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Summary. The Schelling model of neighbourhood racial segregation is extended to include agents who can authentically 'see' their neighbours up to a distance *R*, called 'vision'. By exploring the consequences of systematically varying *R*, an understanding has been developed of how vision interacts with racial preferences and minority concentrations and leads to novel, complex segregation behaviour. Three regimes have been discovered: an unstable regime, where societies invariably segregate; a stable regime, where integrated societies remain stable; and an intermediate regime where a complex behaviour is observed. Detailed results are presented for the symmetrical case (which maximises conflict), where equal numbers of agents of two races occupy the same cityscape. The policy implications of these simulations are briefly indicated.

1. Introduction

Neither the passage of time—35 years since the Civil Rights movement—nor of laws—the Fair Housing Act of 1968 or the Equal Credit Opportunity Act of 1974, for example—have eliminated neighbourhood racial segregation in the US. It is true (Farley and Frey, 1991; Farley *et al.*, 1993; Thernstrom and Thernstrom, 1997) that there has been some decrease in the intensity of racial segregation in small and medium cities with relatively small Black populations. But, the levels of residential segregation of African Americans in the major metropolitan areas continue to be pervasive and persistent (Massey and Denton, 1987, 1993).[1]

The scholarly analyses of the explanatory factors possibly influencing this sociological condition have been quite exhaustive. Differences in income, housing affordability, location of employers and businesses, crime, job opportunities, neighbourhood racial preferences, racial steering by real-estate professionals, lending practices of financial institutions and a host of other factors have been invoked as likely causes (Carr, 1999). The status of the literature on this explanatory enterprise is represented, quite fairly in the authors' opinion, by the following quote

> In the debate about the relative role of these forces, the consensus is that the patterns of separation have a multifaceted explanation: Among the explanatory fac-

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> tors, neighborhood composition preferences have been singled out as a critical variable both by economists, who view preferences from the perspective of consumer behavior theory, and by geographers and sociologists, who use preferences and expectations as elements of models of residential choice within cities and neighborhoods (Clark, 1991, p. 1).

This study further explores the consequences of individual preferences on neighbourhood segregation.

In two pioneering papers, Schelling (1969, 1971a) introduced a model system of two distinguishable types of agent with discriminatory individual preferences for certain neighbourhood compositions and then quantitatively explored the dynamics of this model system.[2] In effect, this work was perhaps the first concerted and systematic application of what is now called the agent-based modelling approach to sociological systems. The towering status of Schelling's legacy in this area is such that, before writing yet another paper on the subject, perhaps one ought to pause and ask, "Didn't Schelling already say that?" (Martin, 1999, p. 74).[3] The goal in this introduction is simply to locate this paper's specific points of departure from Schelling's model and from his overall insight. For the limited purpose of framing the present study, therefore, and because it is seen as an extension of the Schelling model, the following brief, though admittedly narrow, characterisation of Schelling's rather deep insights is now presented.

His insight in this subject has frequently been described by scholars by comments of the following kind: "Quite minor differences" in individual preferences lead to "aggregate results that are strikingly different" (Clark, 1991, pp. 1–2). Schelling's seminal work has since been supplemented by numerous scholars who—for example, conduct "a Test of the Schelling Segregation Model" and "confirm the view that stable integrated equilibria are unlikely" (Clark, 1991, p. 1). Another author (Krugman, 1996, p. 19) concludes, "Guess what: even though individuals are tolerant enough to accept an integrated pattern, they end up with more or less total segregation". A very recent paper (Wasserman and Yohe, 2001, p. 13) "examines the robustness of his conclusions in two slightly more realistic environments" and found "strong support" for Schelling's conclusions. They write (p. 16), "The second case expanded residents' vision … The segregation in the equilibrium neighborhood was, in fact, even more obvious than before". Other scholars (Epstein and Axtell, 1996) have written of Schelling's work: "He found that even quite colour-blind preferences produced quite segregated neighborhoods" (p. 3). In the present work, these claims are qualified and the contingencies surrounding assertions of this kind are made explicit.

This way of framing the implications of the Schelling model, and the corresponding tone of surprise about the apparent disconnect between agent intent and consequences, have also found their way into influential popular writings on the subject. A good example of a commentary on the Schelling model is found in a well-researched recent essay in the literary magazine *The Atlantic Monthly*, where the essayist writes

> In the simulation I've just described, each agent seeks only two neighbors of its own colour. That is, these "people" would all be perfectly happy in an integrated neighborhood, half-red, half-blue. If they were real, they might well swear that they valued diversity. The realisation that their individual preferences lead to a collective outcome *indistinguishable* from thoroughgoing racism might surprise them no less than it surprised me and, many years ago, Thomas Schelling. (Rauch, 2002, p. 36; italics added).

And a particularly bad example—not only because of its failure to understand the nuanced nature of Schelling's work, but also because of its illogical concatenation of Schelling's observations with racist ideology—can be found in an article entitled, “Racial segregation is an inevitability”. This article has been posted on the website of a British Aryan Unity group; the author has used—abused in the present authors’ view[4]—Schelling’s work to pronounce

> But this does not undermine Schelling’s central insight. Marked segregation can arise from only rather mild individual preferences. The main problem faced by British society is neither one of racist attitudes nor of residential segregation. Rather, it is the ideology of multiculturalism (Ormerod, 2002).

In the present work, evidence is provided against such claims of inevitability of segregation in Schelling-like models.

There is robust empirical evidence (Farley and Frey, 1991; Thernstrom and Thernstrom, 1997) that there has been some significant decrease in the intensity of racial segregation in small and medium cities in the US. Is Schelling’s model simply incompatible with these empirical findings? The intention of the present paper is to revisit Schelling’s model to see if one forgot, as it were, to look in some areas where there might be evidence against this notion of inevitability of segregation.

It is important to acknowledge that there have been other studies that have extended agent-based models of racial segregation and racial transition of neighbourhoods, typically by trying to make the model more complex and realistic. One early, but important, example of such studies is a policy simulation (Vandell and Harrison, 1978) which postulates a third party—the real estate speculator—who stands in for the array of institutional intermediaries that play, in reality, a major role in the racial transitions in neighbourhoods. Having acknowledged this class of studies, the thrust of the present work is quite different. It argues for the inclusion of an *essential* new feature of the agents, their vision, in this class of models. Without ‘vision’, it is believed, these models will remain fundamentally incomplete.

2. Scope of This Study

The thrust of this work is to revisit Schelling’s model and examine it closely, comprehensively and systematically with respect to one particular parameter believed to be quite significant—i.e. the *range of vision, R* of the agent. It is not claimed that this is the first article to have studied the effect of vision in this context. After finishing the simulations and during the writing phase, the authors became aware of two very recent studies, one unpublished (Sander *et al*. 2000) and the other published (Wasserman and Yohe, 2001), which are related to the present work. Both these studies recognise the importance of ‘seeing’ other agents who are at some distance from the agent who is making the choice whether and where to relocate, and the authors include this effect in different ways in their analyses.

One study (Wasserman and Yohe, 2001) introduces a utility function that decreases exponentially with the distance from the agent making the decision, as a way to include the effects of racial composition away from the agent. They (Wasserman and Yohe, 2001) conduct computer simulations in a portion of the parameter space and conclude with a “strong support” for Schelling’s claim of segregation. They report

> The second case expanded residents’ vision … The segregation in the equilibrium neighborhood was, in fact, even more obvious than before. … This result suggests that segregation is positively correlated to the vision parameter—an observation that is also consistent with Schelling’s hypothesis (Wasserman and Yohe, 2001, p. 16).

