Language Change and Network Games

Abstract

Studies of language change and variation in sociolinguistics investigate the correlations between social variables and phenomena like vernacular speech norms, code switching, and dialect continua. In multiple studies, researchers claim one variable as i) particularly decisive and correlative for a number of phenomena, and ii) almost universally applicable: the social network structure (Milroy 1980). This article summarizes previous work incorporating network theory in questions of language change and discusses a practice noticeably absent from classical sociolinguistics: the simulation of language change. In simulation experiments, sociolinguistic theories of language change – especially those employing social network structure – can be tested in a virtual society free from the hindrance of data sparseness. In this context, the model of game theory can be utilized to construct individuals' interaction for more robust and feasible results.

1 Introduction

Two dominant issues in sociolinguistics are language change and variation. A significant amount of sociolinguistic research investigates how social variables affect linguistic usage over time and space. In particular, linguistic behavior can vary between groups differentiated along lines like status, gender, ethnicity, or education. Of these properties, it has been noted that the structure of a person's social network (links to family members, colleagues, friends, etc.) might be crucially important for explaining language variation and change (c.f. Labov 2001, Eckert 2005, L. Milroy and Llamas 2013), particularly because of its universal character, a quality that other social features generally lack. Since the early 1980s, the social network approach (L. Milroy 1980) has been used in various field studies. Their results document social network structure as a robust and impartial predictor of language change.

Since the late 1990s, a number of studies have emerged that analyze language change in a more universal sense – abstracted away from the specifics of usage – by conducting 'virtual field work' in computer simulations (Nettle 1999, Ke, Gong and Wang 2008, Fagyal et al. 2010). With a computer program simulating and documenting a virtual linguistic community, many of the possible shortcomings of network approaches in fieldwork – like a sparse coverage of essential data in time and space – can be overcome. As a virtual society gives full access to spatial and temporal data, network properties can be defined and observed in a very fine-grained way. Admittedly, virtual computer programs cannot reproduce speech communities in every detail, but we claim they are a valuable tool for both reproducing field studies and reassessing the subsequent theoretical developments.

Despite their upside, most of the previously mentioned simulation studies do not include an essential aspect of simulating language change: the actual act of communication (in terms of a speech production and perception process). Thus we argue for a more fine-grained and realistic approach, incorporating game-theoretic techniques that model how speakers and hearers arrive at linguistic conventions. To get a fair impression of how such a combination can be applied to test theories of language change, we will present an exemplar for a virtual study at the end of this article.

The article is structured as follows: Section 2 gives a short introduction to the social network approach in sociolinguistics. Section 3 introduces a noted social network theory related to language change, called the 'weak tie'-theory (J. Milroy and L. Milroy 1985). Section 4 discusses the obstacles that bedevil sociolinguistic theories like the 'weak tie'-theory from being directly verified in field research. Section 5 points out alternatives for evaluating theories of language change, inter alia simulation studies, which are discussed in Section 6 in more detail. Section 7 presents and advocates for game-theoretic models of language change. Section 8 presents a sample study that integrates a game-theoretic model towards examining the 'weak tie'-theory. Finally, Section 9 points out further theories of language change that may be amenable to computational models.

2 Networks in Sociolinguistics

Early field studies recognized that social variables like status, gender, ethnicity or the level of education cannot give a universal explanation for linguistic diversity (c.f. Labov 1963, 1966, 1972, J. Milroy and L. Milroy 1978, Eckert 1989). In contrast, the 'social structure' of the community seems to be a source of variation that might be highly independent of environmental circumstances and universal in character.[1] In an early study, James Milroy and Lesley Milroy (1978) found a positive and significant relationship between so-called network scores and the use of vernacular language in different communities in Belfast. This led to a number of subsequent works illustrating the practice of social network analysis in sociolinguistics (c.f. L. Milroy 1980, J. Milroy 1990 and Chambers 1995).

In questions of language diversity, such as the emergence and coexistence of different socio- and dialects of the same language, some properties of network structure seem to be particularly important. One significant distinction is that of a 'close-knit' and a 'loose-knit' network. In a pioneering work – by being a systematic account of articulating network structure – Lesley Milroy (1980) defines a close-knit network as one that has a high 'density' and mostly 'strong ties'. Here density referring to the ratio of ties and members of a community, and strong ties are defined as incorporating multiple relationships between two members, such as kin relationship, friendship or work fellow. In close-knit net-

