speakers are initialised. Speakers have the capacity to be connected according to the following conditions: the network is of binary connections between speakers (Kauhanen 2017:333) i.e., two speakers are either connected or not connected. The connections are symmetric and multiplex (Kauhanen 2017:333), i.e., two connected speakers are connected reciprocally by one edge. There is no notion of edge weight or strength of tie (cf. Granovetter 1973; Milroy & Milroy 1985). The position of edges is determined via submodels *Calibrate* and *Rewire*.

3.7.2 Calibrate

The *Rewire* submodel is run for $100N \times 10^4$ iterations to settle the network's degree distribution (Kauhanen 2017:340), i.e., to determine the initial pattern of connectivity in the network.

3.7.3 Rewire

Each iteration of the simulation involves the removal of a stochastically selected speaker. This is replaced by a new speaker, whose connections are determined via a "socialisation algorithm" (Kauhanen 2017:334). This is the process by which the speaker is given K connections, where $1 \leq K \leq N - 1$, to create a network of speakers with varying levels of connectivity. For the precise details of this, see Kauhanen (2017:334). To summarise the

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[3] Kauhanen's code is not provided: I cannot establish whether any (or which) coding libraries have been used in his model.

process, speakers are ranked according to their degree (the number of connections they have to other speakers (Kauhanen 2017:333)), starting with those with the highest degree. A preferentiality parameter in the form of probability σ ($0 \leq \sigma \leq 1$) is used to connect the new speaker to the highest-ranked speaker in the network: the speaker with the most connections. The remainder, $1 - \sigma$, is used to also connect the new speaker to a stochastically selected speaker from the list. This stochastically selected speaker is then removed. This process involving σ is repeated until the new speaker has received K connections.

3.7.4 Set variant

The new speaker's variant is determined according to the following equation. The variant of speaker i is determined as follows (Kauhanen 2017:353); "For each possible variant r, the probability of setting $v_t(i) = r$ is to equal:"

$$\frac{\mu}{C} + \frac{1-\mu}{K} \sum_{j \in E_t(i)} \chi_t(j,r).$$

Equation (1) *(Kauhanen's equation (9) (2017:353)*

where:

μ = the innovation parameter, $0 < \mu < 1$
C = the number of variants in competition
K = the number of connections received by the new speaker according to the rewiring parameter
j = a neighbour of speaker i
$X_t(j, r)$ = an indicator function which iterates over all neighbours of i, defined as:

$$\chi_t(i,r) = \begin{cases} 1 & \text{if } v_t(i) = r \\ 0 & \text{otherwise} \end{cases},$$

Equation (2) *(Kauhanen's equation (7) (2017:352).*

By this means, the speaker's variant is set and cannot change hereafter. This is Kauhanen's notion of a critical period; the speaker's variant is set based on their "interaction" with the speakers in their neighbourhood via equation (1), upon being added to the network.

3.7.5 Report

The frequency of each variant in the population is reported.

3.7.6 Repeat

Repeat *Simulate* for 5×10^4 iterations.

4. Methodology, presented via the ODD protocol

4.1 Structure

This section presents my model using the ODD protocol. Section 4.2 describes my model's purpose. Section 4.3 consists of the entities, state variables, and scales. In section 4.4 I present the process overview and scheduling. Section 4.5 describes the state of the model at initialisation. Section 4.6 presents external input to the model. Section 4.7 explains the submodels presented in section 4.4.

4.2 Purpose

The purpose of this model is to explore Kauhanen's critical period through a partial recreation of his model; investigating the implications of speaker invariance after the "point of acquisition" (Kauhanen 2017:334). The broader aim is to explore the extent to which a model can be applicable to different domains of language change. This model contributes to the field by exploring the findings and conclusions of a previous piece of research, investigating its results and applicability. Three versions are used to explore the effect of implementing, removing, and altering Kauhanen's assumption of speaker invariance in a static population. These versions are as follows:

1) *Variable speakers:* speakers do not have a critical period. They have the potential to change variants each time they are stochastically selected for interaction from the total set of speakers. Whether they change variants is determined only by the variant setting parameter.

2) *Fixed speakers:* speakers are invariant after the point of acquisition; the point at which their variant changes in the simulation. Speakers' variants cannot change after acquisition of a new variant. They may still be stochastically selected, but their variant is fixed.

3) *Alternative critical period:* this version begins to explore an alternative means of implementing a critical period, enabling plasticity after the point of acquisition.

> Speakers can change variants up to 50 times during the simulation. This critical period is arbitrary; the aim of this version is to explore implementation of a greater level of plasticity than Kauhanen's model.

The trajectories produced by each version will be considered in terms of S-curve production and Kauhanen's qualitative descriptions of his well-behavedness criteria (see section 3.2). Additionally, I use an alternative quantification of monotonicity, explained in section 4.7.5.

4.3 Entities, State Variables, and Scales

4.3.1 Entities

The entities, henceforth nodes, represent individual speakers. The model uses 100 speakers, following Kauhanen (2017).

4.3.2 State variables

Speakers have an attribute named variable A, representing a linguistic variable, of which there are two variants. These are denoted by values of 0 and 1. Thus, speakers have a variable A value of 0 or 1, referred to as *variant 0* and *variant 1* respectively. Kauhanen presents his model using three variants as a minimum, however, two are used here for simplicity. Following Kauhanen (2017:333) speakers can only entertain one variant at any time. In the fixed speaker version, speakers have a second attribute named "acquired" which has values Y and N – "yes" and "no". These represent whether the speaker has acquired a new variant during the simulation. Speakers with an acquired value of Y can be stochastically selected to interact, but their variant cannot change. In the alternative critical period version, speakers each have a counter attribute, which increases in value by + 1 each time the speaker is selected for interaction. The limit to this counter is set to 50, thus, speakers have the opportunity to change variants 50 times.

4.3.3 Scales

Following Kauhanen (2017), the temporal scale is defined in terms of iterations. Each iteration represents one "interaction" between a speaker and its neighbours. The model is run for a maximum of 1×10^4 iterations due to limitations in computational power. A run of the simulation will end before 1×10^4 iterations is reached if the population remains monotonic for N interactions, with N being the population size. Thus, the simulation ends where there is no change during a period over which the model has the potential to iterate over all N speakers. At this point, the particular simulation run is monotonic; there has been no change for N interactions, so all speakers have converged on one variant.