In the other study (Sander *et al*., 2000), the neighbourhood of approximately 2500 homes is divided into 25 fixed tracts each containing 100 cells. The utility function of the agent depends upon, apart from the Moore neighbourhood (see Figure 1), upon the racial composition in the tract in which the agent is currently located and the tract which contains the trial site where the agent

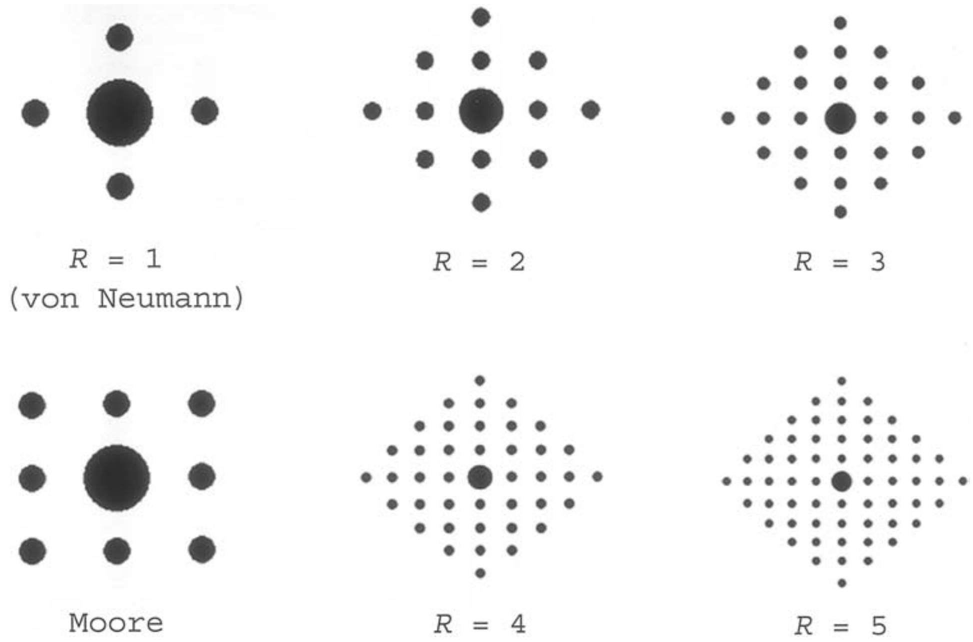

Figure 1. Neighbourhoods specified by vision. The large dots in these figures represent the agent evaluating its neighbourhood and the smaller dots represent those agents it considers part of its *R*-neighbourhood. The Moore neighbourhood is also shown for comparison. Roughly speaking, the Moore neighbourhood is equivalent to what might be called '$R = 1.5$'.

is considering to move. They can vary the relative weights of the Moore neighbourhood and of the tract. They find that, as the weight of the extended tract is increased from 0 to 1, the dissimilarity index increases from about 0.4 to 0.8. This conclusion is similar to that of Wasserman and Yohe (2001)—i.e. increasing the vision makes segregation worse. In the present study, a different way of including vision is introduced and its effects are studied by systematically varying the range of vision. It is discovered that the effect of increased vision is, in fact, more complex and interesting than implied by these very recent studies.

In the standard Schelling model of a two-race 'artificial society' (Epstein and Axtell, 1996), agents are characterised by a parameter *p*, which is a measure of their preference for agents of their own kind. Agents evaluate the racial composition of their *immediate* neighbourhoods and compare the composition with their own value of racial preference, *p*, to determine whether they will attempt to relocate elsewhere. The variant in the present paper differs from this in that the agents in fact '*see*' their neighbourhood up to a certain 'distance' *R* from their own home while evaluating their decisions to relocate.[5]

It is found, depending upon the values of *p* and *R*, that the system evolves in one of two possible modes. In one region of the parameter space, the system displays the familiar (Schelling, 1969, 1971a, 1971b, 1978; Epstein and Axtell, 1996; Sander *et al*. 2000; Wasserman and Yohe, 2001) mode where initially integrated communities are unstable and quickly resegregate. This is called the *unstable* regime. But it has been discovered that there is a large region of the parameter space (p, R), particularly for moderate values of R ($2 \leq R \leq 7$), where integrated communities remain stable for arbitrarily long times. This is called the *stable* regime.

It is important to note that what is called the stable regime does not correspond to some unrealistic, Gandhian levels of racial preferences/tolerances of the agents. Once the range of vision R is expanded from myopic levels (say, $R = 1$) to rather modest levels (say, $R = 3$–5), non-segregated stable communities are found to be fully consistent with non-zero and quite substantive values of p. If this insight were to diffuse into the collective consciousness of policy-makers and of the general populace, it could help to generate an optimistic outlook for the future of neighbourhood integration.

3. Details of the Extended Schelling Model

One of the central issues in agent-based modelling approaches to sociological problems is the level of complexity that is appropriate: it needs to be realistic enough to lead to an acceptable level of congruence with empirical findings without being so complex as to provide no insight. It is worth paying heed to what Schelling himself had to say on the subject very recently

> Thomas Schelling points out that the more complex and therefore realistic the model becomes, the more difficult it will be to discern cause–effect relationships—just like real life (Holden, 1996).

Since one is interested in maintaining, if possible, a sense of cause–effect relationships, caution is adopted in this study and his model is extended by including just one additional parameter—i.e. range of vision. In particular, it is intentionally restricted to agents of only two distinct kinds. It is perhaps better to refer to them as 'type one' and 'type two' because the model does not care about the underlying reason for the preference p, which is simply a parameter that can be set to any value between 0 and 1. There are two reasons why, nevertheless, the rest of the paper uses the racial labels 'White' and 'Black'. First, in a journal that does not accept colour pictures, the only reasonable way to construct a graphic depiction of agents of two types *and* vacancies is to use black, white and empty sites. Secondly, it is only fair to acknowledge that this paper's primary interest is in bringing the issue of range of vision to the discourse on racial segregation.

This notion of range of vision is best introduced by referring to an aspect of the Schelling model that can be a bit confusing at times. For example, Rauch says "In Schelling's model, unhappy agents, like the modeler himself, could survey the whole scene to find a better situation" (Rauch, 2002, p. 38). This needs to be made more precise. There are two quite distinct kinds of surveying that the agents are capable of. When deciding *where* to move, the agents do survey the whole scene for an available spot, as Rauch states correctly. But when it comes to deciding *whether* to move, the agents scan *only* their immediate neighbours. As if these agents possess a dual vision! The actual situation in the literature is slightly more complicated than this. In all previous studies, however, the vision for determining the 'neighbourhood composition' is exceedingly myopic, whereas the vision for locating satisfactory sites is unrestricted.

The R-neighbourhood of an agent is defined as the set of all sites that can be reached by travelling R spaces in any combination of the cardinal directions. In the present model, the agent *does*, in fact, evaluate the racial composition in this extended R-neighbourhood to determine the satisfaction of his/her racial preferences in deciding whether to look for a site to move to.

