Emotions as infectious diseases in a large social network: the SISa model

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Supplementary Material

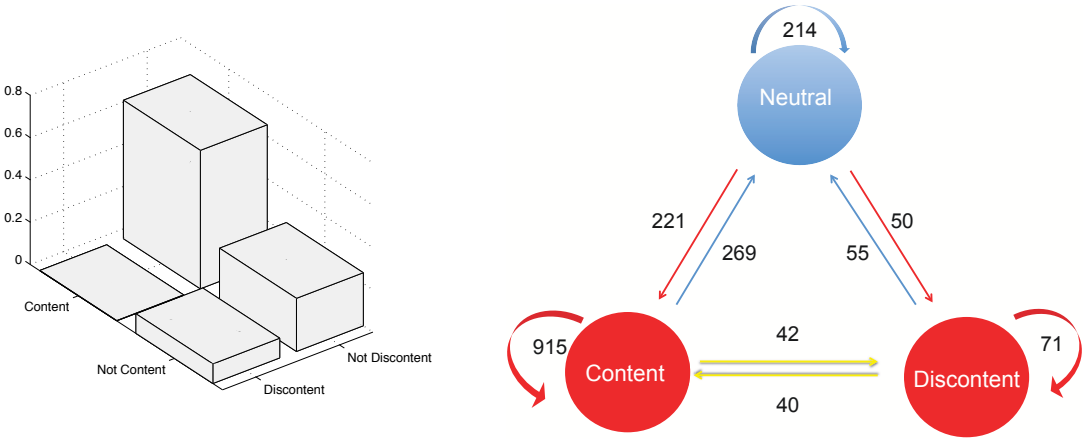
Framingham Heart Study Dataset

In this study, we evaluate the assumption that emotions behave like infectious agents. We use data from the Framingham Heart Study (Dawber, 1980) and the framework discussed above to test whether positive and negative emotions fit the dynamics of an infectious disease. The Framingham study was initiated in 1948 in Framingham, Massachusetts and has continued enrolling subjects through the present. We examined individuals in the Offspring Cohort, enrolled starting in 1971. Subjects come to a central facility at regular intervals (approximately every 3 years) for medical examination and collection of other survey data. In additional to information on mental and physical health, subjects were asked to name at least one close friend at each exam, and were also connected to all first-order relatives, coworkers, and residential neighbours.

For each subject, the following social connection data is available: (i) each other person to whom they were connected, (ii) the dates of initiation and termination of that relationship, (iii) the type of relationship (neighbour, coworker, first-degree relative, or friend), and (v) the geographic distance between the two subjects. The social network for each exam was constructed by creating a network matrix G, where $G_{ijk} = 1$ if subject i nominated subject j as a connection before or during the time that subject i was administered exam k. All relationship types are mutual except for friendships, which are self-nominated, such that $G_{ijk} \neq G_{jik}$ is possible for friendships.

Individuals in the Framingham Heart Study were administered a widely validated psycho-social exam called the CES-D (The Center for Epidemiologic Studies Depression Scale, (Radloff, 1977)) at exams 6 and 7 (administered on average in 1997 and 2000). The full version of this survey style exam is commonly used to classify depressive symptoms (Rush, 2007; Radloff, 1977; Schroevers et al., 2000) and a subscale which comprises a distinct factor (Thorson and Powell, 1993; Joseph and Lewis, 1995; Pressman and Cohen, 2005; Radloff and Teri, 1986; Sheehan et al., 1995) has also been validated as a measure of positive affect (Moskowitz, 2003; Ostir et al., 2000; Pressman and Cohen, 2005). Similar measures of positive affect using subjective surveys have been shown to be highly correlated with objective measures of well-being (Oswald and Wu, 2010). We have chosen to call this positive state measured by the CES-D *content*, though it has been called 'happiness' by others. It is also related to optimism and self-esteem. The negative emotion measured by the full CES-D scale is generally called 'depression', though as described in (Rush, 2007), this measure is generally agreed to represent a long-term emotional state of depressive symptomology that is distinct from (and less severe than) the mental illness state of clinical depression. To prevent confusion, we have called this measure *discontent* throughout the paper.

