

Christaller and "big data": Recalibrating central place theory via the geoweb

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Abstract

This paper utilizes central place theory (CPT) to navigate the "deluge" brought about by big data. While originating in the 1930s, CPT is a theoretical monument of 1960s spatial science. CPT aims to understand settlement geographies based on consumption behavior, and often presented as a singular, outdated, rationalist theory. After critically reviewing the history of CPT, we assess the microfoundations of Christaller's CPT—the threshold and range of goods—for various central functions in Louisville, Kentucky. The microfoundations are estimated through data from social media platforms Foursquare and Twitter. These sources alleviate many of the operationalization issues that traditionally hamper empirical use of CPT. The empirical application of CPT reveals that: i) Central functions have typical ranges and thresholds relating central places to population spread; ii) Central functions cluster based on an approximate hierarchical structure. The findings indicate the ongoing importance of CPT in shaping urban-economic geographies.

Keywords: Central place theory; big data; Twitter; Foursquare; Louisville, KY

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1. Introduction

1.1 Central Place Theory's relevance in a big-data era

A big challenge in contemporary analytical geography is dealing with the information overload associated with handling big data. How do we navigate the seemingly infinite analytical possibilities offered by the sudden availability of huge largely-unstructured datasets? and how can theoretical propositions guide in asking the right questions? (Crampton et al., 2013; Kitchin, 2013; 2014). Due to the technological focus of many big data debates, it is sometimes overlooked that geography has been here before (Barnes, 2013; Graham & Shelton, 2013). In the 1960s, during the "spatial science" quantitative revolution, geographical theory and models were mobilized to guide geographers through the information torrent generated by the emergence of computers and advanced statistical methods, which had "exploded the data matrix" (Haggett & Chorley, 1967). Theory alleviated information overload by providing a "mental picture" that suggests which of the infinite possible patterns and associations to study (idem, 32). Fast forward 50 years and geography is confronted with a similar situation as big data has exploded the data matrix again.

Of the spatial science theories, Walter Christaller's ([1933] 1966) Central Place Theory (CPT) is iconic. CPT describes the possible relations between population distribution and the provision of central functions—procurement of goods and services subject to the friction of distance experienced by the consumer. These possible relations depend on the interplay between the minimum number of customers necessary for a central function to exist (the threshold of a central good) and the maximum distance a consumer is willing to travel to obtain a central function (the range). This interplay defines a theoretical hierarchical distribution of settlements. The resulting ideal landscape, with its characteristic hexagonal geometry, can be compared to empirical observations (Rushton et al., 1967), which provides a partial explanation for settlement geographies.

The iconic, monumental, status of CPT has several connotations. William Bunge, a prolific ambassador for spatial science, dedicated the epitomic *Theoretical Geography* to Christaller stating that "the initial and growing beauty of central place theory is geography's finest intellectual product and puts Christaller in a place of great honor" (Bunge, [1962] 1966, p. 133). However, after the critical turn of the 1970s, CPT became a different kind of monument. To some, CPT exemplified what was wrong with spatial science as "counter-revolutionary" theory, for instance when Harvey (1972, p. 6) declared that "yet another attempt to identify the range of a good, serve[s] to tell us less and less about anything of great relevance." For humanistic geography, CPT was the example of how spatial science led to austere formulations "which have limited value in understanding real world situations" (Guelke, 1978, p. 50). Although CPT continued to be widely studied throughout the 1970s before output started tapering off, another meaning of the term monument—that of some musty artifact

which belongs in a museum and needs to be retired (Blotevogel, 1996)—gradually emerged. This meaning is implied by Scott (2012, p. 31) when he states that the "rather rapid fall of central place theory from grace can almost certainly be understood by the fact that even given its internal logical coherence, it has so little to say about the great issues of urbanization and regional development that we face in today's post-Fordist world, apart from some modest continuing applications in retail geography."

The few contemporary studies (e.g. Boussauw et al., 2014; Dale & Sjøholt, 2007; Morrill, 1987; Neal, 2011; Shearmur & Doloreux, 2015) that apply CPT all find meaningful associations between central functions and settlements, thus casting doubt on the theory's alleged obsolescence. It seems that Christaller's ([1933] 1966, pp. 100-107) speculations on how car ownership and changing retail modes (i.e. mail order, idem, p. 49) might influence the central place system have stood the scrutiny of time. Nevertheless, although the above-cited studies are empirical, they engage with central place analysis on the macro level, where they tend to assume rather than examine the contemporary validity of CPT's microfoundations: the interplay between range and threshold.

The aim of this study is to fill that gap by gauging the endurance of CPT's microfoundations through the use of big data and analytic capabilities that were unheard of in the 1960s. The corollary result is an exploration into how CPT can provide structure to analyze big data. However, before commencing, we have to manage expectations as these were—perhaps unsurprisingly with a monumental theory—too high in the past. Whereas Christaller ([1933] 1966, pp. 16-17, 139, 198) repeatedly stresses the restricted scope of his theory, "a whole generation of geographical theorists has sought to account for almost any economic geographical pattern on the basis of central-place notions" (Vance, 1970, p. 5). CPT addresses the location of central functions, is a partial theory of settlement structure, and does not have the pretension to explain populations and/or cities in their totality: a central place is not a city (Carol, 1960; Preston, 1975). A second necessary prelude is recognizing that there exists no singular "rationalist" (Barnes, 2003) CPT. CPT has become entrenched in geography's collective consciousness through canonical, but always partial, interpretations of the theory (e.g. Beavon, 1977; Berry, 1967; Berry & Garrison, 1958a; Berry & Pred, [1961] 1965; King, 1984; Vance, 1970). It is not difficult to find contradictory statements regarding any aspect of CPT in the vast literature the topic has spawned in eighty years. For instance, Saey (1973) argues that Christaller ([1933] 1966) and Lösch ([1940] 1956) are fundamentally different theories built on different axioms and hence attempts (e.g. Beavon, 1977) at reconciling the two run into difficulties. Neglecting this variety has spawned many popular myths—such as the theory's alleged "staticness" (addressed by Preston, 1985)—around CPT.

In this paper, apart from mythbusting, we explicate some of these incompatible interpretations and propose reconstructed CPT—relatively close to Christaller's original—that answers to some post-positivist critiques (e.g. Barnes, 2004a; 2004b). We contextualize these

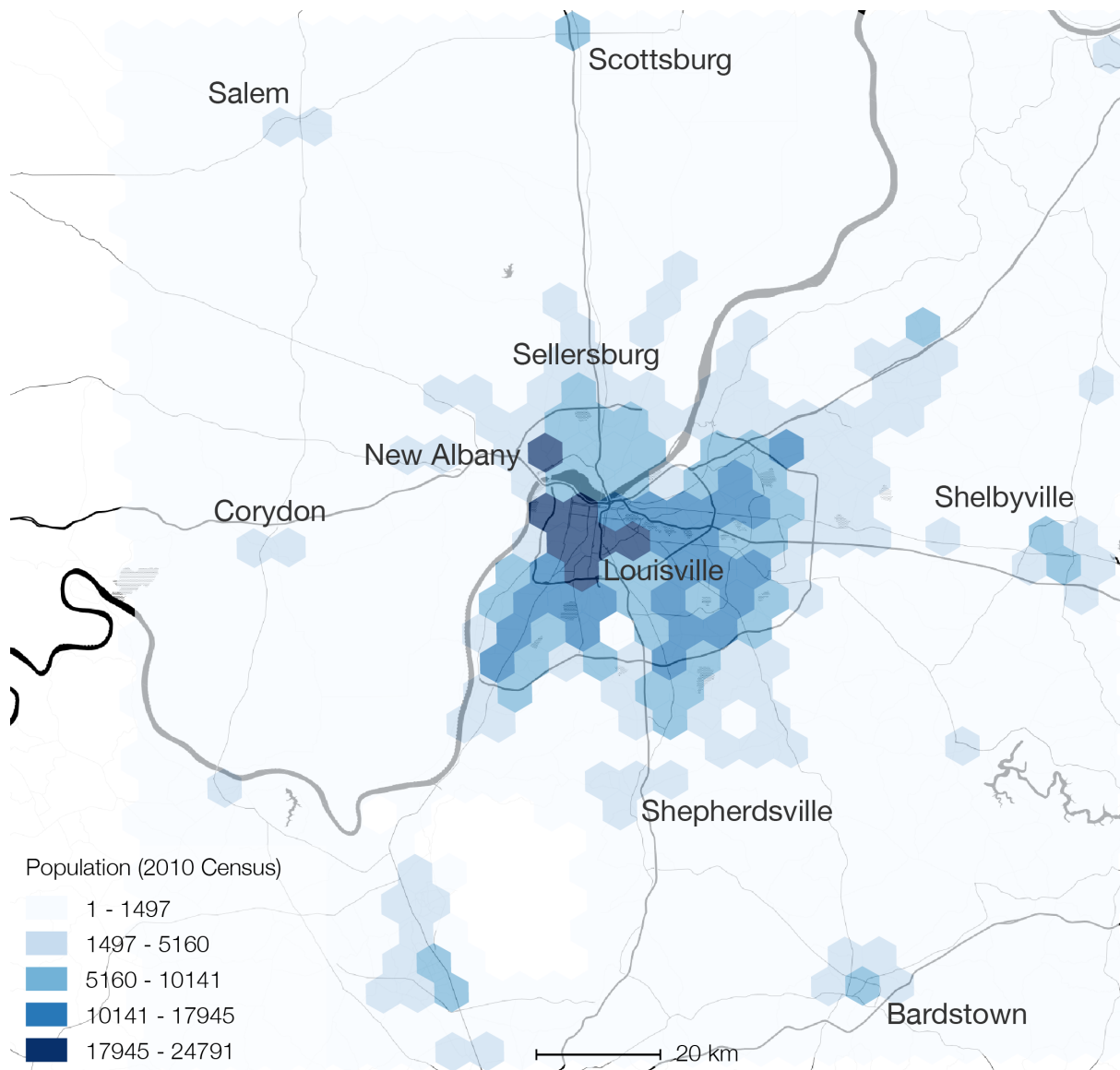
theoretical issues empirically by studying the central place system of the metropolitan area of Louisville, Kentucky, utilizing data harvested from the social networking platforms Foursquare and Twitter.