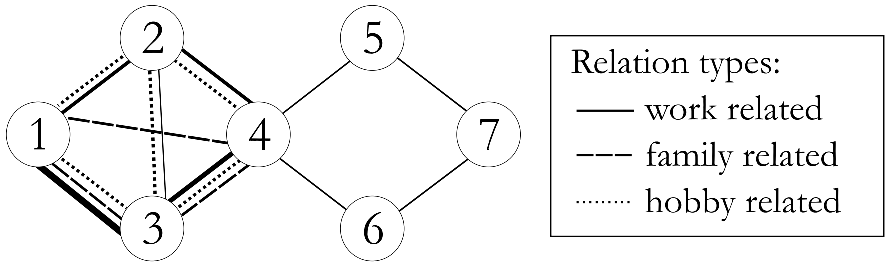

Figure 1: The subnetwork containing 1, 2, 3 and 4 represents a typical close-knit network: i) all members know each other (there is at least one tie between any two members), thus the network has maximal density, ii) almost all members have multiplex ties (except of member 1 and 4, all members are connected via more than one relation type), and iii) all members have frequent contact (the thickness of a tie represents the frequency of interaction). Conversely, the subnetwork containing 4, 5, 6 and 7 represents a typical loose-knit network: i) not all members know each other directly (4 and 7, 5 and 6), ii) all connections are uniplex (only work related), and iii) the members have a low frequency of interaction (represented as thin ties).

works it is expected that all members

i) mostly know each other,

ii) interact frequently with each other inside a defined area,

iii) have a great volume of exchange and shared knowledge, and

iv) are susceptible to the obligation to adopt group norms.

In contrast, a loose-knit network is a structure with a low density and mostly 'weak ties', thus single-type relationships. Members of such a structure are attested to have an open personal network and no particular linguistic markers of identity (c.f. Fried and Fitzgerald 1973) or a high degree of dialect diffuseness (c.f. Le Page and Tabouret-Keller 1985). Figure 1 illustrates the structural differences between a close-knit and a loose-knit network.

We introduce network features like *close-knit* and *loose-knit* as exemplary sociolinguistic factors to yield the following point: the network structure of a language community has two properties that are suitable for developing more general theories of language variation and change: i) a universal character (c.f. Milroy 1980, see endnote 1) and ii) an obvious correlation with linguistic behavior. This leads us to discussing the role of network structure in language change.

3 The Role of Network Structure in Language Change

In its most general sense, language change can be seen as a new linguistic variant replacing an old one across some set of contexts. Although each instance of linguistic change has its temporal and spatial inception, one of the greatest challenges in sociolinguistics is determining which social variables support the initiation and propagation of a new variant (c.f. Labov, Yaeger and Steiner 1972, Trudgill 1972, Labov 1973, 2001, 2010, L. Milroy 1980, Rogers 1995, Croft 2000, Chambers 2002). To better understand language change, we should ask: Which social circumstances support linguistic innovation? And which social environment is a fertile ground for a new variant to spread?

An insightful theory about the role of 'social network structure' in language change is the 'weak tie'-theory (J. Milroy and L. Milroy 1985)[2]. As a result of speaker innovation, a new variant i) emerges generally on so-called 'weak ties' – ties that have a low strength or multiplexity and connect mostly detached communities (see Figure 2) – and ii) spreads via 'central' members of the local community. A number of studies indirectly support the 'weak tie'-theory (Labov 1973, 1991, 2001, Trudgill 1988, L. Milroy and J. Milroy 1992, J. Milroy 1996, Wolfram and Schilling-Estes 1998, Llamas 2000, L. Milroy and Gordon 2003), but studies that directly verify the theory are hard to conduct, for reasons that we will soon delineate.

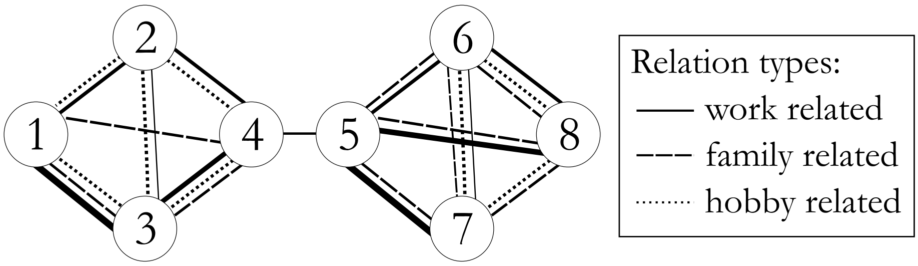

Figure 2: The connection between member 4 and 5 constitutes a typical weak tie: it i) has a low strength/frequency (thin line), ii) has minimal multiplexity (uniplex), and iii) connects two detached communities, here community A (members 1, 2, 3, 4) and B (members 5, 6, 7, 8). According to the 'weak tie'-theory, innovation emerges on such weak ties and spreads via central members of a community like A or B.

4 The Quantity Problem of Empirical Studies

A systematic analysis of the impact of a linguistic community's network structure on language change involves the calculation of network features of particular members of that community. As we will delineate later, an important role in language change is assigned to so-called 'global features', that are network properties with respect to a 'global environment', a part of the network that goes far beyond the local neighborhood of this member. The calculation of such features needs a quantity of network data that generally field work studies cannot deliver. This obstacle leads to a practice in field work of generally considering first-order networks, as explained by L. Milroy and Llamas (2013:411):

> "A social network may be seen as a boundless web of ties which reaches out through a whole society, linking people to one another, however remotely. [...] However, sociolinguistic research has generally focused on face-to-face interaction, and usually on first-order network ties – that is, those persons with whom an individual directly interacts."

