S1 File

S1 Appendix  Derivations of theoretical results. The Lagrangian for the problem to optimize (9), subject to the epidemiological dynamics given by (1), reads

\[ L = \sum_j \sum_{t=0}^T \delta_j \left\{ \left( S_{jt} + I_{jt} \right) u^e_j(c_j) + Q_{jt} u^q_j + R_{jt} u^r_j + D_{jt} u^d_j + \delta_j \lambda_{jt}^r \left( -S_{jt+1} + S_{jt} - \beta c_{jt} S_{jt} \sum_l I_{lt} \right) \right. \\
+ \delta_j \lambda_{jt}^i \left( -I_{jt+1} + \beta c_{jt} S_{jt} \sum_l I_{lt} \right) + \delta_j \lambda_{jt}^q \left( -Q_{jt+1} + (1 - \alpha_q - \gamma_q) Q_{jt} + I_{jt} \right) \\
+ \delta_j \lambda_{jt}^r \left( -R_{jt+1} + R_{jt} + \gamma_q Q_{jt} \right) + \delta_j \lambda_{jt}^d \left( -D_{jt+1} + \alpha_q Q_{jt} \right) \left\} \right. \]  \hspace{1cm} (20)

The first-order necessary conditions (10a) to (10f) for optimal social distancing are obtained by setting equal to zero the derivatives of the Lagrangian with respect to \( c_{jt} \) (equation 10a), \( S_{jt} \) (equation 10b), \( I_{jt} \) (equation 10c), \( Q_{jt} \) (equation 10d), \( R_{jt} \) (equation 10e), and \( D_{jt} \) (equation 10f), for all \( j \) and all \( t \).
S2 Appendix  Calibration of epidemiological parameters.

We estimate COVID-19 mortality rate $\alpha_j^q$ for each population group $j$ as follows: We use the daily number of new known infections and new deaths in Germany reported by the Robert Koch Institute \cite{1}. Here, we consider the time period from January 6 to April 26, 2020, and aggregate them to the weekly level. We use (1) and replace $\theta_j I_{jt}$ and $\alpha_j^q Q_{jt}$ with the time series of reported new known infections $\Delta Q_{j,t+1}$ and new deaths $\Delta D_{j,t+1}$ respectively. We suppose $Q_{j,1} = 0$, since the estimation relies on data $\Delta Q_{j,t}$, making $Q_{j,1}$ unimportant and because reported cases in January and early February were probably still affected by imported cases \cite{2,3}. We then estimate $\alpha_j^q$ by means of ordinary least squares

$$\min \{ \alpha_j^q \} \sum_{j=1}^{4} \sum_{t=1}^{15} (Q_{j,t} \alpha_j^q - \Delta D_{j,t+1})^2,$$

subject to $Q_{j,t+1} = (1 - \gamma) Q_{jt} + \Delta Q_{j,t+1} - \Delta D_{j,t+1}$. This gives $\alpha_j^q$ as shown in S1 Table.

Our estimate for $\theta_j$ is obtained from the time period until an infection is detected, on average, which we assume to be 5 days, which corresponds to an exponential detection rate of $1/5$ days in a continuous time model. In our discrete time model the detection rate is $\theta_j = 1 - e^{-7/5} = 0.75$ per week. The initial basic reproduction number $R_0$ was estimated to be between 2 and 3 \cite{4,7}, although higher values with a range of 3 to 12 \cite{8} or up to 14.8 \cite{9} have been suggested. We calibrate our model to the more conservative and widely accepted value of $R_0 = 3$ for the German population during the initial phase of the pandemic. From this we obtain $\beta = 2.25$.

We calibrate $\gamma_j^q$ such that 90% of COVID-19 patients recover within two weeks after the infection is detected. In our discrete time model the recovery rate is $\gamma_j^q = 1 - e^{-7/6}$ per week. The assumption of an exponential distribution captures the fact that some individuals need much longer to recover.