4.4 Process overview and scheduling

Below is an overview of the process. The functions represented in this overview are subsequently explained in section 4.7.

1. Setup
    - 1.1 Initiate network
    - 1.2 Assign variants

2. Simulate
    - 2.1 Select speaker
    - 2.2 Interaction
    - 2.3 Report

3. Repeat (2) until iteration number = 1×10^4 / monotonicity reached.

4.5 Initialisation

At the point of initialisation, there are N speakers. $N = 100$, as in Kauhanen's model. All speakers are assigned variant 0; following Kauhanen's model, the simulation begins with one variant having strict dominance. In the fixed speaker version, the "acquired" attribute values are set to N for all speakers. In the alternative critical period version, the counter attribute values are set to 0 for all speakers. The network is initialised via the NetworkX (Hagberg et al. 2008) Watts-Strogatz generated graph, which involves a rewiring parameter of a different nature from that of Kauhanen's model. This parameter rewires the edges of a regular network structure *once* before the simulation starts, to create a highly clustered small-world network. After initialisation the network shape is stable. This is explained in section 4.7.1.

4.6 Input

The external input to this model is the NetworkX Python library, and the DORM (Cuskley et al. 2021)[4], introduced in section 4.7.5.

4.7 Submodels

Here, I explain the submodels presented in section 4.4.

4.7.1 Initiate network

Network initiation involves the initialisation of nodes (speakers) and edges (connections between speakers). In accordance with Kauhanen's model, edges are binary and symmetric (Kauhanen 2017:333), i.e., a connection between two nodes must be reciprocal. The network is not multiplex (Kauhanen 2017:333), i.e., is uniplex; there is a maximum of one connection between any two speakers. There are no speakers that are disconnected from the rest of the network.

The network is initialised using the Watts-Strogatz generated graph via the NetworkX library. The rewiring function that determines the initial network shape creates differential levels of connectedness throughout the network, i.e., nodes with different degrees. A node's degree is the number of other nodes it is connected to (see e.g., Scott 2000:67). This leads to a highly clustered network (Watts & Strogatz 1998), in which there are multiple small groups of highly connected nodes, i.e., a high density of edges, connected to other small groups by nodes with fewer edges. The Watts-Strogatz graph is used to emulate the clusterisation in Kauhanen's network, due to the omission of his rewiring parameter. Kauhanen states that "stable variation should be more likely [and "much faster"] in clusterised communities than in well-mixing ones" (Kauhanen 2017:352). The Watts-Strogatz graph requires four

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[4] See appendix for the code.

parameters, *n, k, p,* and *seed*. *n* is equal to the number of nodes; *N*. *k* is the number of neighbours each node is connected to in a ring topology. These are the node’s nearest neighbours. In this model, $k = 6$, thus, each node is connected to 6 others before rewiring. *p* is the probability of rewiring each edge in the network. In this model, $p = 0.5$; each edge has a probability of 0.5 of being rewired. An intermediate *p*-value, $0 < p < 1$, is what creates the particular small-world network presented by Watts and Strogatz (1998), featuring this property of high clusterisation. The *seed* parameter is set to 1. A consistent and defined seed is used so that the results of this study can be replicated. As mentioned in section 4.5, in the fixed speaker version, the “acquired” attribute is set to N for all speakers. In the alternative critical period version, the counter attribute is set to 0 for all speakers.

4.7.2 Assign variants

Variable A values of 0 or 1 are assigned to each speaker, to represent the variant the speaker is currently entertaining. Initially, all speakers are assigned variant 0; following Kauhanen (2017), the model is initialised with one dominant variant.

4.7.3 Select speaker

One speaker is selected uniformly at random using Python’s *random* module. Specifically, the *random.sample()* function is used to select one speaker from the list of all nodes in the network. The function takes a random sample without replacement; the selected node is not removed from the list. Thus, the same node can be selected in a subsequent speaker selection. This selection process is used for both the variable speaker and fixed speaker versions. In the alternative critical period version, *random.sample()* stochastically selects from the set of nodes that have not reached their critical period. This set, termed “selectable nodes” constitutes all nodes with a counter value less than or equal to 50, and is updated each iteration; all qualifiable nodes are appended to the set. Nodes with a counter value over 50, i.e., those that have reached the critical period, cannot be appended to the set, and thus cannot be selected. Once this set is empty, i.e., all nodes have reached their critical period, the simulation ends, as no further change can occur.

4.7.4 Interact

The speaker interaction submodel uses an adapted version of Kauhanen's equation (9) (Kauhanen 2017:353) to determine whether the selected speaker's variant will change. Equation (3) below uses the innovation parameter (consistently 0.005 in this model, following Kauhanen (2017)), the number of linguistic variants (consistently 2 in this model), the selected speaker's degree, and the variable A values of the speaker's neighbours. Equation (3) is used to determine the probability that the selected speaker's variant will be set to/remain at 1. Because there are only two variants in this model, the probability of the speaker having variant 0 is 1 minus *the probability of the speaker having variant 1*. Thus, this probability only needs to be calculated once. In this attempt to recreate Kauhanen's model without the rewiring parameter, *K* is redefined as the degree of node *i* [5]. Thus, the equation for setting speaker *i*'s variant is as follows (Kauhanen 2017:353): "For each possible variant *r*, the probability of setting $v_t(i) = r$ is to equal:"

$$\frac{\mu}{C} + \frac{1-\mu}{K} \sum_{j \in E_t(i)} \chi_t(j,r).$$

Equation (3) *(Kauhanen's equation (9) (2017:353)*

where:

μ = the innovation parameter, $0 < \mu < 1$
C = the number of variants in competition
K = degree of node i
j = a neighbour of speaker i
$X_t(j, r)$ = an indicator function which iterates over all neighbours of i, defined as:

$$\chi_t(i,r) = \begin{cases} 1 & \text{if } v_t(i) = r \\ 0 & \text{otherwise} \end{cases},$$