Gathering data on first-order networks can suffice for analyzing individual-based theories of norm maintenance in close-knit networks, but this fails to predict phenomena that might be correlated to more global networks values, like cluster-related features. L. Milroy and Gordon (2003:119) point out:

> "Network analysis [in sociolinguistics] typically deals with the structural and content properties of the ties that constitute egocentric personal networks, and seeks to identify ties important to an individual rather than to focus on particular network clusters (such as those contracted at school) independently of a particular individual."

All in all, we can see the difficulty of gathering a critical mass of data needed to compare individuals in loose-knit structures in a meaningful way.

Related to the quantity problem is the difficulty of obtaining temporal data. To record language change, it is often not enough to compare different age groups – see e.g. 'apparent-time construct' (c.f. Bailey 2002). Rather it might be necessary to conduct expensive and arduous longitudinal or cohort studies (c.f. Dannenberg 2000), which are comparatively rare in sociolinguistics (c.f. Cukor-Avila and Bailey 1995, Blake and Josey 2003). Delving deeper into this discussion exceeds the scope of this article, but the point remains. In the next section we want to recommend alternatives for surmounting the shortcomings of the aforementioned network analysis in sociolinguistics.

5 Alternative Methods in Sociolinguistics

One consequence of the quantity problem is that feasible computations of global network properties that illuminate the larger picture of a speech community require methods like mining 'communities of practice' (Wenger 1998, Eckert 2005). As a prominent example, in her studies of Detroit schools, Eckert (1989) recorded complete friendship networks, hypothesizing that particular groups organize in specific structures and contain themselves to specific speech norms. Although her uptake is suitable for computing globally-related network properties, the reader should nevertheless note that such a network is only a fragment of the members' network ties, since it considers exclusively the participants of a particular community of practice (e.g. classmates, work fellows, etc.), and is therefore uniplex and incomplete.

A more precise picture of a social network structure can be provided by the study of online chat networks (e.g. Paolillo 2001, Merchant 2001). These, for example, allow us to measure the 'intensity tie strength' quite precisely by measuring the amount of time two members spend chatting together. There are crucial drawbacks to such studies however. For one, note that a chat community can be seen as an 'online community of practice' (Wenger, White and Smith 2009). Furthermore, it is debatable to what degree these results are contributions to questions of language change in the classical sense, since chat via text differs in a number of aspects from verbal communication (for a discussion about similarities and dissimilarities, and the role of written text in sociolinguistics, we refer to Baron 2000, 2008, and Crystal 2005).

A further possibility then is to leave the terrain of field work entirely by doing simulations with virtual societies. In light of the quantity problem, the advantages are clear: first, the researcher creating the whole society has access to the full network structure. It is thus possible to compute the relevant global network properties with absolute precision. Second, it is also possible to record an individual's behavior with full recall. Third, simulations generally run quickly, so interaction over time can be computed in a feasible time frame, thus overcoming the difficulty of longitudinal studies.

The obvious drawback of such virtual experiments is the abstraction from real human behavior. However, as virtual experiments test theories of language change originating from field research, they can remain 'informed' by real human behavior. It should furthermore be noted that in research areas with a much greater quantity problem, e.g. 'language evolution', simulation studies are an established modus operandi for conducting research (c.f. Nowak and Krakauer 1999, Cangelosi and Parisi 2002, Kirby and Hurford 2002, Steels 2002). In the following section, we will introduce and discuss network simulation studies, presenting along the way some noteworthy work on language change.

6 Network Simulation Studies of Language Change

What constitutes a network simulation study? First, the 'simulation' aspect signifies that we are studying a virtual system, in our case a system of agents using artificial language. For that purpose, i) we create and implement a computer-based model of interacting agents , ii) we initialize multiple runs, possibly under different initial conditions (parameters), and iii) we analyze the output of the system. Such an approach tests different theories by integrating theory-driven assumptions and comparing the output of the runs with empirical data. We claim this 'synthetic approach' is an excellent supplement to formal theories about dynamic social systems, especially when real-world data is restricted and/or fragmentary (c.f. the quantity problem).

The 'network' aspect signifies that the interactions are structured according to the varying connections between members in the system.[3] By incorporating a heterogeneous social network structure, we add realism and more robust predictive power. As agents differ in connective properties, e.g. the number of ties to other agents or the centrality of their position in the network. This allows us to detect the impact of network-specific properties on their behavioral patterns.

Note that while a number of simulation studies of language change and contact have emerged in the last 20 years (c.f. Clark and Roberts 1993, Briscoe 2000, Hurford 2000, Yang 2000, Niyogi 2002, Abrams and Strogatz 2003, Schulze and Stauffer 2006), many of them do not consider network structure. In contrast, there are three noteworthy articles that we want to discuss, exemplifying how a network simulation study can be done (Nettle 1999, Ke et al. 2008, and Fagyal et al. 2010).