Note that the R-neighbourhood is not a fixed-boundary neighbourhood or a tract of the sort Sander *et al*. (2000) employed. Each agent is allowed to define its own neighbourhood, centred about itself. It is felt that this is a more realistic definition, especially for agents that would otherwise be near the boundary of a tract.

In the spirit of avoiding unnecessary complication, at least in the present study, all agents in a given ensemble are restricted to having the same range of vision R. R is treated as a non-dynamic, variable parameter and the effect of varying R from one simulation to another is systematically explored. The goal is to develop a qualitative sense of what the consequences are of varying the vision R. In future studies, one might wish to consider non-homogeneous models characterised by a range of distributions for R even within the same ensemble of agents.

The computer simulation essentially does four things: it creates a randomly generated artificial society; it repeatedly evaluates the satisfaction of individual agents and if necessary moves them; it creates a graphic display of the society for the user; and it measures the segregation of the neighbourhoods.

When the goal is to attempt a direct contact between simulations and demographic data for specific cityscapes, one must obviously use the *known* geography and the *known* boundary conditions. But the central goal in this work is to extract and to present an understanding of how varying R affects the nature of segregation, while minimising computational artefacts. Small size effects and edge effects are the two important artifacts that all modellers must deal with, making a compromise between the desire to use a large society (which reduces ensemble-to-ensemble fluctuations) and the limits to computational power at one's disposal. Due to the computer memory limitations of his day, Schelling's pioneering work employed 13×16 or 8×8 arrays. However, in contemporary research such as that of Epstein and Axtell (1996) and in the present research, the chosen geography of societies consists of square N x N arrays, where $N = 50$. Additionally, use is made of periodic boundary conditions in both dimensions—i.e. the 'east' and 'west' borders of the society 'wrap around' to meet one another, and the 'north' and 'south' borders do the same. So, technically the society is on an edgeless torus (i.e. donut), not on a flat grid. This has the additional advantage, in the present context, of suppressing boundary effects, so that any observed variation in segregation pattern can be reliably attributed to variation in R.

The parameter c represents the concentration of the minority race. Since the central goal of this study is to understand the effect of the range of vision R, the model has been intentionally kept symmetrical between the two races. Thus, equilibrium configurations for c and $(1 — c)$ are identical except that labels for 'Black' and 'White' are switched. Therefore c is restricted in the range $(0 < c \leq 0.5)$. An agent's preference p is simply the minimum fraction of agents of its own race it must see in its R-neighbourhood to be satisfied—i.e. to have no desire to move. The parameter v $(0 \leq v < 1)$ represents the concentration of vacant homes.[6]

The code randomly picks $(1 — \mathrm{v})\ N^2$ sites in the array to be initially occupied by $c(1 — v)\ N^2$ 'Blacks' and $(1 — c)(1 — v)\ N^2$ 'Whites'. During each iteration of this portion of the programme, an agent is selected at random for 'evaluation'. The agent looks around in its R-neighbourhood. If the computed ratio of agents of the same race to total agents in its R-neighbourhood is greater than or equal to its preference p, the agent is *satisfied*: it does nothing and this iteration is finished. However, if this ratio is lower than p, the agent makes a series of attempts to move.

In attempting to move, the agent randomly selects a vacant site, anywhere in the society, and performs the same kind of evaluation it performed at the site of its current home. If there would be a greater fraction of like neighbours in the R-neighbourhood of this 'trial' vacant site, thus potentially increasing its *satisfaction*, the agent moves, leaving its old home vacant. If the move would not increase the *satisfaction* of the agent, it randomly selects a different vacant site to evaluate if it can increase its *satisfaction* by moving. This process is repeated up to vN^2 times, corresponding to each vacant site being evaluated an average of once, before admitting defeat, for the time being, and staying put.

For instance, with a 50×50 society with 90 per cent occupancy, an agent would view at most 250 new homes before either finding a suitable new location or admitting defeat until selected again. It turns out that, in actual simulations, very few agents are forced to admit defeat unless the society is characterised by very high values of p, the preference for one's own kind.

The 'evaluation' portion of the programme is repeated until no more agents wish to move: equilibrium has been reached. Typically, this occurs when everyone is satisfied, but equilibrium societies also occur where agents are dissatisfied but no 'better' locations exist to move to. Again, the latter occurs primarily in high-preference societies.

One might wonder why, in the present model, an agent moves to the *first* site it finds with a higher fraction of like neighbours. Would an agent not want to move to a site with the *highest available* fraction? It is noted that, because it has been decided not to include a 'moving cost', this question turns out to be moot. Since agents have no cost of movement, they are able to move freely as many times as they wish. Furthermore, every move increases the fraction of like neighbours for both the agent moving and (for societies with $p \leq 0.5$) for all agents in the mover's old and new R-neighbourhoods. So, only 'utility-improving' behaviour occurs and, in all equilibrium societies that are presented in this paper, all agents are maximally satisfied.

Two additional items of detail are worth pointing out. First, the total number of agents remains the same: the model, by design, does not allow mobility of agents completely off the cityscape (that is a different model altogether). Also, simple two-way trades of homes are not incorporated into the model, because they are, apart from being unrealistic, believed to be irrelevant in determining the final equilibrium configurations.

A metric, S, called the "ensemble averaged, von Neumann segregation coefficient at equilibrium" is constructed as follows. Each agent looks at its von Neumann neighbourhood, calculates the actual fraction of neighbours of like race to the total number of neighbours (this denominator is not always 4 since some agents have vacancies in their neighbourhood). Then, this fraction is 'scaled' in such a fashion that it yields a contribution between 0 and 1, where 0 corresponds to what one would find in a random initial society of the given concentration c, and 1 represents a total segregation. These scaled values are then averaged over all agents to determine S. This metric is closely related to the dissimilarity index used in the demographic literature and approaches the same value (0 and 1) in the limits of complete integration and total *apartheid* respectively.

Formally, S is defined by the following equation,

$$S = \frac{1}{(1-v)N^2}\left[\sum_{j.white}\frac{(f_j - f_w)}{(1-f_w)} + \sum_{k,black}\frac{(f_k - f_b)}{(1-f_b)}\right]$$

where, $f_w(c)$ and $f_b(c)$ represent the expected fraction of White or Black neighbours respectively in a completely random initial society with concentration c of minorities.

Note that S can, in principle, take on negative values! Imagine a 'checkerboard' society with no vacancies and $c = 0.5$, in which the sites were filled with a perfectly alternating pattern of the two races. In this case, the numerical value of S would actually be -1. In this paper, however, an unbiased random number generator with appropriate probabilities generates the initial configuration of a society. At the beginning of the simulation, the configuration is always integrated: typical values of S in this starting configuration are 0.00 ± 0.02. Since the agents only move to locations with greater fractions of their own kind—in this rather conservative model, an agent never moves to a site whose R-neighbourhood is more diverse than its current site—S either remains close to zero or increases with time.