1.2 Louisville, KY as an "ideal" case study

Louisville, Kentucky's largest city, is a fairly typical American city. Like any existing city, Louisville is far removed from Christaller's ideal landscape, but it is nevertheless a particularly "clean" case to study contemporary central place patterns. Throughout the city, the car is the primary mode of transportation, even for shorter distances, which allows us to restrict our analysis to a single mode of transportation. There are two specific noteworthy geographic features that "break" an otherwise fairly uniform urban fabric and might influence our results. The first feature is the Kentucky-Indiana state border, which follows the meandering Ohio River that cuts midway through the metropolitan area (see Figure 1) and can only be crossed by bridge. The second is the economic and racial segregation within the city. Like many of its peer cities, Louisville is still coping with the consequences of a long history of racial segregation, which is manifested in an East-West divide. Neighborhoods in the western part of the city are predominantly home to less affluent African-Americans, while the suburbs in the east are inhabited by more affluent and often white residents (Shelton et al., 2015). Since these geographical features provide a set of contrasts that can assist in gauging the relevance of CPT, we deliberately included them in the analysis. Therefore, we define our research area as confined within a relatively large bounding box¹ that includes not only Louisville itself but also the surrounding smaller towns.

Although CPT is a well-trodden theoretical path in human geography, CPT's multiple interpretations necessitate a brief review. After elaborating the relevant epistemological choices (Section 2), we reconstruct the theory (Section 3). Sections 4 and 5 operationalize the theoretical constructs and provide results for the level of individual central functions and the Louisville settlement geography. Section 6 concludes with a discussion of the usefulness of CPT for understanding contemporary settlement geographies.

Figure 1. Base map and population density of the study area



2. Theoretical considerations

2.1 The 'messy' history of Central Place Theory

The irony of CPT being the iconic theory of 1960s US-based spatial science, is that the theory originates neither in the US, nor in the 1960s. CPT is the result of Walter Christaller's ([1933] 1966) dissertation, which was written during the early 1930s, and which infused ideas from Weberian location theory in German geography (Christaller, [1968] 1972). Contrary to popular myth (the origin of which is explored by Taylor, 1976), the theory was not neglected in western Europe and spawned different offshoots and policy proposals during its early years (Bobek, 1938; Brush, 1953; Dickinson, 1947; Müller-Wille, 1978; Rössler, 1989), including Christaller's involvement with Germany's Nazi regime (Barnes & Minca, 2013; Rössler, 1989). This early diffusion of offshoots has contributed to a wide variety of central place theories

that show differing degrees of affinity and compatibility with Christaller's original version (Buursink, 1975). Therefore, any contemporary assessment of CPT needs to be appreciative of the changing epistemological currents in geography in different places in the world.

Barnes (2004b) argues that different epochs of human geographical praxis adhere to different styles of theorizing of which he explicates two polar varieties: "epistemological theorizing", which characterized spatial science in the 1960s, and "hermeneutic theorizing", exemplary of the 1990s cultural turn. Barnes (2004b, p. 546) defines epistemological theorizing as "the belief that the central task of theorizing is to develop abstract vocabularies that mirror—albeit approximately—an external and independent reality." Hermeneutic theorizing, by contrast, "is not [...theory...] as a mirror held up to the world, but [...theory as a frame for...] conversation and discussion" (idem, p. 547). Barnes (idem, p. 549) treads carefully and emphasizes that the two are not mutually exclusive and that both have contested, complex, and overlapping histories. Although during the 1960s, CPT was widely held up as the "seminal example" of the new style of (epistemological) theorizing (Bunge [1962] 1966), CPT's role as a "selection mechanism" to navigate the data deluge (Haggett & Chorley, 1967, see above) clearly has hermeneutic overtones. Moreover, as the 1960s progressed, how CPT was utilized gradually changed. In the early 1960s, it contextualized tabulations of amenities, ranges and thresholds, culminating in concrete settlement geographies. As the decade progressed, assumptions were increasingly postulated rather than tested and formulations increasingly started to rely on calculus (e.g. compare Rushton 1966 and 1972), perhaps alienating description-inclined geographers (Lukermann, 1961; Curry, 1967). This gradual evolution towards more epistemological theorizing became the stereotypical depiction of the era as a whole, thus muting many in-between positions in disciplinary historiography.

However, can we safely claim that Christaller in the 1930s intended to create this "mirror" associated with epistemological theorizing? We contend that this inference needs careful scrutiny. Christaller ([1933] 1966, pp. 4-7) explicitly situates himself methodologically in the German location theory tradition of von Thünen and Alfred Weber, and describes his theoretical central place landscape as an "ideal type" referring to Max Weber (idem, pp. 4-5, 9, 200). Gregory (1981; see also Saey, 1978, p. 17) notes that Alfred Weber was re-cast in an overly positivist vein in the 1950s and 1960s, and similar observations have been made about translations of von Thünen (by Peter Hall, see Mäki, 2004) and Max Weber (by Talcott Parsons, see Tribe, 2007). Indeed, Carlisle Baskin—Christaller's English translator—admits difficulty and reliance on Talcott Parsons in translating key methodological terms from German to English (Baskin in Christaller, 1966, p. 4). According to Mäki (2004, p. 1720), these German authors utilize the:

[C]ombined method of isolation [...through abstraction...] and de-isolation [...where...] theorizing proceeds first by stating a set of assumptions that are known to diverge from the actual characteristics of the real world, and then by relaxing these assumptions one by one so as to approach a more concrete and complex picture of reality.

Therefore, Mäki (2004) argues that the underlying "ideal landscape" needs to be regarded as a "causal structure" in the realist sense that contingently influences a more complex reality. As Christaller (see Preston, 1985) utilizes a similar methodology, CPT's merit is gauged through investigating its underlying causal mechanisms (see also King, 1984, pp. 76-78; Webber, 1971), instead of matching the ideal landscape to an observed comprehensive settlement geography. This interpretation of CPT's methodology is less rigid as the one commonly applied in spatial science, as exemplified by Christaller's ([1933] [1966], p. 70) explicit skepticism about the over-use of mathematical formulations. According to Christaller, mathematics would suggest undue precision.

Although CPT has antecedents in German geography (Müller-Wille, 1978) and French location theory (Zhong et al., 2017), wedding Weberian abstraction with German geography was innovative. A telling example of this novelty is Christaller's ([1933] 1966, p. 1) opening statement that he wants set aside the then-ubiquitous debate on the urban-rural relation (see also Christaller, 1938), a move explicitly criticized by Bobek (1938). This abstraction from agricultural relations raises doubt about the claim that Christaller's CPT is rooted in Germanic "rural romanticism" (Barnes & Minca, 2013). This alleged rural focus of Christaller can be traced to a conflation of the central place theorems of Lösch and Christaller, probably originating with Ullman's (1941) influential statement. According to Rössler (1987, p. 423), it was the absence of such rural romanticism that fostered an initial dislike of CPT among the Nazis. Perhaps resultantly, Christaller emphasized the rural connection in later CPT statements when he worked in the Nazi bureaucracy (Rössler, 1987; Barnes & Minca, 2013).

Nevertheless, it is important to stress that Christaller is not the only current variety of CPT. After the 1960s various offshoots have been developed that try to incorporate CPT in more abstract theoretical terms, for instance subsumed in a theory of spatial interaction (Wilson, 1970, Zhong et al., 2017) or in a general theory of agglomeration economies (Eaton & Lipsey, 1982; Fujita et al., 1999; Mulligan et al., 2012). Although we are not dismissive of these attempts in any way, it is important to note that they do not necessarily start from Christaller's microfoundations, and therefore might elaborate different explanations for settlement patterns.

2.2 Reconstructing Central Place Theory

Summarizing, CPT is a tree that has branched out in many incompatible directions (Buursink, 1975) necessitating revisionism and taking sides in some major controversies surrounding the theory when assessing its contemporary value. The "best" choice when revising depends on one's own epistemological position and research aims. Our goal is to gauge the contemporary relevance of Christaller's CPT while leveraging the availability of big data. Resultantly, we embrace method innovation and shed analytical procedures that have become technically obsolete. Nevertheless, theoretically, we will primarily base ourselves on Christaller's 1933 "first cut" of CPT without reinterpreting that first text through scattered remarks in his later

writings which are likely to be influenced by the political and academic contexts he was working in after 1933 (Scott, 2012).² These aims lead to the following set of methodological considerations:

- Big data allows analyzing relationships between people and their procurement of central goods independent of administrative boundaries. As GIS is available to analyze central functions and places of residence as point locations and calculate time-distance over the road network, we do not have to define settlements *a priori*, although we are bound to the US census block level to assess population densities. Consequentially, the dichotomy between intra-urban and inter-urban CPT (Beavon, 1977; Berry, 1967) becomes superfluous.
- Consequently, the difference between nodality and centrality loses relevance. Nodality and centrality are defined as those parts of the central function that respectively provision the focal settlement (nodality) and its hinterland (centrality) (Barton, 1978; Preston, 1971). Since we no longer have to define the inside and outside of settlements within our study area, this problem disappears.
- Calculating real travel time over the road network from consumer to central function has become a standard GIS operation. Hence, fitting central place patterns in ideal-typical geometrical constellations (i.e. Christaller's iconic hexagonal patterns) becomes analytically less important. It has been a longstanding assessment that real-world geographical features rapidly distort CPT's hexagonal geometries beyond recognition (Rushton, 1972). Consequently, we are less interested in finding exact geometrical patterns and focus instead on the degree to which we find systems that conform to the microfoundations of CPT (Christaller, [1933] 1966, pp. 27-58; Storbeck, 1988).
- For operationalization, we no longer need to assume that customers frequent the nearest center. Christaller ([1933] 1966, pp. 43, 50) was explicit that in reality people engage in multi-purpose shopping and thus not always frequent the nearest center, but he had to assume it when empirically operationalizing his theory. With GIS, we can easily detect overlapping catchment areas of central functions and their effects, which are unavoidable now that we assign exact locations to central functions. Relatedly, we no longer have to assume that centers of higher levels encompass all lower level functions. Instead, the degree of encompassment becomes an empirical question allowing analysis of functional complementarity endogenously in central place analysis (van der Meulen, 1979; cf. Lambooy, 1969).
- CPT, being a theory of settlement geography, provides a snapshot of a co-evolutionary process between the respective location of consumers and central function providers (Clark & Rushton, 1970; Dale & Sjøholt, 2007; Saey & Lietaer, 1980). Hence, CPT is neither reducible to consumer preferences nor to entrepreneurial decision-making. It regards emergent properties that can only be grasped on the level of the central place system. Resultantly,

inferring individual consumption behavior from the system would be an ecological fallacy, as the wide literature on multi-purpose shopping testifies (e.g. Sheperd & Thomas, 1980).