Nettle's (1999) approach simulated the interactive behavior of members embedded in a grid structure, where spatial distance represents social distance and each agent can only possess one of two competing variants of a linguistic item.[4] In each step of a simulation run, each agent can keep her current variant or can adopt the other one based on which one has the higher 'impact' value. This impact value is a combination of i) a social impact value that integrates the number, social status and social distance of other members using this variant[5], and ii) a functional bias of the variant. Nettle tested his system for a range of different parameter settings and came to the following results: i) a full substitution of one variant over the other can only take place when super-influential high-status agents are involved, and ii) a functional bias alone is never enough for a new variant to replace the old one; there is always a high social impact value required.

Ke et al. (2008) criticize Nettle's study on two points: i) they regard Nettle's regular spatial network structure as unrealistic, and ii) they stress that Nettle's results fail to explain a phenomenon which Labov (2001) calls 'changes from below': linguistic change that has emerged in lower social classes, and not only by super-influential, high-status agents. Thus, Ke et al. adopt a light version of Nettle's impact equation, but integrate it in a model of more realistic social network structures: so-called 'small-world networks'[6] (Watts and Strogatz 1998). Their results reveal that a new variant can replace an old one even without super-influential agents, but it must have an enormously high functional bias in comparison to its competitor. In sum, both Nettle (1999) and Ke et al. (2008) used network simulation models to investigate the propagation of a new variant, but both also integrated a functional bias – a network independent value – that plays an important role in their analyses.

The following simulation study can be considered as 'state of the art' in network simulation studies investigating language change: Fagyal et al. (2010) use 'scale-free'[7] small-world networks with directed ties denoting the direction of influence, considering eight different competing variants. Members of the network i) have a status value proportional to their outgoing ties, ii) adopt a new variant of a neighbor (connected member) with a probability proportional to the neighbor's status, and iii) have only one variant at a time in their inventory. Note that Fagyal et al. – in contrast to Nettle and Ke et al. – i) do not consider any functional bias, and focus on the impact of social biases in terms of status, and ii) define status only in terms of network structural features (outgoing ties). This point advances the social network approach by explaining language change in terms of network properties, and Fagyal et al. follow this direction by taking such properties into consideration exclusively.

Their results show first that the propagation of a variant is realized by 'central influential' members[8], something in accordance with Nettle's result of super-influential agents being a necessary condition for society-wide spread of a variant. As a second result, they show that 'peripheral low-connected' members – so-called loners – are the source for innovations. The results of Fagyal et al. therefore support the 'weak tie'-theory to some degree, although they don't show directly that innovation emerges on weak ties. Instead, they show that innovation starts with loners, who are by definition not (strongly) embedded in a dense local structure. These agents are therefore expected to have weak rather than strong ties. Furthermore, they show that innovation spreads via central members, according with the 'weak tie'-theory. This study therefore exemplifies a sociolinguistic application of network simulation studies.

In summary, a network simulation study investigating language change can be conducted as follows: take a social network structure, where the nodes represent individuals (agents) and the ties are possible channels of influence or communication. Next, give each agent an inventory of variants of linguistic items. Then, update this inventory after each step of a simulation run depending on the impact of the variant. This impact can depend on various factors and therefore be defined in multiple ways, along with the design of the network structure, as outlined through the stated noteworthy studies.

Note that these studies have one thing in common: they depict individual language change simply as the mechanism of one linguistic variant replacing another one. Therefore they exclude an essential feature of language: 'communicating' information from a speaker to a hearer (see Mühlenbernd and Quinley 2013). In the next section, we argue for a more concrete design through game-theoretic modeling: the 'signaling game'.

7 Game Theory and Language Change

Only recently have game-theoretic studies featured in sociolinguistics (c.f. Mühlenbernd and Franke 2012, Dror et al. 2013, Ahern 2014). Broadly put, game theory is a branch of applied mathematics concerned with group interaction and decision-making. Game theory's notions of rationality, expected utility, evolutionary stability, and equilibrium have provided a mathematical foundation for understanding how linguistic conventions can emerge and stabilize in a population through the interaction of rational actors. In the last 25 years, 'game-theoretic linguistics' has grown as a field, but it has mainly concerned itself with two subdomains: language evolution and pragmatics (c.f. Jäger 2008, Benz et al. 2011). As an exception, Quinley and Mühlenbernd (2012) used game-theoretic models to simulate a historic case of language contact and diffusion. In a review article (Mühlenbernd and Quinley 2013:129) they argue:

> "[...]when we want to analyze language use in a more concrete way in terms of how it happens, namely by considering the communicative act itself, game-theoretic methods have appeal as a recently well-vetted techniques to model communication."

Many studies in game-theoretic linguistics have implemented the signaling game (Lewis 1969) as a model of communication between a speaker and a hearer. This model depicts an encoding-decoding process, interpreting linguistic conventions as stable systems from which no rational actor would deviate. As speakers choose variants of messages corresponding to their own private information and hearers choose interpretation of those messages, the meaning of each variant emerges as a correspondence between information and interpretation.