4. Results

4.1 The Effect of Varying R for the Case of Moderate Preferences

All results presented in sections 3 and 4 are for the case $c = 0.5$, corresponding to equal numbers of two races trying to occupy the same cityscape. Initially, the case $p = 0.5$ is explored, because it is the prototypical case and has been the focus of much earlier work. For $R = 1$ (see Figure 2), even though the initial society (left panel) was random and fully integrated, the final, equilibrium society (right panel) is substantially segregated, in agreement with earlier work (Schelling,

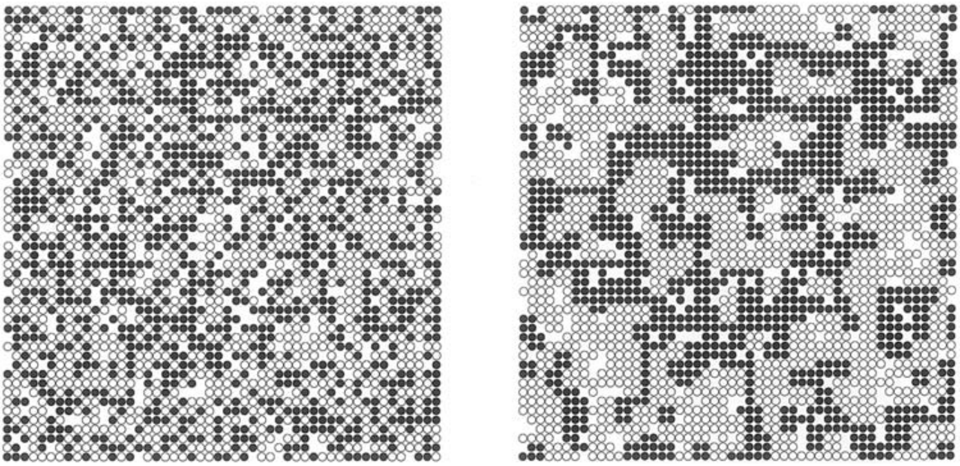

Figure 2. Initial (left) and equilibrium (right) societies for $R = 1$, $p = 0.5$. 'Small-domain' segregation occurs. This is characterised by small, partially interconnected (dendritic) ghettos.

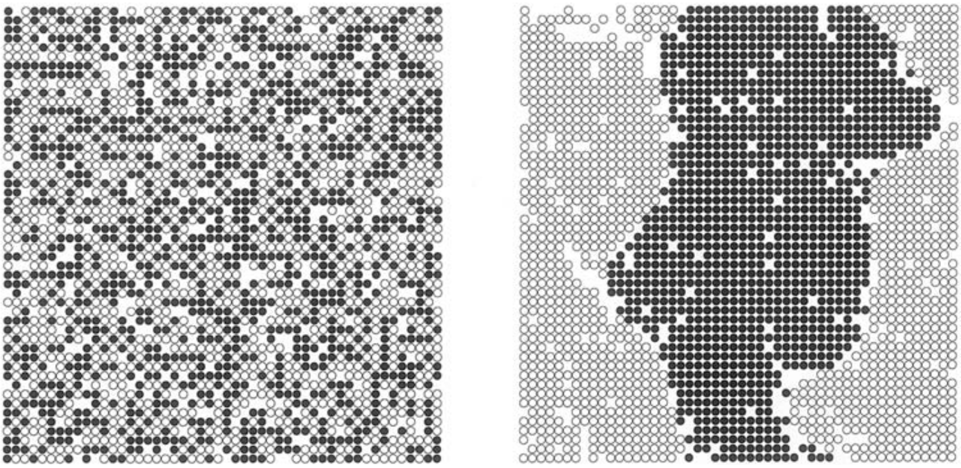

Figure 3. Initial (left) and equilibrium (right) societies for $R = 5$, $p = 0.5$. Since agents require half of their neighbours in a larger R-neighbourhood (containing 60 sites) to be of their own race, 'large-domain' segregation occurs. In fact, a 'complete' segregation occurs, leading to only two domains (i.e. ghettos) at equilibrium.

1971a; Epstein and Axtell, 1996; Wasserman and Yohe, 2001; and Sander *et al*. 2000). But it should be pointed out that the segregation coefficient S is about 0.62, much less than the value of $S = 1$, which characterises *total* segregation. It is therefore inappropriate to describe this as 'almost complete' segregation. The authors also wish to emphasise the dendritic nature of the pattern, which is distinct from the two-domain segregation that is presented next.

Now, the paper exhibits results that demonstrate the consequences of expanding the vision of the agents. For the same preference—i.e. $p = 0.5$—but with the agents enabled to 'see' sites up to 5 spaces away from them—i.e. $R = 5$—the structure of the equilibrium society is strikingly different from the von Neumann case, as evidenced by Figure 3.

Now, the segregation is much 'worse' than in the von Neumann case in two aspects.

First, the pattern is better described as two isolated domains (or ghettos, if one wants to use the term), quite unlike the dendritic, small-domain segregation for the prototypical case of $p = 0.5$, $R = 1$, presented in Figure 2. Secondly, the computed segregation coefficient S for the equilibrium neighbourhood in Figure 3 is approximately 0.97, reflecting the obviously far greater degree of segregation as compared with Figure 2, which was characterised by $S = 0.62$. Perhaps one should reserve the terms 'complete' or 'total' segregation for such two-domain segregation with S close to 1.0.

Wasserman and Yohe (2001) first noticed that, when they expanded their resident's vision (effectively at $p = 0.5$), 'even more obvious' segregation occurred. This is similar to the findings of Sander *et al*. (2000) that as the relative weight of the extended tract (as compared with the Moore neighbourhood) is increased from 0 to 1, the dissimilarity index increases from about 0.4 to 0.8. Even though these two studies (Wasserman and Yohe, 2001; and Sander *et al*., 2000) had introduced the effect of distant agents in quite different ways, the present result—i.e. increased segregation with increasing vision—is in qualitative agreement with their results.

Wasserman and Yohe's utility function incorporates an agent's desire to be near its own kind and the agent's desire to be far from the other kind, according to the formula

$$U_j = \sum_{i=0}^{n} 2^{-(d(i)-1)} + \lambda \sum_{k=0}^{n} 2^{-(d(k)-1)}$$

where, $d(i) \geq 1$ is the distance of a neighbour of individual j's own race; $d(k) \geq 1$ is the distance of a neighbour of a different race; n is the number of neighbours within a range of vision; and λ is a measure of the agent's attitude towards members of the other race.

Negative values of λ correspond to an agent wanting to be far from agents of the other race, but positive values of λ indicate that an agent wants to be near agents of the other race (possibly even more so than agents of its own race if $\lambda > 1$). Wasserman and Yohe always use $\lambda = -1$, so that equal weight is attached to an agent's desire to be near its own kind and its desire to avoid the other kind. An agent will try to move if its utility falls below a certain value and Wasserman and Yohe present results for simulations in which the threshold is zero. Note that this is qualitatively similar to the present study's moving criteria, except that in the present model the effects on utility do not decay with distance from the agent. Thus, Wasserman and Yohe's value of $\lambda = -1$ corresponds to $p = 0.5$ in the language of the present simulations: an agent will move if the (weighted or unweighted) fraction of like neighbours equivalently falls below 50 per cent. Incidentally, Wasserman and Yohe also studied the effect of public goods in their work. However, this work does not include any such external factors.

At first, this consequence of increased vision can appear a bit surprising. But think about a stage where a cityscape has just begun to segregate. Now if $R = 1$, agents directly adjacent to a ghetto may wish to move. But, if R were 5, agents several sites away from the ghetto boundary are also likely to be unsatisfied. Thus, for larger R, a greater number of moves will occur in each simulation and each move increases segregation. It is this 'amplifying' effect of R during the early stages of segregation dynamics that explains the 'worsening' for the case $p = 0.5$.