A content score and a discontent score were calculated for each subject from the raw responses to 20 multiple choice questions from the CES-D. The questions asked subjects to judge the frequency with which they experienced a particular feeling or behaviour, with available answers being 0=(rarely or none of the time, <1 day per week), 1=(some or a little of the time, 1-2 days per week), 2=(occasionally or a moderate amount of the time, 3-4 days per week) and 3=(most of the time, 5-7 days per week). Subjects are classified as *content* if they scored the maximum value of 3 on each of four particular questions related to positive feelings. Summing the answers to the 16 CES-D questions related to negative feelings and adding inverted answers to the 4 positive questions, subjects are classified as *discontent* if they have a total score greater than 16 (out of a possible 60). Individuals who are neither content nor discontent are classified as *neutral*. The distribution of emotional states among our subjects is shown in Figure S1A. We find that less than 1 out of every 1000 subjects are both content and discontent, validating our classification of emotions into the three states content, discontent and neutral. Figure S2B shows the number of people who made each transition between the two examinations.



(a) (b)

Figure S1. A) The distribution of subjects between four emotional states measured by the CES-D. Subjects were classified as first as either 'content' or 'not content', and then separately as 'discontent' or 'not discontent'. Individuals who are neither 'content' nor 'discontent' are classified as 'neutral'. As expected, very few people who are classified as 'content' are also classified as 'discontent', while those that are 'not content' may be 'discontent' or 'not discontent'. Fraction content=0.63, discontent=0.09, neutral=0.28. B) Each circle represents an emotional state, and the arrows and numbers display the number of transitions that occurred between each state.

Super-infection: Direct transitions between content and discontent infected states

Figure S1B shows that direct transitions between the content and discontent states are sometimes observed. There are two possibles explanations for these transitions. Firstly, because exams are only every 3 years, it is possible that some of these individuals actually moved through the neutral state, and thus made two transitions between observations (ie content to neutral to discontent). The second explanation is that these individuals actually moved directly between these states via 'super-infection'. We can predict how often we would expect double transitions to occur within the 3 year window, based on the estimates for each individual transition. These predictions are lower than the observed number of direct transitions. Thus the difference between the observed and expected can be interpreted as the rate of actual direct transitions. This is explained in detail below. The estimated rates of all transitions are visualized in Figure 3 in the main text.

For a Markov process, if an event occurs at a rate a, then the probability that this event has occurred after a time Δt is $1 - e^{-a\Delta t}$. If two events occur at rates a_1 and a_2, and must occur in that sequential order, then in a time period Δt the probability that both occur is :

$$\int_0^{\Delta t} a_1(1 - e^{-a_2(\Delta t - t)})\, dt = a_1\Delta t - \frac{a_1}{a_2}(1 - e^{-a_2\Delta t}) \tag{1}$$

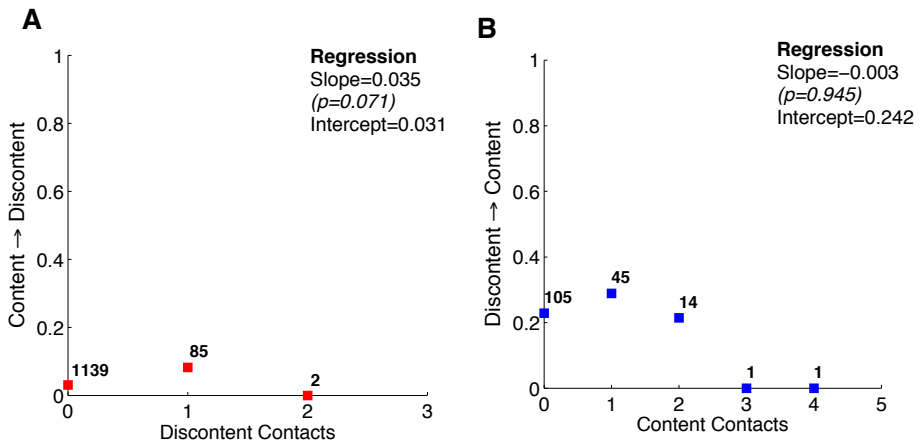


Figure S2. Observed rates of direct transitions between content and discontent and vice versa. We see no significant dependance on the number of infected contacts for these direct transitions.