The versatility of signaling games in linguistics is documented by a diverse set of applications, e.g. the emergence of semantic meaning in homogeneous populations (Skyrms 1996, Huttegger and Zollman 2011) or in network structures (Zollman 2005, Wagner 2009), the rational basis of pragmatic enrichment like implicatures (Jäger 2007a, van Rooij 2008, Franke 2009), and the evolutionarily stable aspects of case marking (Jäger 2007b) and vowel systems (Jäger 2008). In particular, the utility of signaling games in i) pragmatics on one hand, and ii) language evolution and stability on the other lead us to the claim that applying signaling games for studying language change and variation is a natural progression (Mühlenbernd 2014). To get a good impression of how signaling games can contribute to understanding sociolinguistic phenomena, we refer to Mühlenbernd and Quinley (2013).

Let us elaborate on network simulations with game-theoretic communication models like signaling game. First recall the network simulation model introduced in Section 6, based on the exemplary studies presented there: here an agent adopts a new variant by the virtue of its impact on her. If we model linguistic variants as cultural items that spread in dependence of their functional or social bias, this does not dissociate them from the general propagation process of any other cultural item like opinions, trends or non-linguistic conventions. Modeling the adoption and propagation process of a variant of a 'language item' therefore requires a model of communication between a speaker and a hearer, since it is the success of the communicative act that drives a hearer to adopt a variant and a speaker to propagate it.

Thus, our game-theoretic network simulation model involves communication – via a signaling game – between agents in a network. Since we want to model an adoption process, agents play this game repeatedly and get feedback about the result of the game, thus 'learning' the convention based on this feedback. At this point, the designer has to make an additional choice: how do agents update the feedback information? Here, a number of different 'update rules' have proven themselves as good candidates for models of learning and revising previous information (see c.f. Huttegger and Zollman 2011 for an overview).

It is important to note that many signaling game studies have demonstrated how a particular linguistic convention or behavior emerges, but not how it changes.[9] There are two such studies that apply signaling games in network simulation models for questions of language change (Mühlenbernd and Nick 2013, Mühlenbernd 2014). In these studies the update rule of the signaling game is equipped with an innovation mechanism that allows agents to create new forms based on the success of the actual forms in usage. This leads to the result that linguistic behavior does not necessarily stabilize, but rather persists in continuous change. Mühlenbernd and Nick (2014) used this model on a spatial network structure to simulate the emergence and alteration of regions of local conventions, whose outcome resembled a 'dialect continuum'. In addition, Mühlenbernd (2014) used this model on a scale-free small-world network structure and analyzed the sources of innovation and propagation, according with the results of Fagyal et al. (2010) and the 'weak tie'-theory by J. Milroy and L. Milroy (1985), namely that the sources of innovation are peripheral agents with mostly weak ties, whereas agents in central positions are the most influential ones and therefore instigators of propagation.

To give an impression of how a network simulation model integrated with a signaling game might appear in detail, we will next consider an exemplar for such a study, investigating components of the 'weak tie'-theory.

8 A Simulation Experiment for Reassessing the 'Weak Tie'-Theory

With the following study, we want to exemplify how a computational model can aid the examination of sociolinguistic theories by reassessing particular aspects of the 'weak tie'-theory as introduced in Section 3. Recall that one important network property of the 'weak tie'-theory is the 'strength of a tie'. To analyze this property in a formal, computationally tractable way, it is necessary to give a precise, network-theoretic definition. Unfortunately, it is not clear from the literature exactly how these properties are defined.

According to her pioneering work, Lesley Milroy (1980) considers a tie as weak, if it realizes a relationship of a low degree of multiplexity. In defining the 'weak tie'-theory J. Milroy and L. Milroy (1985) build on a definition given by Granovetter (1973:1361): "the strength of a tie is a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding) and the reciprocal services which characterize a tie." J. Milroy and L. Milroy remark that this definition fits roughly with the assumption of defining tie strength by the degree of multiplexity. In accordance with this position, we denote this definition of tie strength as 'Intensity Tie Strength' (ITS).

However, there are further characteristics of tie strength in the original theory. J. Milroy and L. Milroy also align with Granovetter in the following hypothesis: the stronger the tie between two members, the larger the proportion of common members to whom both are tied. This proportion is also known as the 'neighborhood overlap'. Easley and Kleinberg (2010, Chapter 3) point out that the value of neighborhood overlap is increasing with an increasing ITS value. Granovetter's hypothesis and the indication by Easley and Kleinberg both correspond to the assumption that strong ties are found in structures where a high neighborhood overlap between the members is expected. In this sense, neighborhood overlap can be seen as a local support for the strength of a tie, and therefore tie strength can be defined by this support. We denote the definition of tie strength by neighborhood overlap as 'Neighborhood Tie Strength' (NTS).