4.2 The Effect of Varying R in the Stable Regime

The paper now explores the consequences of varying R for the case where the agents' preferences for their own kind are a bit smaller, but still non-zero—i.e. when societies are a bit more enlightened. In this study, the interest is not in utopian societies—i.e. one in which agents actively seek *more* diverse neighbourhoods than their current site. In fact, this is explicitly forbidden in the present model. In this model, agents move only into less diverse neighbourhoods, to find more neighbours of their own kind, to satisfy their racial preferences. Nor is the interest in unrealistic agents with a Gandhian, colour-blind world-view, where one does not care at all about the typology of one's neighbours: this corresponds to $p = 0$. It is worth emphasising, if only because many observers and commentators have mischaracterised $p = 0.5$ as 'quite colour-blind', (for example, Epstein and Axtell, 1996), that the prototypical case of $p = 0.5$ is far from representing colour-blind agents: in fact, it corresponds to an agent who never wants to be in the slightest minority under any circumstance. This agent demands that 50 per cent of its neighbours must be of its own kind, at all times. If not, this agent tries to move, aggressively and repeatedly, until it finds a suitable site or until it has checked out all possibilities.

It would be possible to pick a point half way between being a colour-blind Gandhian ($p = 0$) and one who moves continually to avoid ever being in the slightest minority under any circumstance ($p = 0.5$): this half-way point would correspond to $p = 0.25$. In order to be more realistic, the results for the case, $p = 0.3$ are first presented. Figure 4 shows the results for $p = 0.3$ and $p = 0.5$ for $R = 1$, 3 and 5. Recall that, in this paper, an unbiased random number generator with appropriate probabilities always generates the initial configuration of a society, which is always integrated. Therefore, in the rest of the paper, the initial state of the society is not displayed. All the panels in Figure 4 (and in later figures) correspond to the final, equilibrium configurations of the society.

For $R = 1$, the equilibrium societies for both cases ($p = 0.3$ and 0.5) appear to have what we have called 'small domain' or 'dendritic' segregation. In fact, they are barely distinguishable from each other. And for the $p = 0.5$ case, as demonstrated by the panels on the right half of Figure 4, the 'worsening' effect of increased vision is again quite obvious.

But for the $p = 0.3$ case, displayed by the panels on the left half of Figure 4, it is obvious that, as R is increased, the tendency of the society towards segregation is reduced dramatically and monotonously. Indeed, the equilibrium society for the $p = 0.3$, $R = 5$ case is almost completely integrated: for this case, the computed value of S is 0.03 ± 0.03! Even for $R = 3$, a very modest increase in one's vision, the value of S for the equilibrium society is already down to 0.16 ± 0.04! This result, in and of itself, is important.

Recall that it has been decided to concentrate on the worst-case scenario of $c = 0.5$ (equal numbers of two races trying to live in the same cityscape). And, even in this worst-case scenario, stable, integrated communities are formed with a rather modest increase in vision ($R = 3$–5) and for significant non-zero values of p (0.3 in this case). It is concluded that, in order to have stable, integrated societies, it is not necessary for the agents to have utopian attitudes (actively seeking more diverse neighbourhoods): this is not allowed in the present model. Nor is it necessary for the agents to have a Gandhian, colour-blind world-view, where one does not care at all about the typology of one's neighbours: this would correspond to $p = 0$. All one needs is a rather modest decrease in one's obsession with insisting that one must never be a minority in one's own neighbourhood at any length scale (which is what $p = 0.5$ means)! A decrease from $p = 0.5$ to $p = 0.3$, when combined with the powerful amplifying effect of even a modest increase in vision—from a myopic $R = 1$ to a modest $R = 3$ or 4—leads to stable, integrated societies!

The fact that stable, integrated neighbourhoods form for such modest and eminently reasonable values of the parameters can have significant impact on the perspectives of policy-makers. It provides some reason for the hope that reduction in racial neighbourhood segregation—even complete integration—is a politically and socially viable goal. This result is also reassuring from another point of view. Recall that there is robust empirical demographic evidence (Farley and Frey, 1991; Farley *et al*., 1993) that there has been some significant decrease in the intensity of racial segregation in small and medium cities in the US. Conservative commentators (Thernstrom and Thernstrom, 1997) have laboured to make this point, but usually in the context of challenging what they believe

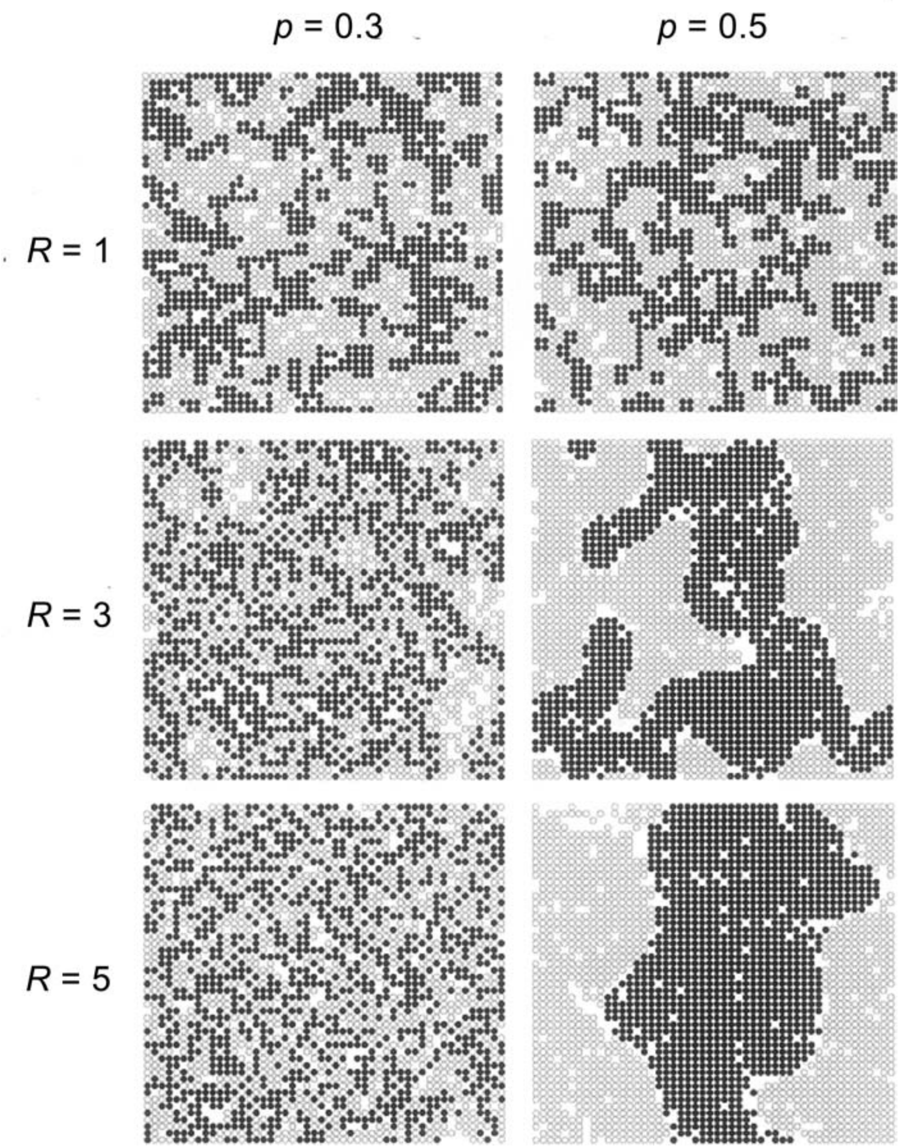

Figure 4. Equilibrium societies for different values of R and p. The left column corresponds to the stable regime ($p = 0.3$) and the right column corresponds to the unstable regime ($p = 0.5$).

to be exaggerated claims of liberal scholars or activists regarding the extent of racial neighbourhood segregation. The present work suggests that Schelling-type models should not be abandoned: when extended to include agent-vision, they have the potential of giving useful insights *and* of being consistent with empirical findings. The work strongly supports the belief that

> Initiatives aimed at changing perceptions that fuel the desire to segregate will have a broader impact on reducing or eliminating segregation (Carr, 1999, p. 144).