Equation (4) *(Kauhanen's equation (7) (2017:352).*

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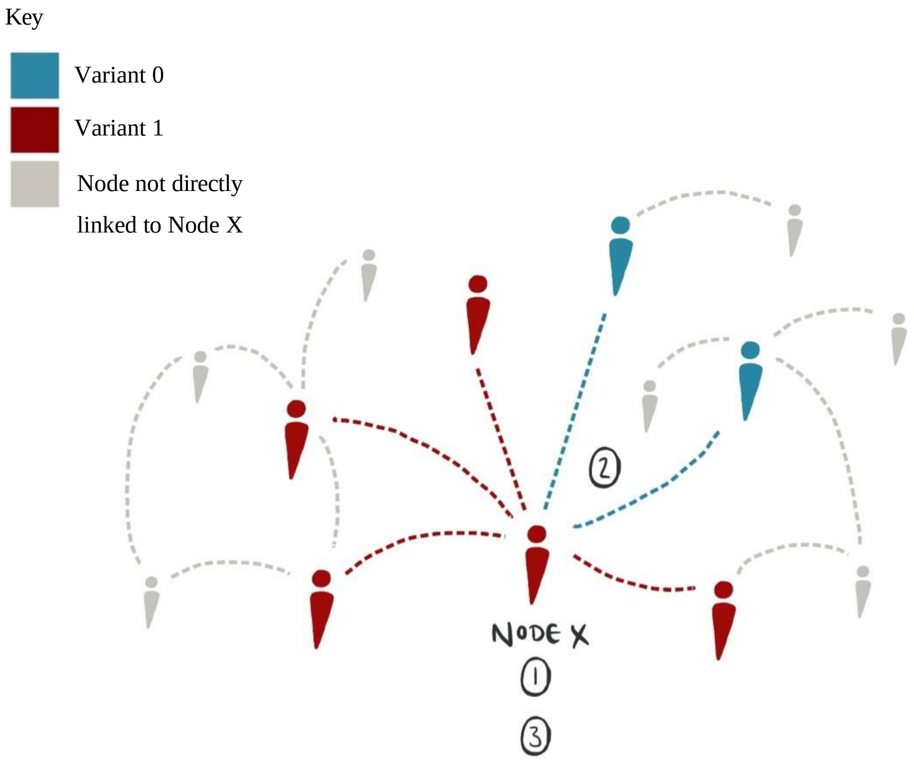
[5] – whereas, in Kauhanen's model, *K* is the number of connections received by node *i* when it is added to the network (see section 3.7.4).

In the fixed speaker version, if the selected node changes variants according to the calculated probability, its “acquired” status changes to Y. This prevents it from being able to change variants again during the simulation. In the alternative critical period version, the selected node’s counter is updated by + 1 to compute the number of times it has been selected for interaction. This continues until the counter reaches 50, at which point the speaker is no longer selectable by *random.sample().*



① Node X stochastically selected

② Probability of Node X having variant 1 calculated using:
- Node X’s neighbour variant values
- Node X’s degree
- number of possible variants (2 – variant 0, variant 1)
- innovation parameter

③ Node X’s variant determined using probability

Figure 1: *an abstract representation of one interaction.*
Nodes represented in colour are involved in the interaction concerning Node X and its neighbours. Grey nodes represent the rest of the network. In this figure, node size is exclusively to make apparent the neighbours of Node X, and edge length is arbitrary – there is no notion of edge length in the model. As stated by Scott, graph theory (the study of graphs, i.e., mathematical networks) has “no interest in the relative position of two points on the page, the lengths of [edges], or the size of [nodes]” (Scott 1991:67).

4.7.5 Report

The data output is the frequency of variant 1 in the population. Additionally, a value for monotonicity is output. This is calculated via the DORM (Deviation Of the Rolling Mean (Cuskley et al. 2021)), a descriptive statistic that I am approximating to Kauhanen's measure of monotonicity, as an alternative means of quantifying informational uniformity. The DORM provides a value for the variance of the deviation of the rolling mean of variant 1 over a window size of N, where $N = 100$. The DORM value is inversely proportional to monotonicity; a lower DORM corresponds to a higher monotonicity. Due to the scope of this study, Kauhanen's quantification of well-behavedness is not replicated. Results are primarily discussed in terms of S-curves and monotonicity, terminology used more widely in the field. Additionally, Kauhanen's qualitative definitions of dominance and shifting (Kauhanen 2017:336), presented in section 3.2, will be used to speculate as to whether the results appear well-behaved.

4.7.6 Repeat

Repeat *Simulate* for 1×10^4 iterations, or until monotonicity is reached. It is necessary to note that variant 1 is artificially introduced to the population at iteration number 10 if it has not entered the population via innovation/mutation before this point. This is to reduce simulation length due to limitations of computational power and time. This does not impact the results or conclusions in relation to the research questions, as I am investigating the trajectory once the variant has been introduced, as opposed to how long it takes for a speaker to mutate and produce variant 1.

5. Results

Here I present the results for each version of the model. Each version is run 20 times; graphs show 20 possible trajectories of the simulation. I discuss variant frequency results in terms of S-curves, adhering to Kauhanen's use of the S-curve as a template for language change. As discussed, Kauhanen quantifies the criteria for his *well-behavedness*, i.e., S-curve production. I do not use his quantitative measures of these criteria due to the scope of this study. Instead, I refer to his qualitative descriptions (Kauhanen 2017:336), repeated below:

1) Dominance: the population reaches a state in which most or all speakers use one variant, i.e., one variant is (nearly) dominant.

2) Shifting: the population shifts from a state in which one variant is dominant to a state in which another is dominant.

3) Monotonicity: the manner by which shifting occurs, with the new variant's frequency increasing "along smooth propagation curves" (Kauhanen 2017:336).

Additionally, I use the DORM (Cuskley et al. 2021) to produce a value for monotonicity. This allows me to further compare the versions of my model, and to quantitatively discuss my results in terms of one aspect of Kauhanen's well-behavedness.[6]

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[6] As discussed in section 4.6, this is not the same measure of monotonicity used by Kauhanen. Thus, my monotonicity values cannot be directly compared to his. Due to time constraints, this is implemented as an alternative means of quantifying the monotonicity of simulations of my model.