Another important feature of a weak tie is its function as a 'bridge': a tie that is the only connection between two communities. Granovetter suggests that "no strong tie can be a bridge", ergo bridges are always weak ties. Since, from a global perspective, communities are generally connected via more than only one tie, bridges are probably infrequent in practice. Granovetter therefore suggests the more realistic idea of a 'local bridge' that has a specific 'bridge degree'. In particular, the degree of a local bridge increases as the number of alternative paths between the members it connects decreases. Since local bridges between isolated communities are an important concept in the 'weak tie'-theory, it is reasonable to define the strength of a tie by its bridge degree, which we denote as 'Bridge Tie Strength' (BTS).

Since J. Milroy and L. Milroy describe a weak tie as i) being a relationship of low intensity/multiplexity, ii) having a low local density and hence a low neighborhood overlap, and iii) being an infrequent and abbreviating connection between close-knit communities (a bridge), they describe a weak tie as a tie with concurrently low ITS, NTS and BTS values. On the assumption that the 'weak tie'-theory is correct, there is a good case to believe that it would be valuable to figure out which of these three tie strengths is mostly responsible for innovation.

Analyzing the properties of a social network in a computational model requires formalizing them. First, we consider a graph structure that allows for determining tie strength in a direct way by providing each tie with a value, generally called the weight of a tie.[10] In this sense, a social network is defined as a weighted graph (G), and $G = (M, T, w)$, where

i) $M = \{m_1, m_2, \dots, m_n\}$ is a set of n members

ii) $T = \{\{m_i, m_k\} | m_i, m_k \in M\}$ is a set of bidirectional ties

iii) $w : T \to (0, 1]$ is a weight function that labels each tie t with a weight $w(t)$, where for all $t \in T : 0 < w(t) \leq 1$

Thus, the weight of a tie must be greater than 0 (otherwise it would be absent) and at most 1. With these prerequisites the three types of tie strength – Intensity, Neighborhood and Bridge Tie Strength – can be defined as follows:

Definition 1 (Intensity Tie Strength) *Given a weighted graph $G = (M, T, w)$. The 'Intensity Tie Strength' ITS for a tie $t \in T$ is defined as follows:*

$$ITS(t) = w(t)$$

Definition 2 (Neighborhood Tie Strength) *Let N_i be a set of neighbors (connected members) of a member $m_i \in M$. Then for a given weighted graph $G = (M, T, w)$ the 'Neighborhood Tie Strength' NTS for a tie $t = \{m_i, m_k\} \in T$ is defined as follows:*

$$NTS(t) = \frac{|N_i \cap N_k|}{|(N_i \cup N_k) - \{m_i, m_k\}|}$$

Definition 3 (Bridge Tie Strength) *Let P_{ik} be the set of all paths*[11] *between every two members $m_i, m_k \in M$, whereby the length*[12] *of a path p is given as $|p|$. Then for a given weighted graph $G = (M, T, w)$ the 'Bridge Tie Strength' BTS for a tie $t = \{m_i, m_k\} \in T$ is defined as follows:*

$$BTS(t) = \frac{1}{1 + \sum\limits_{p \in P_{ik}} (\frac{1}{|p|^2})}$$

Having defined these three tie strength values, the next step is to investigate their impact on innovation. By assuming that weak ties are the source of innovation, it is still an open question as to which of the three tie strength measures contributes most. To that end, we implement here a game-theoretic network simulation model and analyze the contribution of each of the three different tie strengths, under the assumption that these three values are completely independent.

As realistic social networks in human populations have small-world[6] and scale-free[7] properties (c.f. Jackson 2008), we constructed a scale-free network with such properties by a 'preferential attachment' algorithm (Holme and Kim 2002). To have a weighted graph, each tie of the network was labeled with a randomly chosen value greater than 0 and maximally 1. The weight of the tie represents the probability with which each tie is used for communication per simulation step.[13]

During a simulation run, the members of the artificial society communicate repeatedly with their immediate neighbors by way of a signaling game (Lewis 1969), with agents switching systematically between speaker and hearer roles. In the implemented exemplar, members communicate three different concepts to each other through a repertoire of maximally nine different message variants.[14] The members also use a version of reinforcement learning (c.f. Bush and Mosteller 1955, Roth and Erev 1995) to learn the optimal communication strategy. So that innovation can emerge, members deviate from their current strategy with a probability inversely proportional to the efficiency of the local communicative success. This model reproduces a similar study by Mühlenbernd (2014).

For the simulation experiments, we chose a scale-free network with 200 members. We conducted 10 simulation runs, whereby one run entailed 100,000 simulation steps, and in one simulation step the signaling game was played on each tie with the probability defined by its weight. Each simulation run started with a number of pre-established regions of local communication norms (c.f. Figure 3). Members communicated repeatedly, updating their behavior as a function of their previous success.