- A reconstruction of CPT has to acknowledge potential pitfalls. For instance, central place systems are strongly influenced by differences in consumer profiles and spatial variations in purchasing power (Christaller, 1933 [1966], pp. 52-55; Johnston, 1966a; 1966b; Rushton, 1966). Administrative borders also refract central place systems (Ray, 1967). Nevertheless, for methodological reasons, we will infer the spatial behavior of a "generic customer" for specific central functions (King, 1984, pp. 77-79; Saey and Lietaer, 1980). Therefore, we can expect that aberrations to the anticipated relations between central functions and population distributions are related to the particularities of the Louisville area (i.e. Louisville's east-west divide and the influence of the Ohio river mentioned above).
- The patchy quality of big data sources (Crampton et al., 2013) necessitates prioritizing internal over external validity. Neither research goal—gauging microfoundations and providing a proof of concept of combining CPT with big data—requires a comprehensive mapping of the central place system of Louisville, which would be difficult to attain given the quality of the available data and the intricacies of operationalization.

3. Microfoundations of Christaller's central place system

Christaller elaborates his theory in two stages. In the first stage, Christaller ([1933] 1966, pp. 27-58) discusses how the distribution of population, the supply of central functions, and the willingness to procure these functions generate function-specific central place landscapes. Subsequently, Christaller ([1933] 1966, pp. 58-80) theorizes how these individual ranges might add up into distinctive hierarchical patterns of central places. We elaborate our interpretation of the theory in the same order, starting with the microfoundations before conjoining them into a larger system.

Christaller's CPT concerns itself with the question how the spatial distribution of the population in an area can possibly be related to the provision of central functions to this population. A central function, which can concern a good or a service, is defined as social activity that is procured at a central point (place) and for which the consumer has to bear the costs to reach that point. Typical examples on the consumer level are shopping and hospitality services, but certain business services or enterprise procurement may also be central functions (Dale & Sjøholt 2007; Parr, 2002; Shearmur & Doloreux 2015). Different central functions have different ranges. This range has an upper and a lower limit. The upper limit consists of the maximum economic distance a consumer is willing to travel before deciding to substitute or forego consumption, i.e. the distance-weighted elasticity of demand (Christaller, [1933] 1966, p. 53). The lower limit consists of the minimum scale of consumption necessary for a central function to remain in business. Following the influential treatises of Berry and Garrison (1958a; 1958b; 1958c), the upper limit of the range is simply called "range" while

the lower limit of the range is called "threshold".³ The geographical area served by a central place is the "complementary region" (Christaller, [1933] 1966, pp. 21-22). It is evident, assuming *ceteris paribus* operating costs, that the threshold is reached more quickly in areas with higher population density, whereas the range is independent of density. The variable interplay of range and threshold determines the possible supply of central functions in particular places (Christaller, [1933] 1966]; Johnston, 1966a). This interplay already allows the inference that central functions likely agglomerate in denser areas. More diverse combinations of thresholds and ranges will be achieved there, suggesting hierarchical tendencies. It is from these hierarchical tendencies that Christaller ([1933] 1966, pp. 58-80) constructs his iconic hexagonal landscapes. However, CPT's analytical utility reaches further once we take into account that actors make choices.

The landscape of ranges and thresholds is a geographical opportunity structure that determines which central functions are viable to be provided to which parts of the population. Within this geography of potential central function provision both consumers and entrepreneurs make choices to (re)locate, which consequently gradually alters the landscape (Barton, 1978; Morrill, 1963 Parr & Denike, 1970). When a central service provider wants to improve its location only taking the distribution of the potential consumers in mind, we can theorize two opposite maxims to act upon the opportunity structure, which Saey (1990) calls the "Hotelling" and the "Lösch maxims" (see Ó hUallacháin and Leslie, 2013; Parr and Denike, 1970, for similar arguments with different nomenclature). On the one hand, a central function provider might want to monopolize the market, or make sure that all potential customers in a particular area frequent the provider's central function and not the competitor. The associated spatial logic is to locate as far as possible from your competitor. If all central function providers would behave this way, the range becomes equal to the threshold resulting in theoretical Löschian landscapes (Lösch, [1940] 1954; Saey, 1973), hence the name "Lösch maxim". On the other hand, a central function provider might choose to optimize the total number of potential customers. In this case, the best place to locate would be where the highest number of potential customers congregate, even if this is also the most logical place for competitors to locate. The situation that thus emerges is explicated by Hotelling (1928).⁴ Instead of monopolizing the market, competition between the co-located suppliers occurs. One would expect that this competition results, through a division of labor between suppliers, in specialization of and complementarity between suppliers. Resultantly, the variety of central functions offered at the central place increases and the central place becomes more attractive, better equipped, and rises in the hierarchy as a result.

Which of the two maxims would optimize profits depends on the kind of good. The higher the spread between the range and the threshold of a good, the higher the potential for specialization of suppliers and hence for the consumer to engage in comparison shopping. By contrast, for goods with a low spread between range and threshold, closeness of supplier is more important than specialization resulting in convenience shopping. Therefore, the classic

distinction between convenience goods and shopping/comparison goods in CPT (Beavon, 1977; Curry, 1962) retains its usefulness, where central function patterns are hypothesized to be more spread out with convenience vis-à-vis comparison goods. The agglomeration tendencies based on these maxims clarifies Christaller's ([1933] 1966) insistence on step-wise discrete categories of central places.

To simplify empirical research, Christaller ([1933] [1966], p. 64) makes the pragmatic assumption that "central places of a higher order also contain all the central functions of the lower orders", what Parr (2002) calls the "successive inclusive hierarchy". In his 1933 book, Christaller never explicitly mentions "hierarchy", but only articulates the relation between two places: one place is of a higher order than another, by which he wants to convey that there are discrete size categories of central places. The word "hierarchy" gradually emerges in the ensuing CPT discourse (Buursink, 1975), and is used by Christaller (1950) himself in a later introduction to the theory. Eventually the hierarchy concept is declared to be the "generic base and single most important statement of central place theory" by Berry and Garrison (1958c, p. 146). Until today, the potential absence of this successively inclusive hierarchy of central places is an argument to question CPT in its totality (e.g. Meijers, 2007). Although the notion of complementarity (Ullman, 1956) is at odds with the notion of a successively inclusive hierarchy, it is not at odds with the notion of hierarchy as such (van der Meulen, 1979).

Complementarity between two central places occurs when both places contain a central function that the other does not have and for which a demand exists—within the parameters of range and threshold of both central functions. At that point there is "symmetrical" exchange between places inducing complementarity in these places' relation⁵ (Limtanakool et al., 2007). In other words, the successively inclusive hierarchy that was convenient for Christaller and became dogma for Berry and Garrison (1958c) needs to be re-interpreted as an extreme case of non-complementarity (van der Meulen, 1979; Saey, 1990). The most important consequence of the re-conceptualization is that "hierarchy" and "complementarity" cease to be each other's conceptual opposites (Lambooy, 1969) as hierarchy refers to the relative dominance of one place over others in the total supply of central functions.

It was already evident to Christaller ([1933] 1966, pp. 100-101), that as technology evolves central goods might change, as do the costs of procurement (Morrill, 1963). Although e-commerce did shake-up the retail landscape in the last decades, it did not render central place activity superfluous, but rather changed the relative importance and range of certain central functions (see Aoyama, 2001; Rotem-Mindali and Weltevreden, 2013; Wrigley et al., 2002). Resultantly, it is to be expected that the structure of the central place system changes over time, but this does not make fundamental logic of CPT superfluous. For example, changes in range, threshold and travel modality might make a shopping mall on the border of a

metropolitan area a more important central place than the historic city center. A revamped CPT can account for this gradual "displacing" of centrality in cities if it does not rely on administrative borders, a liability big data can circumvent.

4. Operationalization and results I: Range and threshold

4.1 Data Collection and Preparation

We conduct our analysis of the microfoundations of CPT in a similar stepwise manner as Christaller ([1933] 1966). This section starts with an analysis of the range and threshold of individual central functions to examine the applicability of the Hotelling and Lösch maxims. In the subsequent Section 5 we regard the interplay of central functions and the settlement system of Louisville and its environs. To conduct this analysis, we make use of several fairly unconventional datasets in this context, derived from social media platforms.