5.1 Variable speakers

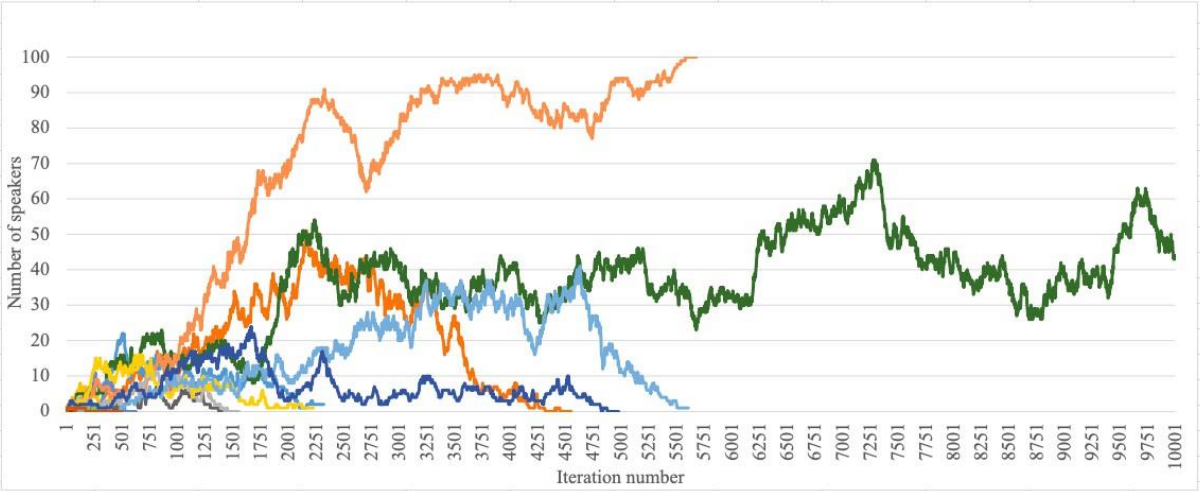

Figure *2*: *Number of speakers with variant 1.*

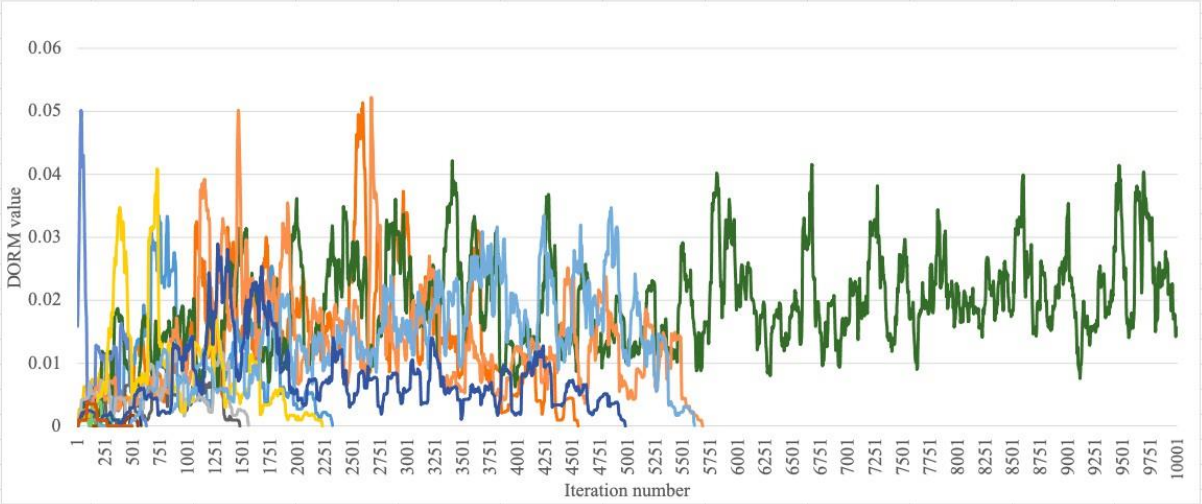

Figure 3: *DORM values (monotonicity).*

Figure 2 shows notable variation between the 20 simulation runs. The majority, 15 runs, quickly reach a state of monotonicity. This occurs in the first 2500 iterations. The population stabilises, in this case with 0% of the population having variant 1. Thus, variant 1 does not make it past the innovation phase of the S-curve model. Three runs end between 2500 and 5750 iterations, reaching a state of monotonicity with variant 1 being present in 0-2% of the population. One run shows a population-wide shift to variant 1. This is 5% of total runs. However, this does not resemble a smooth S-shaped curve. It features multiple trend reversals, as would be expected of a model of drift according to Blythe and Croft (2012), including a notable decrease in variant 1 frequency after a rapid increase in the first 2328 iterations. It resembles Kauhanen's example of ill-behaved change (Kauhanen 2017:337); his description of shifting is satisfied – the whole population shifts from one variant to another – however, neither variant is dominant for the majority of the run. The change is not monotonic; figure 3 shows the monotonicity fluctuates greatly, reaching a DORM value of 0.05 at multiple points, i.e., low monotonicity. Thus, Kauhanen’s dominance and monotonicity are not satisfied according to his qualitative definitions. Finally, one run never reaches a state of monotonicity, instead continuing to fluctuate until the end of the simulation. To summarise, one simulation run (5% of total runs) shows population-wide change without a critical period. This trajectory does not resemble an S-curve; no S-curves are produced by this version.