As a basic result, it turned out that innovation – in terms of a member using a new communication system – emerged sporadically (0.04% of all cases of communication) and sometimes spread to a fair amount of the network. Since we were exclusively interested in the circumstances that support innovation itself, and not spread, we computed the 'innovative support' INV of each tie. The INV value of a tie t is defined by the proportion of events where a node adjacent to t was innovative compared to the total of all communicative events on t. In this sense INV represents the frequency of a tie being supportive to innovation. By calculating the correlation of INV with the tie strength values,

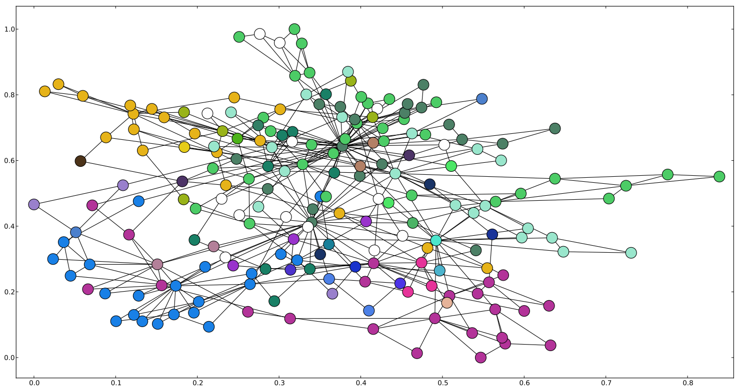

Figure 3: Exemplary scale-free network of 200 members, initially divided in pre-established regions (indicated by color)

(ITS, NTS and BTS) it was possible to deduce which property was most supportive for innovation, and whether there are significant correlations. The results are depicted in Figure 4 as scatter plots between INV, ITS, NTS and BTS (3940 data points).

A T-test revealed that there is no significant linear correlation between each combination. In a further step we computed the 'Spearman'-correlations that detects non-linear correlations. To see if particular tie strength values might impact innovation, we then computed the correlations between INV and each individual tie strength, The results are given in Table 1: the only noteworthy result of the single tie strength values is the correlation between INV and NTS. In a further step we computed the P value for all combinations (Table 1) and

	ITS	NTS	BTS
INV: Spearman correlations	.05	-.3	-.02
INV: P values	.018	$< .001$	.19

Table 1: 'Spearman'-correlations between 'innovative support' INV and the tie strengths ITS, NTS, BTS plus the possible combinations as products.

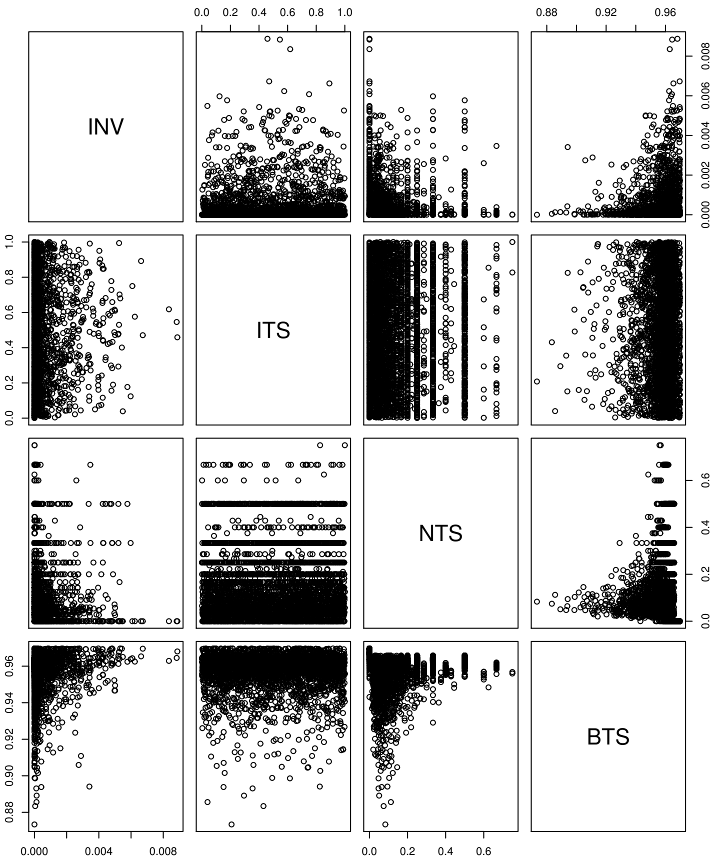

Figure 4: Scatter plots of combinations between 'innovative support' INV and tie strength values ITS, NTS and BTS

only the correlation between INV and NTS revealed an extremely low value ($<$ .001) that is interpreted as absolutely highly significant. In other words: while we found no significant correlation between INV and ITS or BTS, we found a highly significant negative non-linear correlation between INV and NTS. Furthermore, the correlation reveals that INV increases exponentially with decreasing NTS, giving a power law ($x^{-\alpha}$) relationship. This result implies that as neighborhood overlap (NTS) decreases to particularly low values, innovative support (INV) increases.

