Supplementary Text

Appendix S1. Extremely strong selection

Here we describe the results of our simulations when selection is extremely strong or δs ≈1. To compare with Rendell et al.'s (2010) results, we consider synchronous updating with Mode II (vertical and horizontal) transmission. Figure S1 compares pSL, the long-term average frequencies of social learners (SL), in lattice-structured and well-mixed populations when maladaptive behavior is extremely costly. When the environment is fairly stable, pSL is higher in lattice-structured than well-mixed populations, which suggests that spatial structure favors the evolution of SL. Figure S1 shows that there are threshold values of L above which pSL drastically increases. While the threshold values are smaller for higher cost of individual learning (Figure S1 (a) and (b)), the difference in pSL between lattice-structured and well-mixed populations for a fixed value of L is largest for moderate cost of individual learning (Figure S1 (c) and (d); comparable with Figure 1 (A) in Rendell et al. (2010)). Although the increase of pSL is slower in Rendell et al. (2010), the outcome of our model under extremely strong selection is similar to that of Rendell et al. (2010).

Appendix S2. Different update rules

Spatial game theory has shown that update rules can alter the outcomes of evolutionary models. In the main text, we assume the birth-death rule, where an individual is chosen to reproduce with probability proportional to fitness and then another individual is chosen at random to die. Here we consider two other update rules, the Fermi and death-birth rules.

**Fermi rule**

A focal individual, X, adopts the learning strategy of a randomly chosen neighbor, Y, with probability 1/{1+exp[−α(PY−PX)]}, where PX and PY are the fitnesses of X and Y, respectively, and α is a measure of the intensity of selection. In the asynchronous updating model, a focal individual is chosen at random from all individuals for each time period. In the synchronous updating model, every individual plays a role as X once for each time period. Simulation settings except for the update rule are the same as in the main text.

Figures S2 and S3 compare pSL in lattice-structured and well-mixed populations under Mode I and Mode II transmission, respectively. Results are qualitatively equivalent to those for the birth-death rule. Under unstable environments, pSL is lower in lattice-structured than well-mixed populations, where the difference in pSL can be considerably large when maladaptive behavior is highly costly. When the environment is relatively stable, pSL in lattice-structured populations can exceed that in a well-mixed population, which is more likely for the asynchronous than synchronous updating model.

**Death-birth rule**

An individual is chosen to die from all individuals and one of the neighbors replaces it with probability proportional to fitness. We only consider asynchronous updating (a death-birth rule with synchronous updating would have to assume that all individuals die prior to reproduction). Figures S4 and S5 compare pSL in lattice-structured and well-mixed populations under Mode I and Mode II transmission, respectively. The results are qualitatively the same as those for the birth-death and Fermi rules.

Figure S6 compares pSL in lattice-structured populations across update rules. There is no qualitative difference among update rules under weak selection and/or low cost of maladaptive behaviors. However, under strong selection and high cost of maladaptive behavior, the Fermi rule can promote the evolution of social learning.

Appendix S3. Synchronous and asynchronous updating with high cost of maladaptive behavior

In Figures 1 and 2, pSL generally increases with increasing L and there are threshold values of L above which pSL is positive. Mostly, the threshold values are smaller for synchronous than asynchronous updating (Figures 1a-d and 2a-c). This is presumably because the spread of adaptive behavior tends to be faster in synchronous than asynchronous updating. However, this trend is reversed for Mode II transmission when the cost of maladaptive behavior and the selection intensity are large both in lattice-structured and well-mixed populations (Figure 2d).

To understand how this reversal occurs, we compare population dynamics with Mode II transmission for s = 0.15, δ = 1 (Figure 2b) and for s = 0.15, δ = 5 (Figure 2d). Specifically, we track changes in the frequencies of IL, SLC and SLW for 50 generations following an environmental change, where initially each individual is either IL or SLW with equal probability.