5.2 Fixed speakers

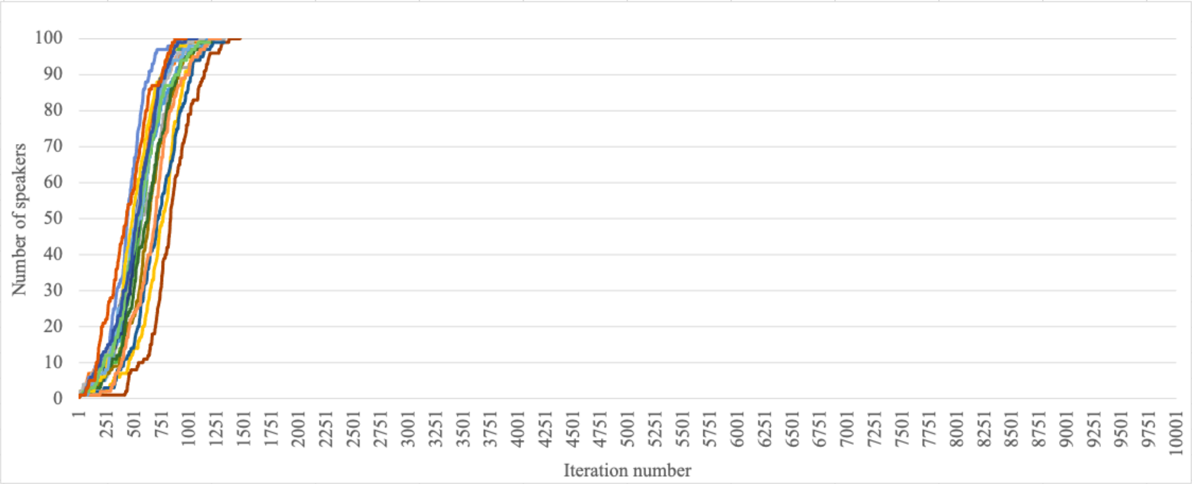

Figure 4: *Number of speakers with variant 1.*

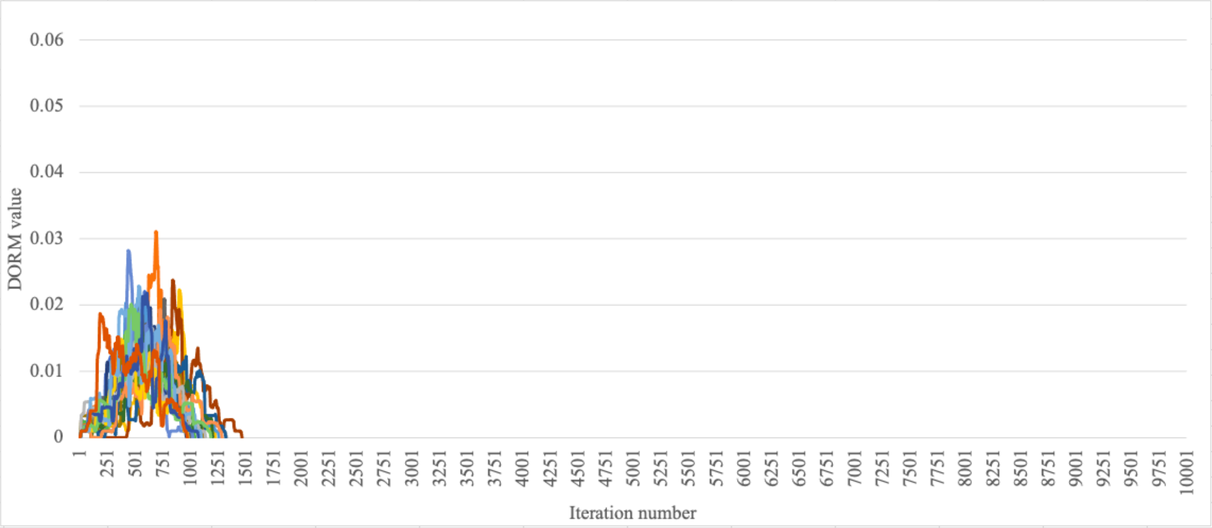

Figure 5: *DORM values (monotonicity).*

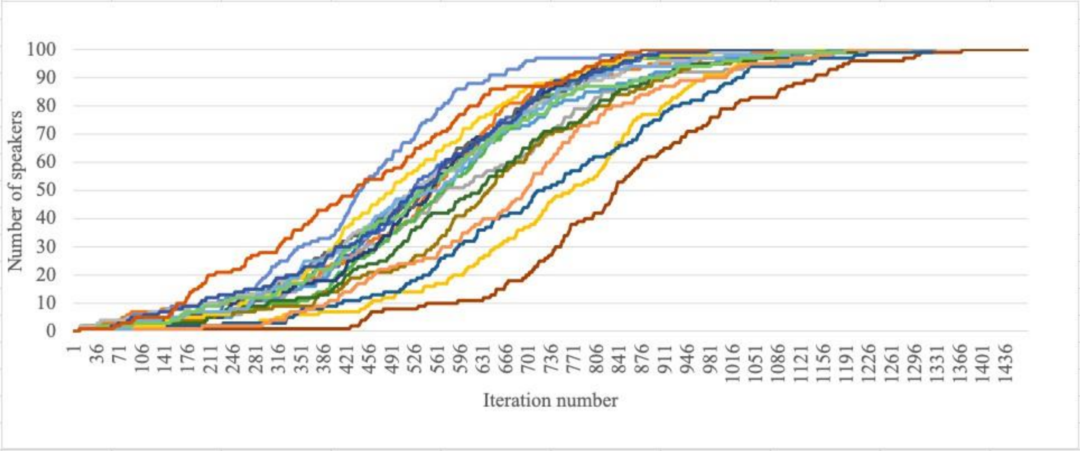

Figure 6*: Section of Figure 4, showing only the period of change.*

Figure 4 shows the fixed speaker version produces smooth S-curves for all simulation runs. All feature a gradual start, a more rapid period of propagation, and a slower final period once the variant is established, i.e., most speakers have it. The trajectories can be seen more clearly in figure 6, which exclusively shows the period in which change is observed. Population-wide change occurs quickly under this condition relative to the other model versions. All simulations finish within 1500 iterations, where they reach a state of monotonicity in which all, or almost all (minimum 97%), of the population have variant 1. Figure 5 shows this change is also relatively monotonic; the DORM value is below 0.032 in all runs, while they reach 0.05 in the variable speaker version. To summarise, the fixed speaker version produces smooth S-curves, which conform to Kauhanen's qualitative definition of well-behavedness.