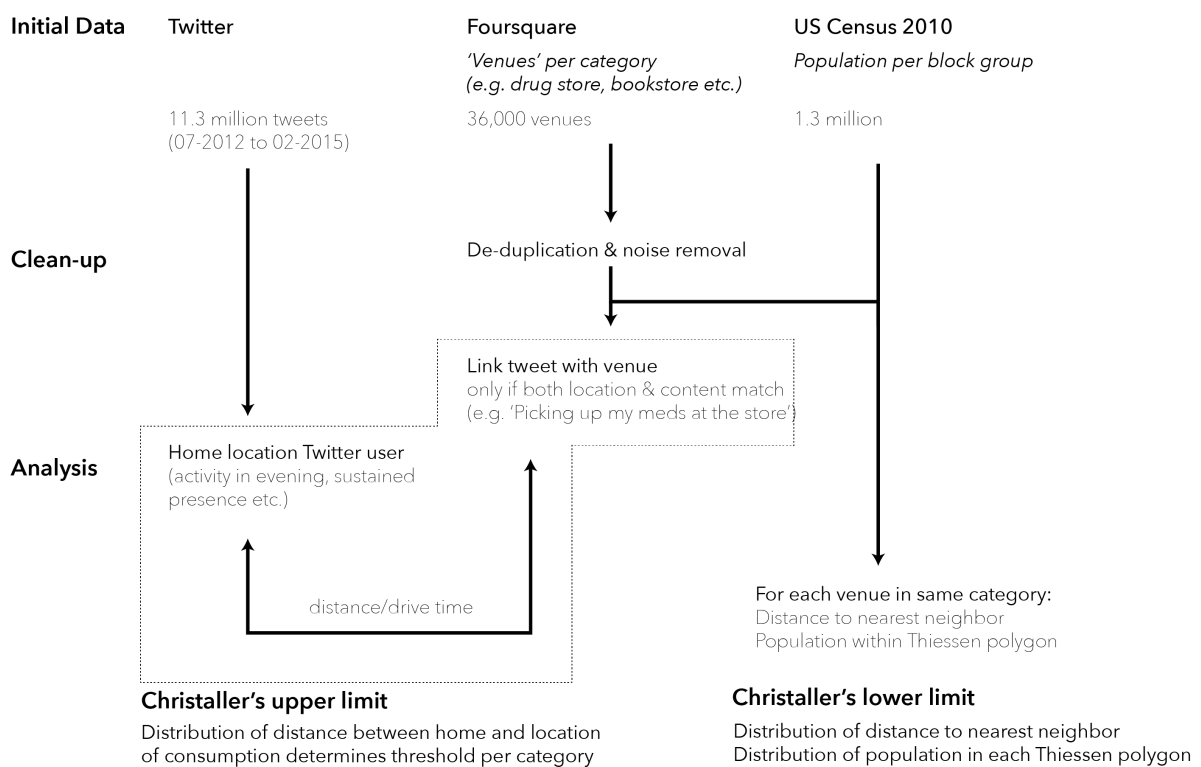
Since the emergence of Web 2.0, geographers have paid close attention to the ever-increasing amount of data generated through a myriad of platforms enabled by new technologies. Goodchild (2007) coined the term "Volunteered Geographic Information" (VGI) to indicate how many of these platforms allow ordinary people to create spatial data, which was formerly the prerogative of governmental or commercial "experts". Whether or not people create this data consciously and willingly is unclear (Elwood, 2010), and its accuracy and applicability is certainly not guaranteed (Haklay, 2010). Whatever name is used to refer to them—big data is the *nom du jour* (Kitchin, 2014)—these data shadows (Dodge & Kitchin, 2005; Shelton et al., 2014) both reflect and produce the social world in general, and people's spatial behavior in particular (Shelton et al., 2015; Silm & Ahas 2014).

This analysis utilizes data shadows of two sources. The first is a Twitter-based dataset of all geotagged tweets (~11.3 million) sent from Louisville between July 2012 and February 2015. Twitter data is used to determine whether a person at a specific location is indeed "consuming" a certain a good and to estimate a person's home location. Second, we use a dataset derived from Foursquare to derive the locations of specific central functions ("venues" in Foursquare's parlance). Data on the location of businesses across different industries is relatively hard or expensive to acquire from more conventional sources, especially when administrative boundaries are crossed. As the location of specific venues is instrumental to Foursquare's core business, the location data used here can be assumed to be relatively accurate, especially after the cleaning steps discussed below.

An advantage of these geoweb data sources is that they are generally unconstrained by administrative boundaries. This allows for replication of this study in other cities where comparable data is available, or at other scales. A seeming disadvantage is the potential bias present within such data (Li et al., 2013; Longley et al., 2015). Depending on the kind of tweets and spatial context, different biases in representativeness can occur, which are not

straightforwardly similar across contexts. For instance, contrary to the thrust of the main conclusions of Li et al. (2013), in Louisville, underprivileged groups were sufficiently represented in samples of locally georeferenced tweets for Shelton et al. (2015) to draw inferences about the spatial mobility of these groups. Therefore, biases in the representativeness of this data are likely, but their direction is uncertain. However, as our study limits itself to a "proof of concept" of the interplay between threshold and range, and given that we do not aspire to describe a comprehensive model of the Louisville central place system, the influence of the bias is not likely to harm our general conclusions. Of course, this warrants additional attention—and triangulation with additional data sources—in follow-up studies, especially before this approach can be used for comprehensive modeling of central place systems.

Figure 2. Operationalization of range and threshold



We will now go over the steps how the two datasets (tweets and venues) help operationalize the range and threshold (Figure 2). There are 36,101 venues within our research area in Foursquare's database. Each venue can belong to several categories. Foursquare maintains a hierarchical category list⁶ that contains main categories such as "Arts and Entertainment" and "Food", and sub-categories such as "Bowling Alley" and "Ethiopian Restaurant". Our research goal prioritizes internal over external validity and does not aspire comprehensiveness. This implies that whenever in the operationalization process a manual judgment call had to be made, type I errors (false positives) were avoided at all cost at the expense of making type II errors (false negatives). This played an important role in the selection of the central functions

studied. After a trial and error process, we manually selected 10 categories that are hypothesized to cover a range of different combinations of range and threshold (see Table 1). The second column in the table indicates whether we expect that category to be a comparison or a convenience good. In all subsequent Figures, comparison goods are indicated in orange shades (and where appropriate the shopping bag symbol) while convenience goods are indicated in purple shades (and where appropriate the shopping cart symbol). The categories can all be classified as "retail", are relatively unambiguously categorized within Foursquare's taxonomy, and are relatively likely to be tweeted about. Since Foursquare's data contains duplicates, miscategorized venues and non-existing venues, we used a set of de-duplication rules that look at both the physical distance between venues and the similarity of the name of each venue. If both physical and semantic distance is very small, it can be reasonably assumed to concern a duplicate. Since the total number of venues for the ten categories is relatively modest, after this de-duplication we manually checked each venue to ensure it is indeed a real business. We discarded the venue in case of any doubts to prevent false positives. The third column in Table 1 reflects the final number of venues in each category.

To determine each category's threshold, we take a two-tiered approach. First, we calculate the distance to the nearest neighbor of the same category for each venue, as the distribution of these distances allows inferences regarding the Lösch and Hotelling maxims. Second, to compensate for differences in the underlying population distribution, we calculate a Thiessen polygon⁷ for each venue and determine the approximate population in each polygon. This is done by using population data from the 2010 Census on the block group level. Block groups are the smallest areal unit for which this data is available (~33,000 block groups within the research area; a total of 1.3 million people). Together these two indicators can estimate the (relative) threshold value of central functions.

To determine the range, we first need to establish the most likely home location for each Twitter user in our dataset, and subsequently try to determine definitive links between a specific tweet and consumption at a specific venue. These steps are outlined graphically in Figure 3. To determine home locations, a grid of 600 meter hexagons is laid over the study area and tweets are joined to the grid cells. Users with less than 20 tweets during the study period are discarded as data would be too scarce for subsequent steps. To determine home location, not only the raw number of tweets per grid cell is taken into account but also whether the temporal pattern can be considered as "home"-like (as detailed in Figure 3, see also Ahas et al. 2010). The 11 million tweets in the dataset are sent by a total of 133,168 users. We are able to determine the home location for only 15,506 users in this way—recall that thresholds are purposely strict as we try to minimize type I errors.

Table 1. Properties of central function categories in dataset

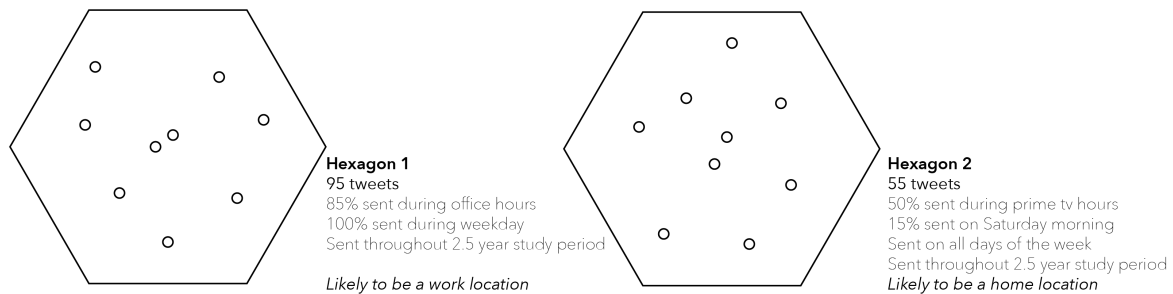
Category	Type of good (expected)	# of venues	# of user-venue pairs	Threshold (Skewness Population Distribution)	Range (Third Quantile Drive Time)
Bookstore	Comparison	49	139	0.42	21.0
Clothing Store	Comparison	516	4784	0.44	22.5
Drugstore	Convenience	142	453	0.09	17.3
Furniture & Home	Comparison	293	1431	0.44	20.0
Grocery Store	Convenience	110	410	0.21	20.5
Hobby Shop	Comparison	55	220	0.41	20.9
Jewelry Store	Comparison	72	257	0.47	22.5
Liquor Store	Convenience	205	130	0.24	20.2
Nail Salon	Comparison	103	67	0.30	19.4
Supermarket	Convenience	106	652	0.20	19.3

To determine whether a specific tweet sent from around a venue indeed means that consumption has taken place, we select all tweets sent from within 25 meters of the venue. The goal is to match tweets to venues not only based on location but also based on the tweet content (see Figure 3). To do so, we manually code a random sample of 1,000 tweets for each category and indicate for each one if the content of that tweet indicates consumption within that category. This sample is then used to train two supervised machine-learning algorithms (Support Vector Machine and Generalized Linear Model). If both algorithms agree AND they are more than 90% certain that a tweet contains content related to a category (e.g. "Picking up a new dress!"), we consider it a match. We also consider tweets a match if the name of the venue is mentioned directly in the tweet text. This ultimately results in pairs of user home locations and specific venues for each category (fourth column in Table 1). For each pair, we finally calculate the car travel time between the two points to make the road network endogenous to our analysis of the range.