The simulations also lend some theoretical support to two specific policy initiatives (Yinger, 1995): to improve the availability and the flow of housing market information

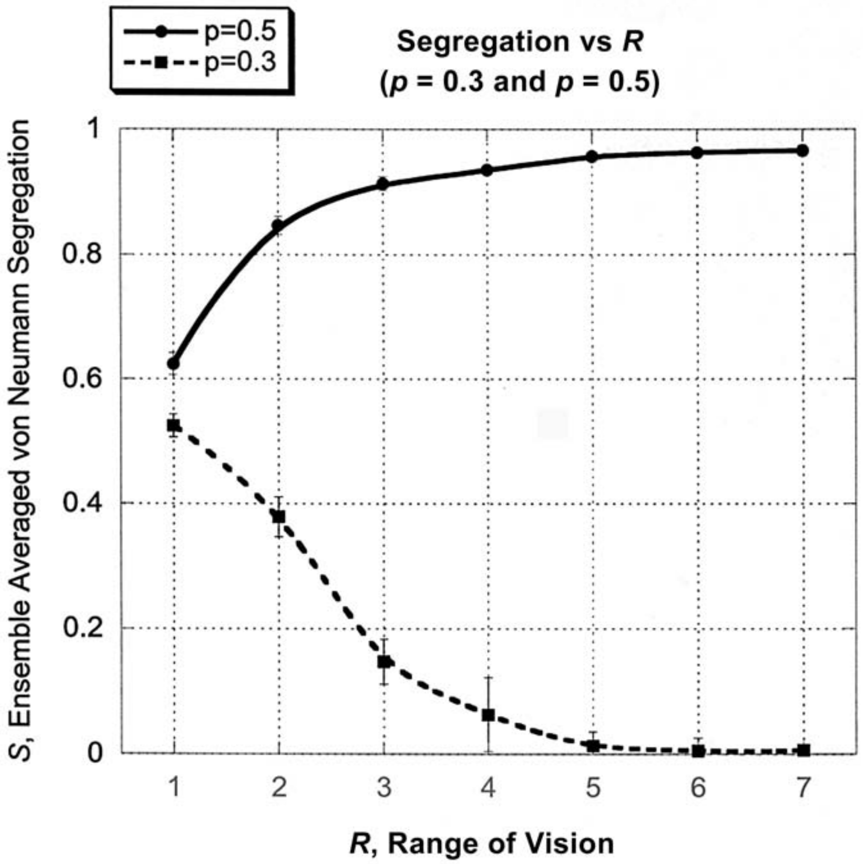

Figure 5. Segregation vs. R in the unstable and stable regimes.

(increase R) and to encourage home-seekers to consider alternative neighbourhoods where their own race is not concentrated (increase R, effectively encourage a decrease in p).

It has been discovered that the phase diagram of this model is much richer than previously believed: there are two distinct regimes of behaviour in this model. In one regime, typified by $p = 0.5$, initially integrated cityscapes segregate, the value of S increases with time and it approaches a large value at equilibrium. This equilibrium segregation, $S(R)$, increases if R is increased: this is called the unstable regime. In the other regime, exemplified by $p = 0.3$, initially integrated cityscapes segregate very little and S approaches a small value at equilibrium. This equilibrium segregation, $S(R)$, decreases if R is increased: this is called the stable regime. Figure 5 graphically summarises the results for $S(R)$, $1 \leq R \leq 7$ for the cases $p = 0.3$ and $p = 0.5$: the bifurcation and the two regimes are quite self-evident in this phase diagram. To the best of the authors' knowledge, this is a new technical result, whose importance lies in suggesting a new way of talking about the relation between agent-intent, agent-vision and the degree and nature of segregation in this and related models.

The behaviour of the simulations in the stable regime is actually a bit more straightforward than the behaviour in the unstable regime. For a moment, think about the case at hand—i.e. $c = 0.5$, $p = 0.3$. In an initial random society corresponding to these parameters, an agent has approximately a 75 per cent chance of having at least 30 per cent of its von Neumann neighbours being of the

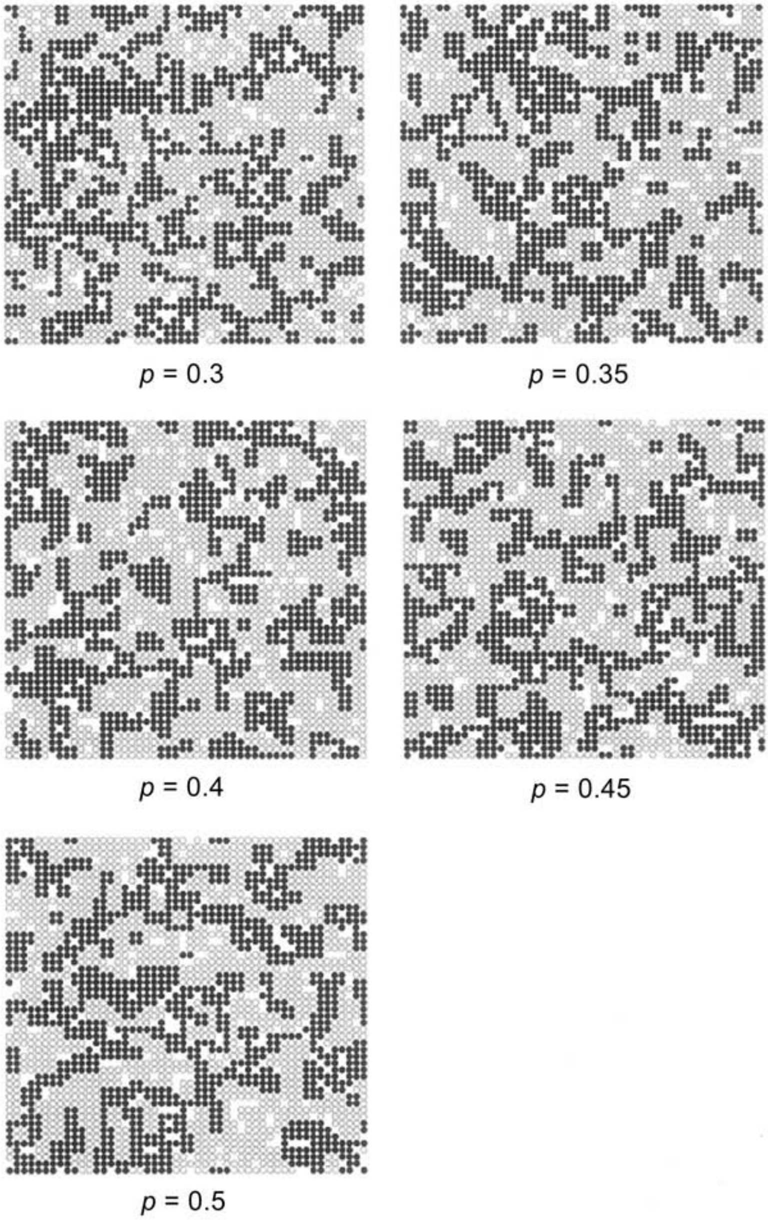

Figure 6. Segregation occurring for moderate preferences at $R = 1$ in equilibrium neighbourhoods.