5.3 Alternative critical period

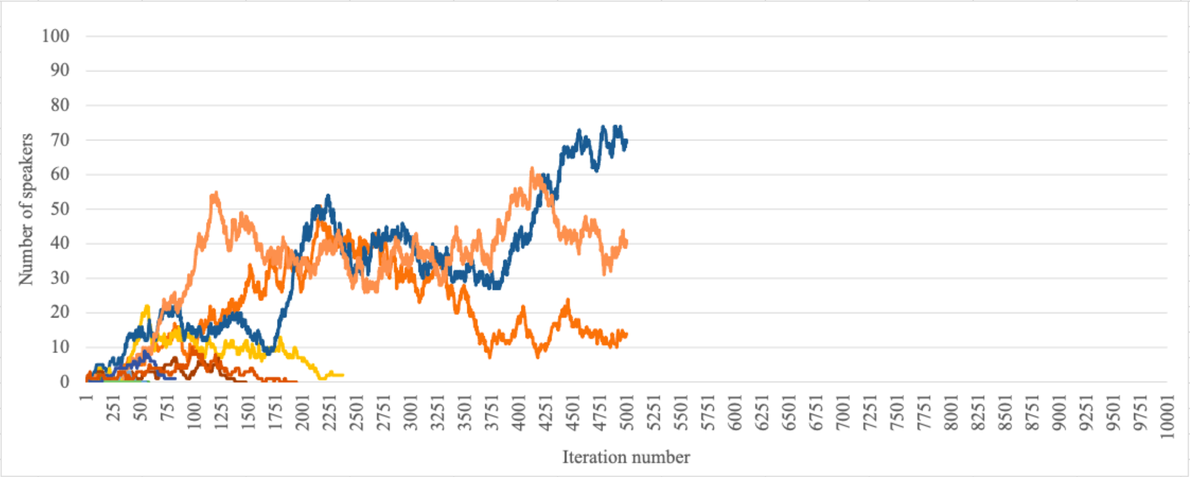

Figure 7*: Number of speakers with variant 1.*

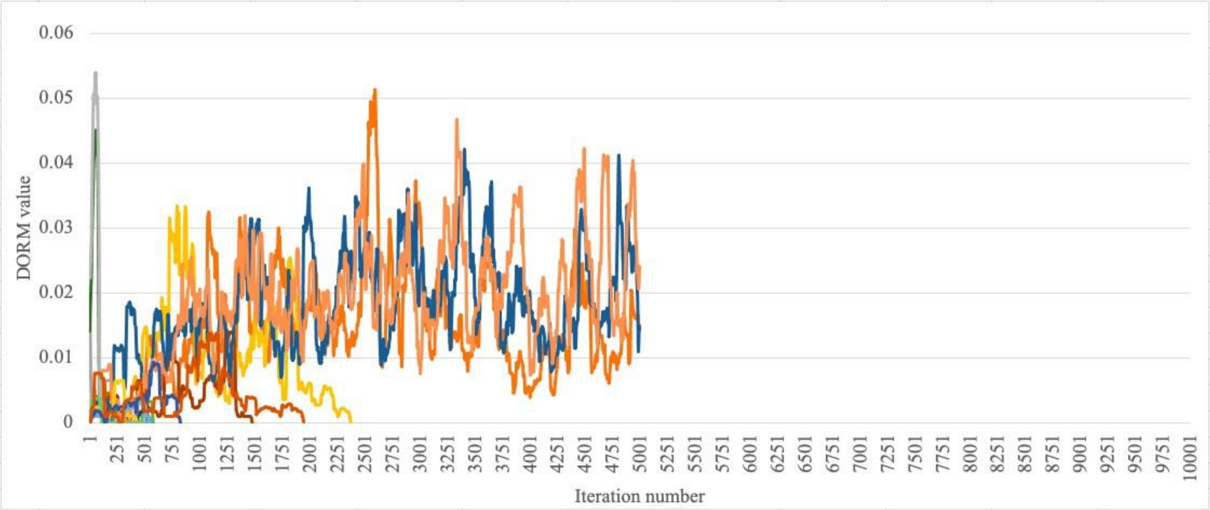

Figure 8: *DORM values (monotonicity).*

Figure 7 shows that the alternative critical period version of the model does not produce Kauhanen's well-behaved S-curves. Out of the 20 simulation runs, 17 finish before 2500 iterations; they become monotonic with a small minority of the population having variant 1. Three runs continue until all speakers have been stochastically selected – i.e., have had the potential to change variants – 50 times. At this point, the simulation ends as no further change can occur. These three runs feature trend reversals and large fluctuations in monotonicity, shown in figure 8. One run ends with 70% of the population having variant 1. However, the trajectory is not monotonic. It also does not satisfy Kauhanen's (2017) dominance; no one variant is present in the majority of the population for the majority of the simulation. Nor does it satisfy shifting; 30% of speakers still have variant 0 at the end of the simulation. To summarise, the alternative critical period version does not produce S-curves.

6. Discussion

6.1 Results

This study investigates Kauhanen’s (2017) implementation of a critical period in his model of language change via a simplified replication of his model. I aim to explore the following questions:

1. What are the implications of Kauhanen’s assumption of a critical period on the applicability of his model, and specifically its applicability to the lexicon?

2. What are the effects of implementing, removing, and altering this assumption on a static version of his model?

These questions are explored via three versions of the static model – a fixed speaker version in which the critical period is implemented, a variable speaker version in which the critical period is removed, and an alternative critical period version in which speakers have some degree of later-life plasticity. Ultimately, the results show Kauhanen’s observed S-curves can be replicated in my static version of his model, provided that his strict critical period is implemented. This suggests the S-curve production of Kauhanen’s model is dependent on the implementation of his strict critical period. The implication of this is that his model would not be applicable to cases of later-life change, and notably to change in the domain of the lexicon. My results also imply that drift can produce S-curves in a static model, contrasting with the findings of Kauhanen (2017), Fagyal et al. (2010), and Blythe and Croft (2012).

I will now discuss the results of each version of the model and consider their implications for the applicability of Kauhanen’s model. As explained in sections 4.7.5 and 5, I discuss my results in terms of S-curves. The use of the S-curve as a template is common in this field due to the prevalence of the s-shaped trajectory in language change across domains (e.g., Blythe & Croft 2012; Chambers 2002). The S-curve model shows smooth patterns of change without trend reversals (Blythe & Croft 2012:285). It appears this monotonic model does not always capture the nuances of language change. For example, individual speakers can fluctuate between variants for some time (Wolfram & Schilling-Estes 2017:717). Trajectories can feature significant trend reversal(s) and still reach the stage of establishment/fixation[7] e.g., periphrastic do in the affirmative transitive adverbial context (Kroch 1989:223). It is not certain that all types and instances of language change follow an S-curve trajectory (Kauhanen 2017:336). However, it is deemed descriptively adequate to describe language change processes over time (Nevalainen 2015) for the reasons discussed.

The variable speaker version does not produce S-curves and only exhibits population-wide change in 5% of simulation runs. The singular instance of change is not monotonic, featuring notable fluctuation in variant frequencies and multiple trend reversals. It corresponds with Kauhanen's (2017:337) "ill-behaved" change and Blythe and Croft's (2012:285) expectations of trajectories produced by neutral change/drift. This indicates that without a critical period, Kauhanen's model would produce this nature of trajectory i.e., would not produce S-curves. The alternative critical period version does not produce population-wide change. Variant 1 does not make it past the innovation stage of the S-curve (Fagyal et al. 2010) in 85% of simulation runs. The remaining 15% show fluctuations of variant frequencies until all speakers have reached their critical period, i.e., can no longer change variants. Increasing speaker plasticity by this means does not produce S-curves in this model. In contrast, S-curves are consistently produced by the fixed-speaker version, which imposes Kauhanen's strict critical period onto speakers in a static population.