Christaller discussed the range of goods as "typical ranges" by "generic" or "average" customers (Christaller, [1933] 1966, pp. 33-35; see also King, 1984; Saey & Lietaer, 1980). While there is always the proverbial outlier who will travel 100 kilometers to buy a croissant, there is a typical maximum distance beyond which people will forego the French delicacy, although social group variations apply (Johnston, 1966b; Rushton, 1966). For most lower level goods, people tend to adhere quite fittingly to the heuristic assumptions—such as the nearest center hypothesis—of classical central place studies (Warnes & Daniels, 1979). Spatially, ranges of central functions exhibit field distributions (Haggett, 1965; van Meeteren et al., 2016). A field distribution is a "theoretically continuous distribution with a very rapid fall-off near the center [of the field] and a very slow, almost asymptotic fall-off at its outer range." (Haggett, 1965, p. 41). Therefore, in empirical operationalization of the range, using a

measure of central tendency that accommodates skewed distributions is advised. The final indicator "range" that we employ here is the 3rd quartile of the ranges found for specific central functions (sixth column in Table 1).

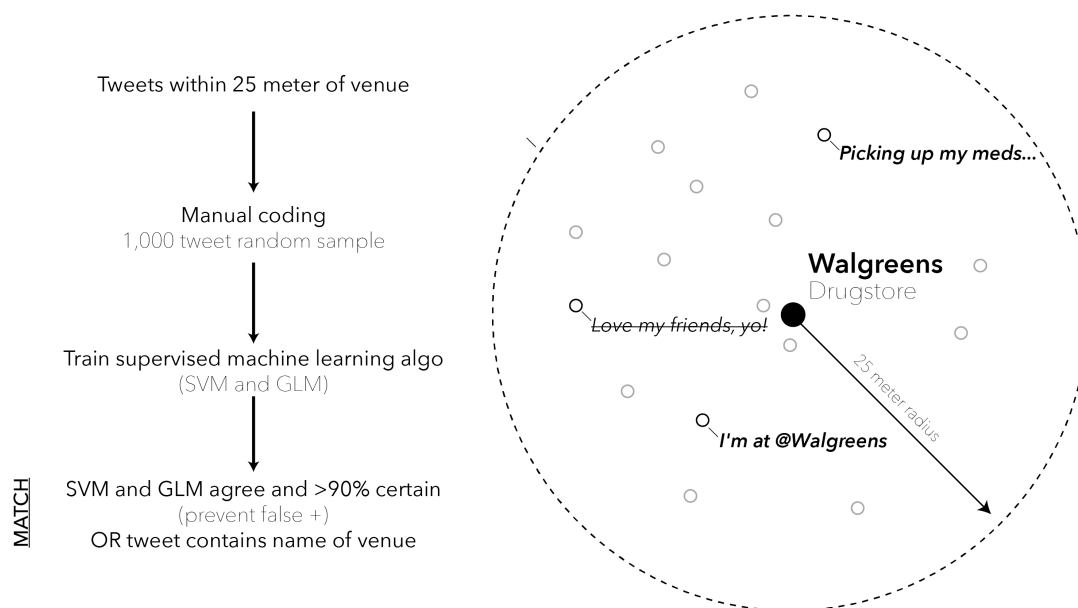
Figure 3 Determining home location (top) and determining consumption (bottom)



Home location not determined by raw count, but weight based on 'homey' temporal pattern

- Different hours of the day
- Weekdays and weekends
- Throughout study period

- TV hours
- Saturday morning
- 1 - (office hours)

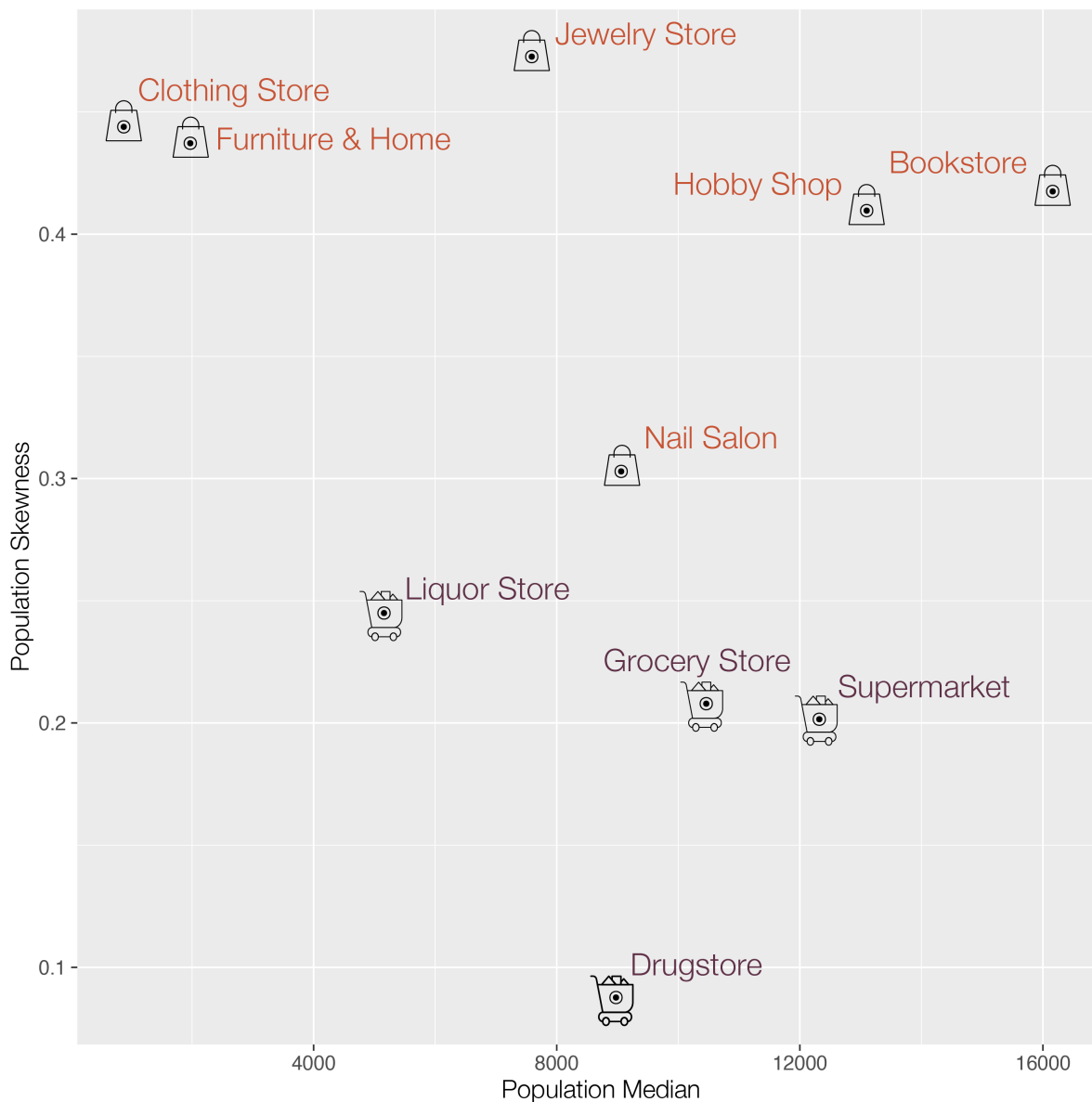


4.2 Determining the threshold

When a central function provider acts according to the L6sch maxim, which is expected for convenience goods, this will result in the convergence of range and threshold. Figure 4a plots the median population per Thiessen polygon of a central function, indicating threshold (X-axis), and the "population skewness" of that central function (Y-axis). The population skewness indicates the Pearson's median skewness $(\mu - v) / \sigma$, thereby quantifying the skew of the population distribution of Thiessen polygons per central function. The smaller the population skewness, the more equally this central function is spread over the region, and hence the closer its spatial distribution is to the L6sch Maxim. In Figure 4a, if there would be

a perfect linear relationship, a hierarchy reminiscent of a (Löschian) CPT ideal landscape would appear where threshold and degree of clustering converge. In figure 4a's actual distribution, central functions in the lower-right quadrant are "Lösch maxim functions" where threshold is more important in determining the central place location than clustering. Central functions in the upper-left quadrant are "Hotelling maxim" functions where co-location is more important than the threshold.

Figure 4a. Relationship between threshold and population skewness



The results in Figure 4a make intuitive sense: the lower-right quadrant contains typical convenience goods: the drugstore, the grocery store and the supermarket. The clothing store, the furniture home store and the jewelry store are in the opposite quadrant. Here, co-locating is more important than monopolizing complementary regions. This underlines the comparison goods character of these three latter central functions.

The metrics used in Figure 4a presume that all central functions are equally sensitive to

population density. In reality, however, this sensitivity is determined by the interplay between range and threshold. Some central functions which have a low range can only exist in denser areas to meet their threshold, and are thus less likely to be located in less-densely populated areas. Figure 4b provides a scatterplot that examines the influence of population density on the availability of central functions.