From this expression we can calculate the expected rate of double transitions between content and discontent (going through the neutral state) in a single time period between exams.

For content $\rightarrow$ discontent, the two transitions that must occur are : content to neutral ($a_1 = g_c$) and neutral to discontent ($a_2 = a_d + \beta_d n_d$). There values are:

- $g_c = 0.088 \pm 0.006$ /year
- $a_d = 0.040 \pm 0.006$ /year
- $\beta_d = 0.04 \pm 0.02$ /year

For discontent $\rightarrow$ content, the two transitions that must occur are : discontent to neutral ($a_1 = g_d$) and neutral to content ($a_2 = a_c + \beta_c n_c$). There values are:

- $g_d = 0.13 \pm 0.02$ /year
- $a_c = 0.18 \pm 0.01$ /year
- $\beta_c = 0.02 \pm 0.01$ /year

Using Equation 1, the expected rate of double transitions are (with standard deviations included):

- content to discontent: $c_{expected} = (0.004 \pm 0.001) + (0.004 \pm 0.001) * n_d$ /year
- discontent to content: $c_{expected} = (0.025 \pm 0.004) + (0.003 \pm 0.002) * n_c$ /year

Observed double transition, from Figure S2:

- content to discontent: $c_{observed} = (0.013 \pm 0.002) + (0.014 \pm 0.019) * n_d$ /year
- discontent to content: $c_{observed} = (0.097 \pm 0.016) + (-0.0013 \pm 0.043) * n_c$ /year

Note that the contact dependent terms for the double transition are observed to be non-significant, and also expected to be overlapping with zero due to the margins of error on the calculated rates. We hence ignore them for the reported rates of double transitions. The rate of direct bypass transitions is the extra number of transitions that cannot be accounted for by double transitions. This is found by subtracting the expected rates ($c_{expected}$) from the observed rates ($c_{observed}$)

Rate of direct bypass transition:

- content to discontent: $s_{cd} = (0.009 \pm 0.003)$ /year
- discontent to content: $s_{dc} = (0.07 \pm 0.02)$ /year

It is interesting to note that in Figure S1B, the number of individuals transitioning directly from content to discontent is very similar to number transitioning from discontent to content. The same is true of the transitions between content and neutral, and between discontent and neutral. Thus the system is in *detailed balance*, suggesting a unique subset of the population may be responsible for the direct transitions between content and discontent. For example, it could be those suffering from bipolar disease, who represent about 1% of the population and switch between manic and discontent episodes on the order of months.

References

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CES-D Questions.
Questions #4, 8, 12 and 16 were used to construct the 'content' scale.

1. I was bothered by things that don't usually bother me.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
2. I did not feel like eating; my appetite was poor.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
3. I felt that I could not shake off the blues even with the help of my family or friends.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
4. I felt that I was just as good as other people.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
5. I had trouble keeping my mind on what I was doing.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
6. I felt depressed.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)
7. I felt everything I did was an effort.
   - ○ Rarely or none of the time (<1 day)
   - ○ Some or a little of the time (1-2 days)
   - ○ Occasionally or a moderate amount of the time (3-4 days)
   - ○ Most or all of the time (5-7 days)

8. I felt hopeful about the future.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

9. I thought my life had been a failure.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

10. I felt fearful.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

11. My sleep was restless.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

12. I was happy.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

13. I talked less than usual.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

14. I felt lonely.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

15. People were unfriendly.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

16. I enjoyed life.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

17. I had crying spells.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

18. I felt sad.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

19. I felt that people disliked me.
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

20. I could not get "going".
- ○ Rarely or none of the time (<1 day)
- ○ Some or a little of the time (1-2 days)
- ○ Occasionally or a moderate amount of the time (3-4 days)
- ○ Most or all of the time (5-7 days)

Scoring for All Except Questions 4, 8, 12, and 16:
- 0 points Rarely or none of the time (< 1 day)
- 1 point Some or a little of the time (1-2 days)
- 2 points Occasionally or a moderate amount of the time (3-4 days)
- 3 points Most or all of the time (5-7 days)

For questions 4, 8, 12, and 16, the scoring is exactly the same except that it is reversed: "Most or all of the time" is scored 0 points, "Rarely or none of the time" is scored 3 points, etc.