These results suggest Kauhanen's model would only produce the idealised S-curve trajectory where speakers have this strict critical period. Thus, his model would not be applicable to the cases of phonological and syntactic later-life change discussed in section 2.3. These are later-life changes in vowel production (Sankoff & Blondeau 2007) and use of the periphrastic versus inflected future tense (Wagner & Sankoff 2011) in Montréal French, and in the vowel production of Queen Elizabeth II (Harrington et al. 2000) and Chomksy (Kwon 2018). Most significantly, Kauhanen's model appears not to be applicable to change in the lexical domain. Lexical change does not have a strict critical period; it continues into adulthood, developing throughout the lifespan as vocabulary is learnt or acquired (e.g., Curtiss 1981; Bloom & Markson 1998; Meyerhoff 2006). His model appears not to be applicable to the lexicon despite the fact that drift has been suggested as a driver of lexical change (e.g., Reali &

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[7] – using Fagyal et al.'s (2010) descriptive terms for the stages of the S-curve model.

Griffiths 2010; Ventura et al. 2022; Dircks & Stoness 1999). This is a domain in which change can follow S-curve trajectories, as observed by Chambers (2002) and suggested by Fagyal et al. (2010).

The significance of these results is that they suggest Kauhanen's model is not able to account for all types of language change. Generally, researchers in this field do not need to specify the precise linguistic feature being modelled, as a sufficiently abstract model would not require this (Baker 2008:290). Kauhanen's implementation of a critical period is investigated in this study because it renders his model less abstract, raising questions regarding its applicability. The effects and implications of his critical period are not explored in his study. Thus, I use my partial replication of Kauhanen's model to speculate about the effects and implications of the critical period for the applicability of his own model.

My results also suggest that S-curve production via drift is possible in a static population. This contradicts the observations of Kauhanen (2017), Fagyal et al. (2010), and Blythe and Croft (2012). Due to the scope of this model, I do not replicate Kauhanen's rewiring parameter. My model uses a static population; thus, I am concurrently testing this observation from past literature. I find S-curves can be produced by drift in my static model, provided that Kauhanen's strict critical period is implemented. I suggest the difference between my results and those above is due to the critical period. This prevents speakers from reverting to variant 0 after acquisition of variant 1. Thus, the cumulative adoption of variant 1 produces an s-shaped trajectory due to the process outlined in section 2.2. To review this process, once variant 1 is introduced into the population, the high frequency of speakers with the ability to change variants and the stochastic speaker selection facilitate its propagation. There is a period of relatively rapid spread as an increasing number of speakers are exposed to variant 1. Once the majority has acquired it, the rate decreases as few speakers are left with the ability to change variants.

Fagyal et al. (2010) and Blythe and Croft (2012) do not model a critical period. Kauhanen (2017:334-336) also finds S-curves are not produced when he "turns off" his rewiring parameter. However, his implementation of the critical period appears to be dependent on the rewiring parameter; speakers' variants are determined upon their introduction to the network. Thus, removing his rewiring parameter would remove the critical period; hence, the lack of S-curve production. I, however, implement Kauhanen's critical period without the rewiring parameter, hence the difference between our results. My static model's S-curve production supports the findings of the aforementioned model of Dircks and Stoness (1999), which suggests drift as a mechanism to produce convergence of a population on a lexical term for an object, specifically in the absence of population flux. These results suggest, firstly, that Kauhanen's model can be simplified and still produce S-curves. This is significant; simplification is "one of the strengths of computational modelling", an approach which aims to uncover "the few key parameters [] appear[ing] to underlie the real world" (Stanford & Kenny 2013:124). If Kauhanen's results can be replicated in a model with fewer parameters than his own, it suggests his model may be overly complex. Secondly, these results suggest that drift is possible in a static network model, however, it appears to be dependent on a strict critical period.

An additional finding of this study is the importance of clarity and reproducibility in this field[8]. Some elements of Kauhanen's (2017) model could not be easily interpreted for presentation via the ODD protocol or replicated in my own model; specifically, his rewiring parameter and quantification of well-behavedness. This is due to a level of complexity in these elements' description or implementation beyond the scope of this study, due to limits of time and computational power. Had Kauhanen's model been presented using the ODD protocol, these elements may have been more understandable and reproducible. This is particularly important as Kauhanen states that future research should systematically explore the removal of the critical period from his model (Kauhanen 2017:331, 335). The provision of his code alongside explicit model presentation would facilitate accurate replication of his model and the systematic exploration of his critical period parameter.

6.2 Limitations and future research

The complexity of elements of Kauhanen's model, alongside constraints of time and computational power, has created various limitations for this study. I will now discuss these limitations and suggest how they could be overcome. I also consider questions and how these could be addressed in future research.

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[8] See Wieling et al. (2018) for a comprehensive discussion of reproducibility and data/code provision in computational linguistics.

The omission of Kauhanen's rewiring parameter limits the extent to which these results can be interpreted in relation to his model. Thus, his model's applicability must be discussed speculatively. My model aims to recreate that of Kauhanen without the rewiring parameter, using a stochastic process of speaker selection for the variant-setting interaction. The Watts-Strogatz graph is used to mimic the clusterisation brought about by Kauhanen's rewiring parameter. However, because it is not an exact replication, I cannot definitively predict the results Kauhanen's model would produce under the conditions explored. Similarly, because Kauhanen's measure of well-behavedness is not used, my results are not quantitatively comparable to his. However, I have made qualitative comparisons, and the DORM has provided a quantitative measure of one element of his well-behavedness: monotonicity. Thus, via my results, I have been able to suggest how Kauhanen's model would behave under the conditions investigated. This study begins to explore his critical period parameter. Future research should aim to systematically explore this via an exact replication of his model and may consider using his quantitative measure of well-behavedness to facilitate direct comparison with his results.