Figure 4b. Relationship between population skewness and nearest neighbor distance skewness



The skewness of the nearest neighbor distance per central function—again defined as Pearson’s median skewness—is plotted on the X-axis in Figure 4b. The higher this indicator, the more sensitive the central function is to a density effect. For reference, the population skewness is again plotted on the Y-axis. Particularly the jewelry store, the clothing store, the bookshop and the grocery store are dependent on density. Hence it both concerns archetypical comparison goods (jewelry, clothing) and convenience goods (grocery). The

latter can be explained intuitively. If the density in the neighborhood is too low to support a grocery store, people will immediately frequent the larger supermarket instead. Consequently, the supermarket is the central function in this study least sensitive to population density.

Figure 5. Thiessen polygons of exemplary central functions

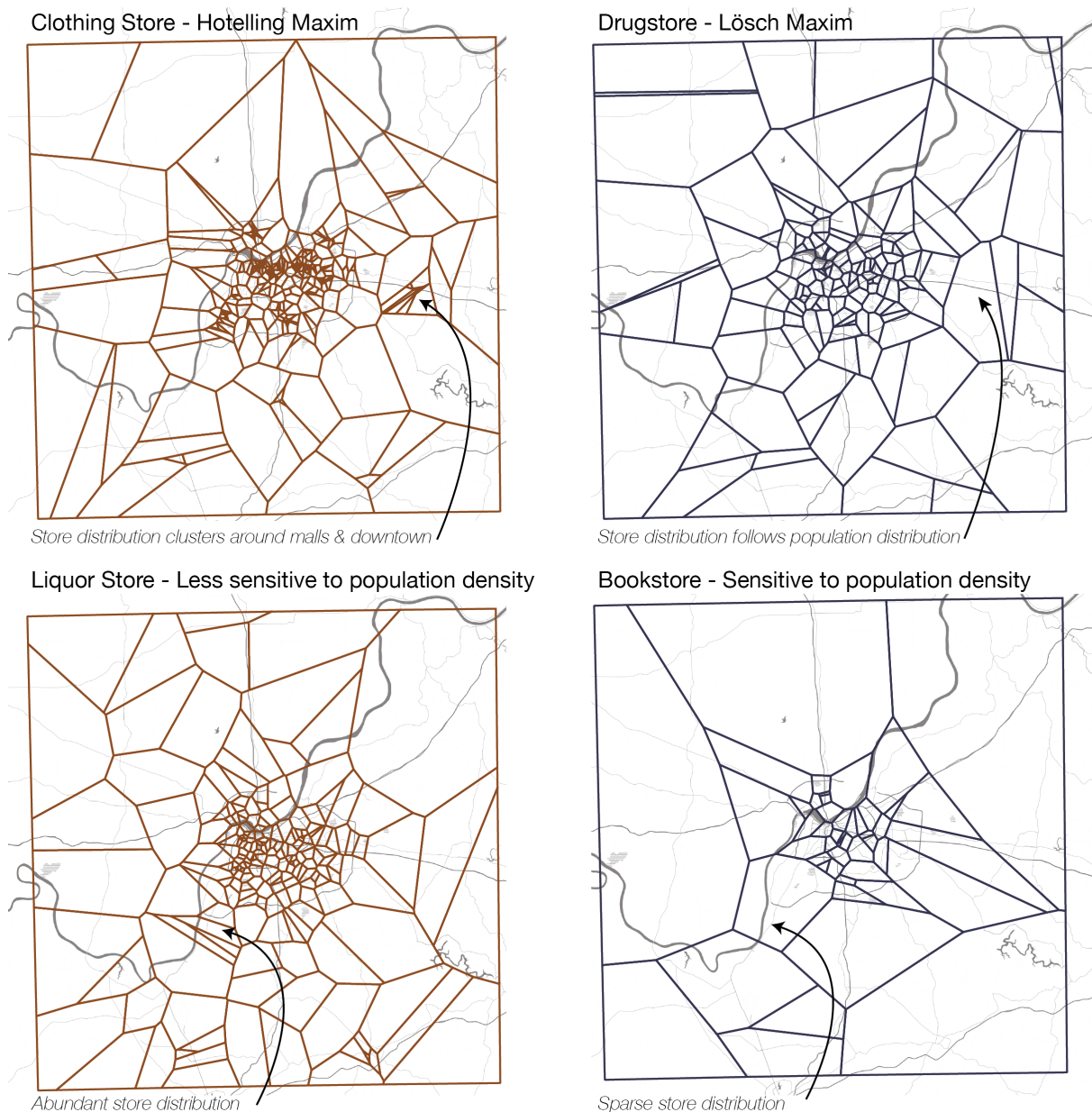


Figure 5 illustrates these two aspects of the threshold cartographically. The top two panels map the Thiessen polygons for two central functions that score relatively high and low values on the "Population Skewness" variable: the drugstore (Lösch maxim, in blue) and the clothing store (Hotelling Maxim, in brown). Where the distribution of the drugstore seems to largely follow the population density of the area (Figure 1), the clothing stores are much more

concentrated. In the centers, particularly mall areas and Louisville's Central Business District (CBD, see Figure 8 below), clothing store Thiessen polygons are much more packed than one would expect based on population density figures alone.

The bottom panels map two central functions that elucidate contrasting scores on the Nearest Neighbor Distance Skewness indicator: the liquor stores (brown) and the bookstores (blue). Here, a minimum density appears to play a larger role for bookstores than for liquor stores. As soon as the population density permits it, a place to procure alcoholic beverages appears and people will travel to the nearest pickup point. However, a physical bookstore requires many local costumers. Likely, if the bookstore is too far away, people will just order books online.

4.3 Determining the range

Figure 6 summarizes the analysis of the range. The X-axis of Figure 6 features the drive time in minutes to procure the central function. The Y-axis on the upper half of Figure 6 shows the density—the fraction of cases per unit of the variable on the X-axis—for each central function. As expected, the curves represent a field distribution with many scattered outliers at large distances. Comparison goods show higher ranges than convenience goods and generally tend to have greater numbers of outliers. These outliers are likely to be the result of periodic shopping trips for which larger distances are travelled from more remote settlements. The outlier pattern of the grocery store is unexpected as the function was hypothesized to be very local. Examination of the underlying data reveals that the Foursquare category "grocery store" both includes convenience corner stores and specialized "ethnic" (e.g. Chinese or Vietnamese) stores that are mostly found within the Louisville urban core. We suspect that particular demographic groups have a larger range for specialized cuisine central functions. This also explains the unusual spread between the median and the Q3 values for the grocery store (Figure 6). This prompts critical consideration of outliers in follow-up research as these can help identify when the categories available on foursquare or other sources are particularly heterogeneous and likely contain distinct sub-types which, ideally, should be used instead. Nevertheless, the box plots (Figure 6) corroborate our general distinctions. Some central functions (clothing store, furniture store, supermarket) have many outliers in the range while others (drugstore, bookstore and nail salon) have few. These particular outlier patterns confirm our assessment of density-sensitive functions (Figures 4b, 5b): nobody in the study area was willing to drive more than 37 minutes to visit a nail salon.