Figures S7 and S8 show changes in the frequencies of phenogenotypes averaged over simulation runs under weak (δ = 1) or strong (δ = 5) selection, respectively. Under weak selection, SLC becomes more prevalent than IL at an earlier generation for synchronous than asynchronous updating both in well-mixed and lattice-structured populations (Figure S7). Under strong selection, however, SLC becomes more prevalent than IL at a later generation for synchronous than asynchronous updating, that is, the trend is reversed (Figure S8). This is at least partly because asynchronous updating can accelerate the spread of adaptive behavior under strong selection, which makes the increase of SLC and/or decrease of IL faster. This is particularly true for the first generation following an environmental change: during the first generation, no SLC exists in synchronous updating, while SLC gradually increases toward the end of the first generation in asynchronous updating. In fact, this point is illustrated in Figure S8, in which the initial increase of IL is smaller for asynchronous than synchronous updating both in well-mixed and lattice-structured populations.

Appendix S4. Movies

A supplementary movie file named lebs2012\_movies.zip is downloadable from <https://sites.google.com/site/tmrkohei/storage>. Movie S1 and S2 show the evolutionary dynamics in a lattice-structured population for initial 1000 generations with Mode I (oblique) and Mode II (vertical and horizontal) transmission, respectively. Asynchronous updating is assumed. Parameter values are: s = 0.05, c = 0.01, δ = 5, L = 30. The blue, white and pink cells represent IL, SLC and SLW individuals, respectively, located in a lattice.

Macintosh HD:Users:kohei:Desktop:extreme:fig_S1.eps

Figure S1. The upper row shows the long-term average frequencies of SL with Mode II (vertical and horizontal) transmission and synchronous updating, plotted against environmental stability. The lower row shows the long-term average frequencies of SL, plotted against cost of individual learning. Cost of maladaptive behavior δs is set to 0.99.

Macintosh HD:Users:kohei:Desktop:ws2:fig_A1.eps

Figure S2. Long-term average frequencies of SL with oblique (Mode I) transmission plotted against the environmental stability using the Fermi rule as the update rule.

Macintosh HD:Users:kohei:Desktop:ws2:fig_A2.eps

Figure S3. Long-term average frequencies of SL with vertical and horizontal (Mode II) transmission plotted against the environmental stability using the Fermi rule as the update rule.

Macintosh HD:Users:kohei:Desktop:ws2:fig_S3.eps

Figure S4. Long-term average frequencies of SL with oblique (Mode I) transmission plotted against the environmental stability using the death-birth rule as the update rule.

Macintosh HD:Users:kohei:Desktop:ws2:fig_S4.eps

Figure S5. Long-term average frequencies of SL with vertical and horizontal (Mode II) transmission plotted against the environmental stability using the death-birth rule as the update rule.

Macintosh HD:Users:kohei:Desktop:l:figS5.eps

Figure S6. Comparison of the long-term average frequencies of SL among update rules plotted against the environmental stability. The left column ((a), (d), (g) and (j)) represents the asynchronous updating model with Mode I transmission. The center column ((b), (e), (h) and (k)) represents the asynchronous updating models with Mode II transmission. The right column ((c), (f), (i) and (l)) represents the synchronous updating model. “Strong” represents α = 10 in the Fermi rule or δ = 5 in birth-death and death-birth rules. “Weak” represents α = 2 in the Fermi rule or δ= 1 in the birth-death and death-birth rules.

Macintosh HD:Users:kohei:Desktop:20121205:mix:fig_S7.eps

Figure S7. The blue, red and green circles represent the frequencies of IL, SLC and SLW in the population, respectively. Parameter values are: δ= 1, s= 0.15.

Macintosh HD:Users:kohei:Desktop:mix:fig_S7x.eps

Figure S8. The blue, red and green circles represent the frequencies of IL, SLC and SLW in the population, respectively. Parameter values are: δ= 5, s= 0.15.