A further limitation of this work is due to the omission of the rewiring parameter. Kauhanen (2017:332-333) criticises earlier research for exclusively considering static populations (e.g., Ke et al. 2008; Fagyal et al. 2010; Blythe & Croft 2012), despite the natural dynamics of human social networks. Kauhanen's rewiring parameter is implemented to model human social network dynamics, as change in the population is expected over the timespan in which a process such as drift takes place (Kauhanen 2017:332). Thus, the lack of population dynamics limits the extent to which my model is representative of a human social network. However, even if Kauhanen's precise network structure and dynamics could be replicated, the extent to which this would be realistic is unknown (Kauhanen 2017:348-349). The underlying properties of human social networks are still not fully understood (Kauhanen 2017:349). Thus, any work in this field has to make approximations. Future research should systematically explore Kauhanen's assumption of a critical period in an exact replication of his model to explore the effects of removing and altering this assumption in a dynamic population. Additionally, drift in a static social network should be further explored, as my results contradict the findings of existing literature (Kauhanen 2017; Fagyal et al. 2010; Blythe & Croft 2012).

The extent to which alternative implementations of a critical period could be explored in this study is also limited by time and computational power. I test the model with an alternative critical period in which speakers can interact a maximum of 50 times. This is an arbitrary critical period, to explore the effects of enabling speakers a greater level of plasticity than Kauhanen's speaker invariance after acquisition. Future research should explore a more realistic implementation of a critical period. As discussed, later-life change is possible in various domains, but the critical period is the window during which language change is easiest (e.g., Meyerhoff 2006). Thus, I suggest a more realistic model of the critical period would make change possible but less probable in later life. This could be explored via a model featuring distinct life phrases, with the probability of changing variants decreasing with speaker age. The model of Nettle (1999) uses five life stages before speaker death, at which point they are replaced by a new speaker at life stage one. This is an alternative means to model population dynamics, using age. In Nettle's (1999) model, change is only possible in the first two phases, representing childhood and adolescence. This could be adapted to model a decreasing probability of change after adolescence. Thus, I suggest future research explores modelling the critical period using this as a starting point, to capture the later-life plasticity observed in various domains. Kauhanen's variant setting equation (Kauhanen 2017:353) could be adapted such that speakers' probability of change decreases with age, to explore the effects of this on his model.

A question that arises and should be further explored is whether such a model could be sufficiently abstract to account for change in the lexicon as well as the nature of later-life change observed in other domains. This question corresponds with the wider lack of consensus in linguistic theory regarding the lexicon and its position in relation to the grammar (Boye & Bastiaanse 2018:1). The lexicon is described as merely "an appendix of the grammar" by Bloomfield (1933:274). Chomsky (e.g., 1957, 1965) adheres to this view, regarding the lexicon as distinct from syntax and grammar, "neglect[ing] the word as a central linguistic notion" (Neef & Vater 2006:35). This distinction has led to models of language in which the lexicon appears entirely separate from the grammar, with the grammar consisting of phonology, morphology, syntax, and semantics (see e.g., Neef & Vater 2006:49)[9]. This perspective may correspond with the necessity for a separate model for the lexicon, as distinct from other domains of language. Future research should consider whether

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[9] See e.g., Contreras Kallens and Christiansen (2022) for a criticism of this idealised bipartite distinction.

lexical change can be encompassed in a model of the nature explored in this study, or whether it requires a separate model due to its differences from, for example, phonology and syntax.

In summary, the extent to which Kauhanen’s model could be replicated is limited due to a combination of factors. Thus, conclusions drawn about the applicability of his model can only be speculative. This is an exploratory piece of research, investigating Kauhanen’s implementation of a critical period and considering its implications. Further research would have to be undertaken to uncover whether Kauhanen’s dynamic model could be made to account for later-life change by implementing a more realistic critical period. Additionally, future work should consider how (or if) the lexicon can be accounted for alongside other domains in a model of language change that involves a critical period. This may or may not use Kauhanen’s model as a basis, to explore the possibility of modelling drift in the lexicon.

7. Conclusions

Two principal conclusions can be drawn from this exploratory study of Kauhanen's (2017) model of neutral change, in which I specifically consider the effects and implications of his assumption of a critical period and the broader theme of model applicability.

Firstly, Kauhanen's (2017) smooth S-curves are reproduced in my model only under the condition that his strict critical period parameter is implemented. This suggests the S-curve production of Kauhanen's model is dependent on the critical period parameter. This would entail his model is only applicable to cases of language change that occur within a strict critical period. Thus, his model would not account for cases of later-life change such as the examples discussed in the domains of phonology (Sankoff & Blondeau 2007; Harrington et al. 2000; Kwon 2018) and syntax (Wagner & Sankoff 2011). Notably, this implies his model would not be applicable to the lexical domain, in which later-life change is expected (e.g., Meyerhoff 2006; Bloom & Markson 1998; Curtiss 1981). Language change modelling is used to further our understanding of the foundations and implications of theories of language change (Baker 2008:289; Fagyal et al. 2010). Kauhanen's model implies S-curves cannot be produced by drift in the lexical domain, despite observations of s-shaped trajectories and drift in lexical change. Future research should further explore his findings and aim to produce a more realistic model accounting for later-life change. Future research should also aim to determine whether one model can account for change in the lexicon and other domains. This should particularly be considered in the context of drift, due to the implications of Kauhanen's model.

Secondly, my results suggest S-curves can be produced by drift in a static population (cf. Kauhanen 2017; Fagyal et al. 2010; Blythe & Croft 2012) provided that Kauhanen's strict critical period is implemented. This suggests Kauhanen's model can be simplified and still produce S-curves corresponding with his qualitative description of well-behavedness. Future research should further explore the key, i.e., essential, parameters of Kauhanen's model, and other models of drift, to explore the underlying parameters of this nature of change in human social networks. Additionally, this finding implies that drift is possible in a static network model, contradicting the findings of existing research. However, this appears dependent on the critical period parameter, which limits the model’s applicability. This possibility should be further investigated.

This study contributes to the field by exploring the results, implications, and applicability of an existing model of language change. It demonstrates the implications of researcher decisions on the conclusions drawn about the underlying processes of language change, which computational models aim to uncover. Future research should systematically explore the implementation of a critical period in Kauhanen’s model, and whether such a model can be rendered sufficiently abstract to account for all domains of language change.

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Appendix

Code accessible via:
https://docs.google.com/document/d/17BEryP3B9QRNKbIn6mB9PsfJ1DLM8twlFMz59BIBE_M/edit?usp=sharing