Figure 6. Outcomes on the range

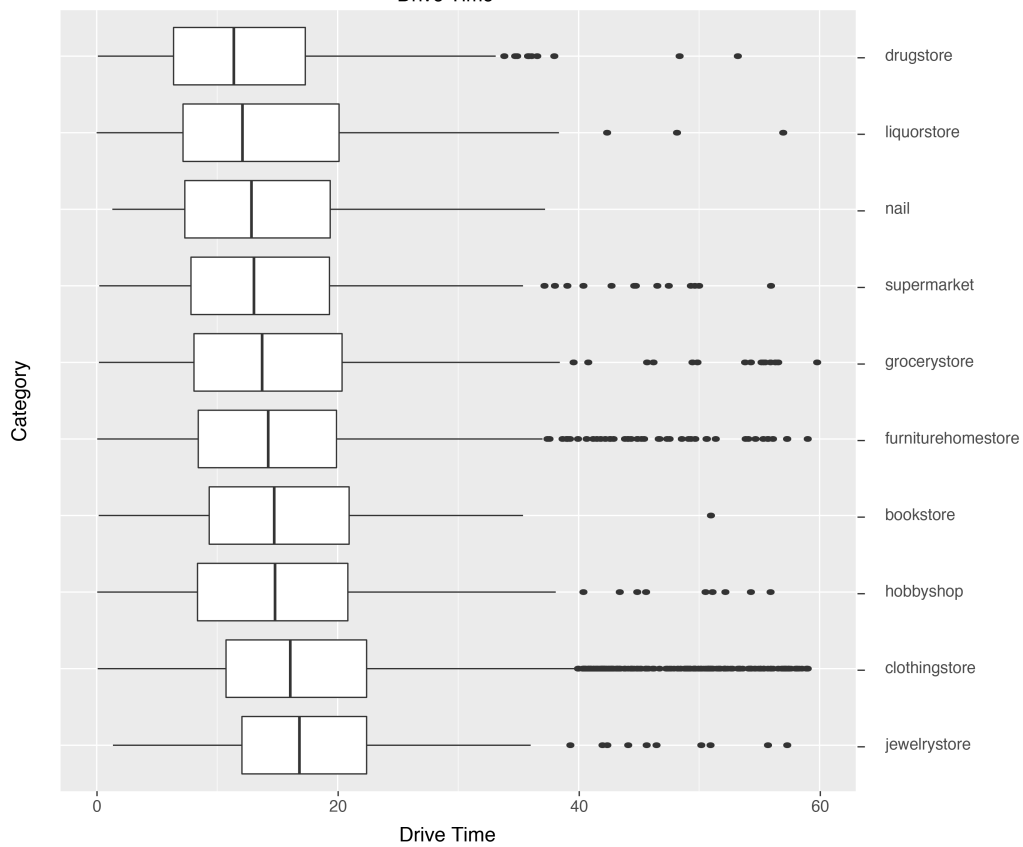
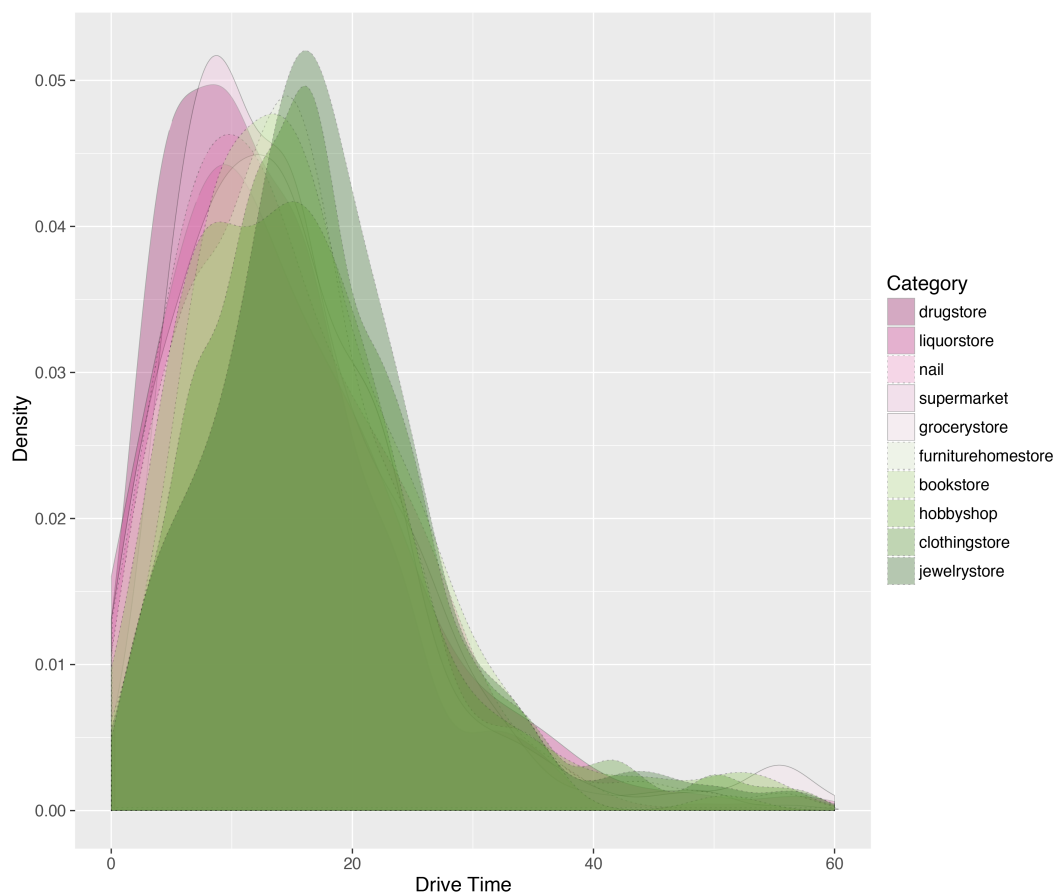
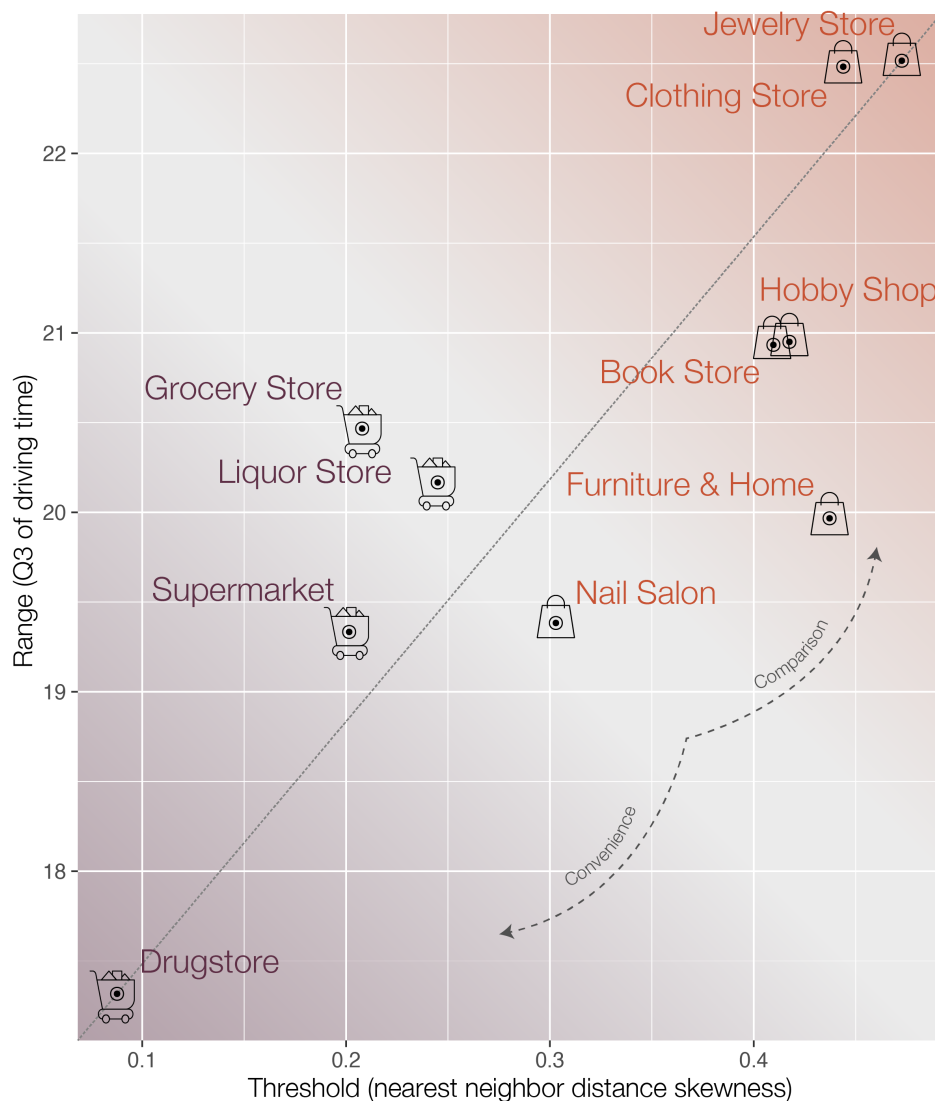


Figure 7 cross-tabulates the threshold and range indicators. The central functions left of the anti-diagonal are those for which people are willing to drive further than expected based on their threshold value. These tend to be "necessities" (to be bought in a supermarket, a liquor store, or a grocery store). If there is no such central function in the neighborhood, people will drive there anyway and hence travel longer. Central functions to the right of the anti-diagonal are those which people will forego consuming at a central place if they are located too far away. Not surprisingly, in this quadrant we find "leisurely amenities" such as the bookshop, the furniture shop, the hobbyshop and the nail salon. Therefore, these are the central functions that are disproportionately found in denser, "urban", areas. On the anti-diagonal we find the drugstore, clothing store and jewelry store where the upper and lower limit are more or less in proportion. Nearly nobody will feel like driving to a remote drugstore, and nearly everybody will have a propensity to travel to obtain clothing or jewelry if those goods are desired, underlining the findings of Rotem-Mindali & Weltevreden (2013, p. 877) that these latter product categories resist online shopping.

Figure 7. Relationship between range and threshold



5. Operationalization and results II: Louisville's central place system

Now that the continuing relevance of the interplay between range and threshold to understand central function provision is established, we continue to the second stage, where the level of analysis shifts from individual functions to the central place system. We want to corroborate Christaller's assertion ([1933] 1966, pp. 30-33) that the interplay of range and threshold exhibits a tendency to form a hierarchy of central places. Ideal-typically this hierarchy optimizes the aggregate consumption in central places in a given distribution of the population, range and threshold. Furthermore, multi-purpose shopping trips and the Hotelling maxim strengthen this centralization tendency. Since we only have data on 10 different central place functions, our analysis is necessarily incomplete. Although we cannot construct a central place system that could be fitted to Christaller's ideal-typical models and which could shed light on the controversies about discrete steps in the hierarchy (Beavon, 1977), we can plot the density of the ten functions to see whether our findings tend toward Christallerian central place systems. A further analysis examines the diversity of functions within central place clusters to relate diversity to population density.