same race. So, if $R = 1$, about a quarter of the agents are dissatisfied and move to 'better' locations. Since movement in this model always leaves behind some pockets of above-average concentration of minority agents, the chain reaction does indeed lead to a modest amount of segregation for the $R = 1$ case. But when the agents' vision is allowed to expand to 5, each agent has a very high probability ($>$99 per cent) of seeing at least 30 per cent of their own race. So, in the $R = 5$ simulations, very few agents are initially unsatisfied and their moves cause very few, if any, of their far-sighted and fairly tolerant neighbours to become dissatisfied.

Thus, in the case where the agents do not

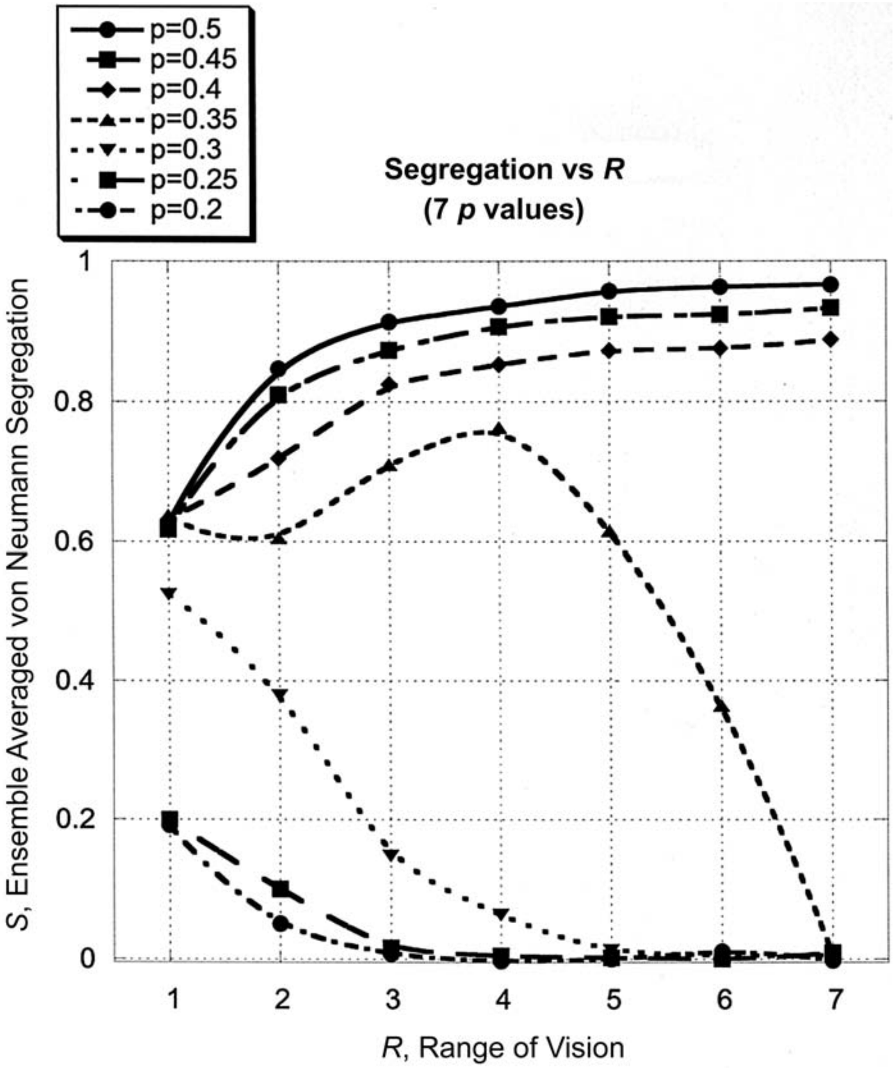

Figure 7. Segregation vs. R for several different preferences.

insist upon quite as many of their neighbours being of the same race as the proportion occurring in the entire society, with high enough vision, segregation ceases to occur! In the extreme case, if the agents were to 'see' the entire society, movement would never occur, regardless of their preference for like neighbours, because they would realise that their 'lot' could not be improved. Although most people, in reality, are likely to be more concerned with those in a fairly small neighbourhood around them, even at $R = 5$, with $p = 0.3$, virtually no segregation is seen, and the society is already quite integrated at a modest value of $R = 3$.

4.3 Threshold (Critical) Value of Preference, p_c, Separating the Two Regimes

The $R = 1$ case of this model has a certain peculiar feature which, if viewed in isolation, can lead one to develop a false sense of a disconnection between agent-intent and the final equilibrium states of the cityscape: a case of 'the invisible hand' notions taken needlessly too far. As indicated in the intro-

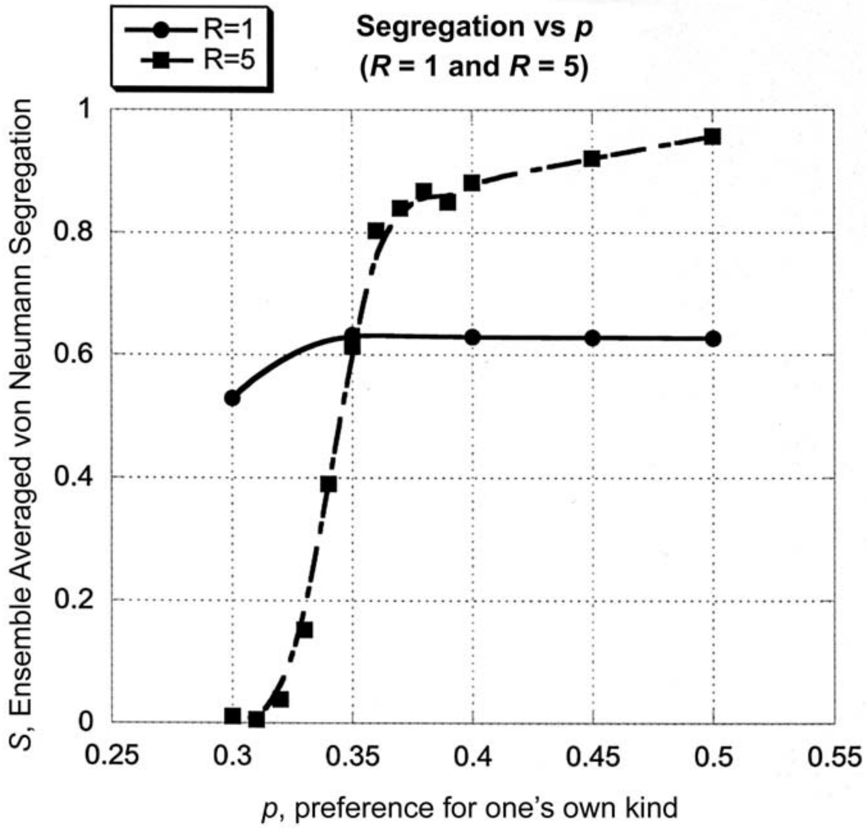

Figure 8. Segregation vs. p at $R = 1$ and $R = 5$. Increasing R has the effect of amplifying the agent's preferences.

duction, one example of such a sense of disconnect in the literature is provided by the claim, that "even quite color-blind preferences produced quite segregated neighborhoods" (Epstein and Axtell, 1996, p. 3). This section first indicates what this peculiar feature is and then goes on to demonstrate that this peculiarity is erased for higher values of R, the range of vision. When the entire scene in the parameter-space is surveyed, there is no need to invoke any mysterious, invisible hand, which somehow and unavoidably leads to segregation. A coherent and direct relationship between agent-intent and the degree and kind of segregation is restored.