All in all, our virtual experiments endorse the 'weak tie'-theory under the assumption that tie strength is defined by 'local support' in terms of neighborhood overlap.[15] Conversely, the definition of tie strength in terms of i) 'direct support' like the intensity of the tie usage, or ii) 'global support' like the existence of alternative 'bridges' both fail to endorse the 'weak tie'-theory. This result shows us that the formal precision required to implement these simulations and their subsequent findings can help us unravel the candidates for the drivers of sociolinguistic variation and change.

9 Conclusion & Outlook

We have detailed the various advantages of simulation approaches to language change in an attempt to overcome the obstacles to lengthy and expensive cohort and longitudinal studies. We have further highlighted the benefits of incorporating game-theoretic methods into social network analysis for this purpose. As an example, we presented a study that endorses – under particular assumptions – one of the dominant theories of sociolinguistic innovation: the 'weak tie'-theory.

Although simulation studies cannot substitute for fieldwork, we argue for their incorporation as a valuable supplement to it. We claim this is but the beginning of the promise of game-theoretic methods combined with social network simulations towards augmenting sociolinguistic theories of language change and variation. In particular, theories like linguistic change spurred by competing grammatical heuristics (Kroch 1989, Yang 2000) or partial blocking could lend themselves nicely to simulations in pseudo-evolutionary environments. We emphasize once again, that these studies are not intended to replace field work, but to open up the field of sociolinguistics to a new tool by which it might further advance.

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Notes

[1]In her book "Language and Social Networks", 2nd edition, Milroy mentions on page 178: "Since all speakers everywhere contract informal social relationships, the network concept is in principle capable of universal application and so is less ethnocentric than, for example, notions of class or caste. [...] Since the network concept, unlike the socio-economic class, is not limited by intercultural differences in economic or status systems, it is a valuable tool of sociolinguistic analysis also."

[2]The 'weak tie'-theory is based on the assumption that members that are weakly connected to a social network are i) more likely to come into contact with new variants, and ii) less likely to conform to group norms. The 'weak tie'-theory is empirically supported, for instance by Labov (1973) and L. Milroy (1980). Note that the opposed 'strong tie'-theory (c.f. Jacobsen 1972) says that innovation emerges on strong ties. This is based on the assumption that i) new variants a mainly adopted from network leaders – central and influential members of a network with a high number of strong ties – since their variants are seen as more prestigious, and ii) network leader are more engaged with other leaders from other networks, thus are more likely to adopt new variants. Also the 'strong tie'-theory has empirical support, e.g. by Labov (1989).

[3]Note that simulation studies without incorporating a network structure mostly abstract from this assumption, and each individual can interact with every other one in the society.

[4]Nettle sees linguistic items as 'cultural traits' (c.f. Cavalli-Sforza 1981, Robert and Richerson 1985), that are passed among generations and possibly changed over time by modification or even replacement through a competing item. In general, a linguistic item can be a semantic meaning, a syntactic marking strategy, a phoneme or anything else that represents a particular concepts in of person's language and can be transmitted via communication. Variants of an item are different manifestations of it. One example is the relationship between a phoneme (linguistic item) and the way it is communicated by different phones (variants of the phoneme).

[5]According to Latané's (1981) 'Social Impact Theory'.

[6]Generally speaking, small world networks require a low number of ties needed to connect two members chosen randomly, even if there is a high probability that these members are not connected directly. Formally, a small-world network is given by having two independent structural features: a high clustering coefficient (probability that nodes' neighbors are connected), and a low average shortest path length (node-to-node distance).

[7]A scale-free network structure has a scale-free degree distribution: many nodes with a very low degree, and very few nodes with a very high degree. Such a structure emerges when new members are introduced via 'preferential attachment': they are more likely to connect to members of higher degree, producing a few local hubs of high connectivity and increasingly more nodes with lower connectivity; this gives the graph the scale-free property.

[8]Note that the scale-free property of the network structure ensures the existence of super-influential agents. Fagyal et al. (2010) made also experiments with the absence of such agents and showed that in such a case propagation was strongly limited to local regions.

[9]This is not surprising, since Lewis (1969) introduced signaling games even for the question of how semantic conventions emerge, under the assumption that there is no previous agreement.

[10]While Granovetter himself posited a discrete value for the strength of ties (strong or weak), his definition demands a continuous value, as L. Milroy (1980) remarks. We claim it necessary to consider tie strength as a continuous value and therefore define a network as a weighted graph.

[11]A path in a network is a finite sequence of ties which connect a sequence of members which are all distinct from one another.

[12]The length of a path is defined by the number of members it connects.

[13]Note that to assign the weights to the ties randomly might not contribute to the realism of the network structure, since these weights represent the intensity of a connection, which is surely connected to further network features. But since i) the point of the experiment is to analyze the three tie strength values' impact on innovation independently of each other, and ii) intensity tie strength is defined by the weight of the tie, it is essential to assign this value randomly to ensure its independence from the other two values.

[14]These numbers were a compromise of a relatively large space of alternatives and low computational costs for the update mechanism.

[15]Admittedly, the low P value solely tells us that the correlation is highly likely not due to chance, so to detect the exact relationship between NTS and INV is a task for further analyses.