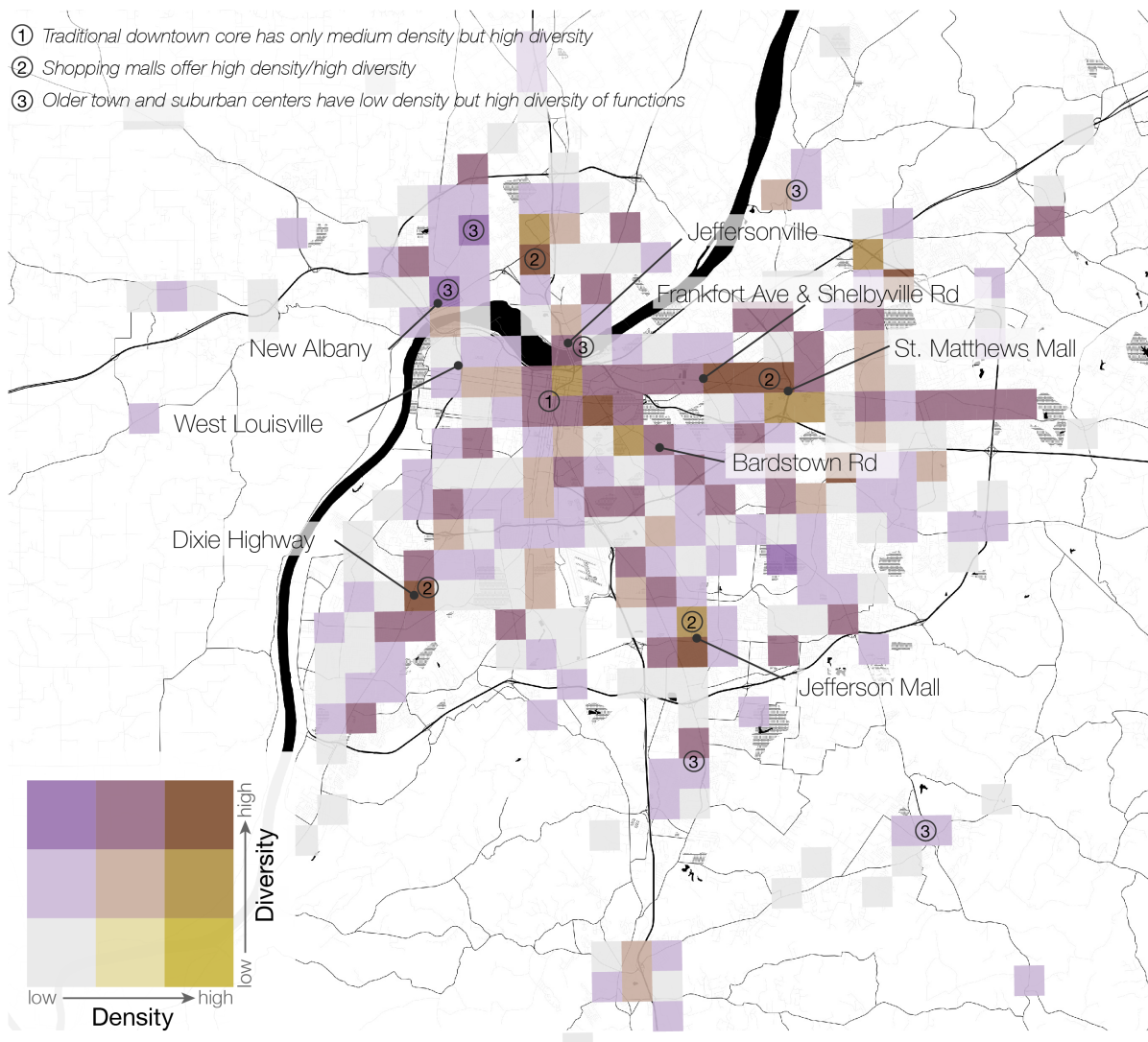
To scale-up the analysis we overlay the study area with a rectangular raster with grid cells of 1.5 kilometer. Although this size is chosen relatively arbitrary, one of the advantages of using geoweb data is that the scale of the spatial unit can be changed. This could help to highlight and examine issues around the modifiable areal unit problem if necessary (Openshaw, 1984), although we do not elaborate this further out of space constraints. For each grid cell in the study area, we can now calculate the number of venues present (referred to as venue-density hereafter), as well as a measure that represents the diversity of different categories within that cell. We choose to represent this diversity through Shannon's diversity index as it is less sensitive to the presence of either very dominant categories or very rare ones (Morris et al., 2014), which is common in many of the locations in our study area. The index (H) is calculated as follows:

$$H = - \sum_{i=1}^S p_i \ln p_i$$

where S is the number of 'species' (i.e. venue categories) and p_i is the proportion of venues that belong to category i . An in-depth discussion of the index is beyond the scope of this paper, but the higher a grid cell scores on Shannon's index, the more spread out its shops are over multiple categories.

Figure 8 visualizes the density and the diversity of venues yielding the following observations. First, when looking at the total density of venues within the 10 categories selected, it immediately becomes apparent that the CBD area ("the urban core") of Louisville is not home to the greatest density of venues. Instead, we see two dense clusters arise: one in the eastern part of town and another one north of the river in Indiana. Both of these clusters are home to a number of large shopping malls.

Figure 8. Venue density and diversity in greater Louisville



When the diversity index is assessed, a more complex picture emerges. The centers of the towns surrounding Louisville, in the corners of our study area, gain much greater prominence. What they lack in sheer number of venues is made up for by the diversity of these venues. Similarly, downtown Louisville itself, not very densely populated with venues, scores much higher on the diversity measure. When we focus on the diversity around the center of Louisville, we observe a number of interesting patterns. The large malls in the eastern part of town indeed do not seem to offer the same diversity of central functions as, for instance, the much older strip malls along Frankfort Ave and Shelbyville Rd as well as Dixie Highway, which are home to many of the area's small and medium-sized businesses. Similarly, one of Louisville's trendy neighborhoods, with a large variety of small shops around Bardstown Road, is also rendered visible. Although definite statements regarding causes would require additional research, these spatial patterns do fit in the spatial sorting patterns described by Borchert (1998), where lower-yielding central functions are driven into older, less-central real estate with lower rents. It is these lower-yielding central functions—e.g. the bookshops, the

hobby shops, the furniture store—that account for the higher scores on the diversity index in this study.

The Ohio river/state border and the economic and Louisville's racial segregation are also clearly visible in both the venue-density and diversity maps. For example, just across the river from downtown Louisville, we find the older town centers of New Albany and Jeffersonville. These older centers also score much higher on the diversity index than on pure density. This is seemingly unexpected as they are so physically close to Louisville's downtown. Christaller ([1933] 1966, 16, pp. 102-103) proposes to understand this kind of feature historically where "bridges, border and custom places" refract the regularities of the central place system and create "auxiliary central places". Here we see the barrier effect of the river: people living in Indiana do not cross the river easily (both physically and mentally), and therefore, the towns on the North bank function as auxiliary central place. Similarly, given the population density displayed in Figure 1, it is evident that West Louisville is one of the most densely populated areas in our study area. However, neither the density nor the diversity of shops is present in that area, even though CPT would predict another cluster to be present there. This is a good example of how CPT can also be utilized in a more critical vein. By comparing actual to theoretical central place provision, the social inequalities related to central function provision, as for instance studied in the "food deserts" literature (Christian, 2012; Wrigley, 2002), can be brought into view.

6. Conclusions

The possibility to use CPT for critical analyses alluded to above indicates that there is nothing inherently "counter-revolutionary" in utilizing theories and methods from spatial science, but that these methods and approaches can just as easily be made part of an emancipatory project (Wyly, 2009). One way to accomplish this is by using CPT for hermeneutic theorizing, to "frame" large, undirected, messy big data. This illustrates how associating one particular episode in human geography with "epistemic theorizing" and another with "hermeneutic theorizing" (Barnes, 2004b) may render useful applications originating from these episodes invisible. Like the 1960s, the 2010s could benefit from using theories such as CPT to generate important conversations in human geography by navigating the data deluge. However, CPT remains epistemological theorizing as well. From that perspective, this paper has showed that calls to relegate CPT to a museum have been premature. Not only do Christaller's microfoundations still hold and can account for the provision of central functions, central functions add up to a recognizable system on the level of the settlement geography. Contrary to Scott (2012, p.31), we argue that this is of more relevance than a "minor application in retail geography". To the extent in which ideas about the "consumer city" with its emphasis on amenities hold water (Glaeser et al., 2001; Storper & Scott, 2009), central places are of paramount importance. Although these amenities involve intangibles such as climatic

conditions (Ullman, 1954), the vast majority of amenities—from a fancy restaurant and a country club to a heavy metal venue and record store— are in fact central place functions (see Friedmann, 1956). CPT is thus foundational to the consumer city.

However, more needs to be done before the method can be scaled-up unproblematically. Although, our analytical capacity and available data has increased, caution remains important. This paper's concentration on avoiding type I errors at the expense of providing a comprehensive picture implies there is a need for further research: refining the method and more generally, assess the limit to which it works in describing full central place systems. Yet, the increased ability to test the robustness of data also cautions against over-optimism regarding the potential of big data (Shearmur, 2015). In this study, we selected ten of the cleanest Foursquare categories available and had to make crude assumptions regarding the homogeneity of our Twitter users in terms of socio-economic background. We could only reach our conclusions after considerable effort and end up with a very partial geography, with limited relevance to the local population and policy makers. This alerts us to the fact that although big data is a defining phenomenon of our times, it requires critical scrutiny (Kitchin, 2014) and we should be wary of embracing it as a panacea that can replace "traditional" data gathering and analysis.

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¹ Latitude 37.75 and 38.70; Longitude between -86.32 and -85.13. In the north the town of Scottsburg, IN is the outer boundary, in the south Bardstown, KY, in the west Corydon, IN, and in the east Shelbyville, KY.

² At the 1960 IGU symposium in Lund, in a transcribed debate between Christaller and his regional science interlocutors (Norborg, 1962, pp. 157-165), Christaller affirms Löschian interpretations of his theory such as the uniform distribution of the agricultural population, which are at odds with his original formulation.

³ Berry and Garrison's (1958b) terms "threshold" and "range" have become synonyms for Christaller's respective lower and upper limits of the range (e.g. Beavon, 1977). However, as Johnston (1966b) notes, originally, Berry and Garrison (1958b) did not regard the threshold and lower limit of the range as synonyms, as threshold initially only referred to the nodality value. Since this distinction has not been widely adopted, we neither adhere to it.

⁴ Lösch (1940 [1954]) accounts for optimization in his landscape by "rotation" towards the highest degree of agglomeration economies (Beavon, 1977, pp. 80-102). However, these agglomeration economies are, contrary to Christaller, exogenous to the basic logic of his central place system.

⁵ Christaller ([1933] 1966, pp. 46-47) provides a discussion on sister [twin] cities where he elaborates

this phenomenon.

⁶ [<https://developer.foursquare.com/categorytree>], accessed Feb 2, 2016

⁷ Thiessen polygons, also called Voronoi or Dirichlet tessellation, are created from a set of input points so that each location inside the resulting polygons is closer to that polygon's input point than to any of the other input points.