The five panels in Figure 6 display the equilibrium societies for a range of values of p from 0.3 to 0.5 in increments of 0.05 for the case $R = 1$. If one had access to results only for this case of myopic vision ($R = 1$), and only for this range of p, one could perhaps not be faulted too much for concluding that this model seems to lead, *almost always*, to a *certain* amount of segregation. And that segregation $S(p)$ seems to be very weakly dependent upon p, *in this range of values of* p, suggesting a disconnect of sorts between agent-intent (p) and outcome (S). But, this is not particularly mysterious. To understand this, think of the initial, random configuration for the case at hand—i.e. $N = 50$, $c = 0.5$, $v = 0.1$—and calculate the number of agents having different numbers n of occupied neighbours (without regard to their colour). It is easy to calculate that the approximate number of agents with 4, 3, 2 and 1 occupied neighbours is 1476, 657, 110 and 8 respectively. For the 1476 agents with

$n = 4$ occupied neighbours, their decisions are *identical* for all values of p in the range $0.3 \leqslant p \leqslant 0.5$: in each case, they require 2 neighbours of their own race to be *satisfied*. The same is true for the 118 agents with $n = 1$ or 2 occupied neighbours: 1 neighbour of their own kind is needed to *satisfy* them. The only decision that varies in this range of p is the decision of 657 agents with $n = 3$ occupied neighbours who need 1 neighbour for $p \leqslant 1/3$ and 2 neighbours for $1/3 \leqslant p < 0.5$. So, one *expects* no difference among the cases $p = 0.35$, 0.4, 0.45 and 0.5 and only a modest decrease in segregation for the $p = 0.3$ case. When viewed in this light, the lack of variability in Figure 6 is a trivial consequence of excessive granularity for the $R = 1$ case.

Without the amplifying effect of increasing R, the bifurcation, that must happen somewhere between $p = 0.3$ and $p = 0.5$ (as is evident from Figures 4 and 5), would not have been apparent at all to researchers who explored only von Neumann or only Moore neighbourhoods. The symbol p_c is used to denote the threshold/critical value of p for which the initial slope of the $S(R)$ graph changes, from a negative value to a positive value. This threshold/critical preference, p_c demarcates societies that will tend to segregate from those where integrated neighbourhoods will be stable. The specific value of this threshold p_c is likely to be of interest to theorists who might explore related models, to empirical demographers and to sociologists who conduct surveys to determine agent preferences in contemporary communities.

Towards this end, it is useful to plot out $S(p, R)$ over a broader range of p, in small increments of p. There are two ways to display this three-dimensional data-set. These data are presented in Figure 7 as a family of graphs $S(R)$ for various values of p. (For all values of $p \geq 0.5$, $S(R)$ increases monotonically. This range is therefore not displayed in the figure.) It is clear that the initial slope of the $S(R)$ graph changes from a positive value to a negative value at $p_c \cong 0.35$. For clarity, in Figure 8, graphs are superimposed representing $S(p)$ for two values of R—i.e. $R = 1$ and $R = 5$. This figure demonstrates how increased vision strongly amplifies the dependence of S upon p. The very weak dependence for $R = 1$ is transformed into a steep variation for $R = 5$: S increases very rapidly between $0.32 < p < 0.36$ for $R = 5$. Thus, for moderate and realistic values of R, a coherent and monotonic relationship between agent-intent (p) and outcome (S) is restored. The value of p for which $S = 0.5$ may be taken as the dividing line, within this model, between segregated and integrated societies. This gives $p_c \cong 0.345$. Thus, even for the worst-case scenario of $c = 0.5$ (the conflict of interest is maximised when equal numbers of two races try to live in the same cityscape) and for realistic values of R, approximately 35 per cent of the parameter-space (p, R) leads to stable, integrated communities.

For the sake of completeness, it may be mentioned that there is a narrow, intermediate region of the parameter space ($p \cong 0.4$, $8 \leq R \leq 12$) where the system displays complex, metastable behaviour, strongly resembling first-order phase transitions in physical systems. The paper refrains from providing details because they are unlikely to have sociological significance.

5. Conclusions

This paper has introduced and studied an extended Schelling model of racial neighbourhood segregation in which the agents authentically ‘see’ their neighbours up to a distance R; this is called the ‘vision’. The consequences of varying R have been systematically and quantitatively explored and a qualitative sense has been developed of how vision interacts with racial preferences p and minority concentrations c to lead to a non-simple, segregation behaviour.

It has been discovered that the parameter space of this model has three regimes of behaviour: the unstable regime, where the societies invariably segregate and segregation increases as vision, R, increases; the stable regime, where integrated societies are stable and segregation decreases as vision, R, increases; and a narrow intermediate regime where a complex behaviour is observed.

The central policy implication of the study is an optimistic note: contrary to popular belief, rather modest decreases in xenophobia and/or preferences for one's own kind, *when coupled with increased vision*, can lead to stable and integrated neighbourhoods. Public policy or procedures can *effectively* increase vision—for example, realtors and clients could be provided with demographic data for $c(R)$ around various locations and/or tax incentives could be offered to avoid regions where fluctuations in $c(R)$ are above the global average. The education community and other social agents who work to lower preference for one's own kind and to increase tolerance for the 'other', can take strong encouragement from this study.

Notes

1. Massey and Denton coined the term, 'hyper-segregation' to describe this multidimensional, pervasive and persistent segregation.
2. While the original journal article (Schelling, 1971a) is a *tour-de-force* in mathematical sociology, the less mathematically inclined can get the same insights from later essays written for broader audiences (Schelling, 1971b, 1978).
3. This delightfully worded question was first asked (Martin, 1999) in a slightly different context of contingency and specificity of formal models in the area of international security studies, "I think of this as the generic 'didn't Schelling already say that?' question".
4. We wish to assert that this sense of inevitability of racial segregation, whether of admiring scholars or of politically motivated groups, receives no support from Schelling's own writings, which are quite circumspect and display an awareness of the contingencies of his celebrated model.
5. In its standard demographic usage, the term 'neighbourhood' evokes a region with fixed boundaries of a specified size. The term 'cityscape' is here used for this and the term 'neighbourhood' is reserved to denote the agent-specific and variable subset of homes within a certain distance of the instantaneous location of the agent.
6. It turns out that R, p and c are the interesting, essential and dominant independent variables in this model, whereas v affects the segregation peripherally. For this reason, all results reported in this paper correspond to a typical value of $v = 0.1$.

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