This implies the infection fatality ratios $\text{IFR}_j = \frac{\alpha_j^q}{\alpha_j^q + \gamma_j^q}$ as reported in S1 Table. The estimated mean IFR of 3.86 percent for the German population is close to the fatality rates reported by the WHO \cite{10}.
S1 Table  Calibrated epidemiological parameters.

|                    | All          | Population group |
|--------------------|--------------|------------------|
|                    |              | Young men (j=1)  |
|                    |              | Young women (j=2) |
|                    |              | Old men (j=3)    |
|                    |              | Old women (j=4)  |
| $\alpha_j^q$       | 0.0306       | 0.00285          |
| $\beta/N_0$        | 2.25         | 2.25             |
| $\gamma_j^q$       | 0.689        | 0.689            |
| $\theta_j$         | 0.75         | 0.75             |
| IFR$_j$ (%)        | 3.86         | 0.41             |

Parameters of the model for individuals in the respective population groups. All rates are in units of 1/week.

S3 Appendix  Descriptive statistics of survey data.

Here we present some extra information about the data we used in our empirical model. S2 Table presents the summary statistics for the variables of interest. S1 Fig shows histograms of surveyed impure altruistic physical social contacts (left) and estimated contacts under purely selfish behavior (right) compared to normal. Overall the purely selfish contacts are higher, although still a substantial fraction reports a very low number of physical social contacts. S3 Table contains the full information about the individual costs of an infection for the different population groups, estimated by means of ordinary least squares. Table shows the result of the statistical test if there is a difference in the responses collected before and after the introduction of the contact ban. We do not find evidence that the contact ban affected the weights attached to the different reasons for individual protection efforts. Finally, S2 Fig shows a significant positive correlation between the reported physical social contacts from the survey and the mobility information derived from cell-phone data.

S2 Table  Summary statistics of the survey data.

|                                | N | Mean | Median | Std. Dev. | Min. | Max. |
|--------------------------------|---|------|--------|-----------|------|------|
| Change in contacts             | 3495 | 4.81 | 4      | 3.48      | 1    | 15   |
| Age                            | 3501 | 50.05| 51     | 15.40     | 18   | 97   |
| Female                        | 3501 | 0.51 | 1      | 0.50      | 0    | 1    |
| Family members and friends     | 3495 | 14.10| 10     | 13.02     | 0    | 100  |
| Reason for defense efforts (%) |      |      |        |           |      |      |
| To protect me                  | 3499 | 51.96| 50     | 21.75     | 0    | 100  |
| To protect family & friends    | 3499 | 30.03| 30     | 15.90     | 0    | 100  |
| To protect others              | 3499 | 18.01| 20     | 14.37     | 0    | 100  |
| Expectations                   |      |      |        |           |      |      |
| Expected income change         | 3494 | 6.98 | 8      | 2.41      | 1    | 15   |
| P(get infected) (in %)         | 3486 | 38.10| 40     | 22.40     | 0    | 100  |
| P(get slightly ill) (in %)     | 3404 | 50.65| 50     | 21.71     | 0    | 100  |
| P(get in acute danger) (in %)  | 3404 | 34.65| 30     | 20.88     | 0    | 100  |
| Change wrt. regulation (%)     |      |      |        |           |      |      |
| According to regulations       | 3501 | 0.30 | 0      | 0.46      | 0    | 1    |
| Less than required             | 3501 | 0.07 | 0      | 0.26      | 0    | 1    |
| More than required             | 3501 | 0.63 | 1      | 0.48      | 0    | 1    |
| General preferences            |      |      |        |           |      |      |
| Patience                       | 3499 | 8.11 | 9      | 2.12      | 1    | 11   |
| Observations                   | 3501 |      |        |           |      |      |
S1 Fig. Histograms of surveyed impure altruistic physical social contacts (left), and estimated contacts under purely selfish behavior (right) compared to normal.

S3 Table Estimates for individual present values of getting infected for the four groups, $V_{j0}$.

|            | Young men | Young women | Old men | Old women |
|------------|-----------|-------------|---------|-----------|
|            | $(j=1)$   | $(j=2)$     | $(j=3)$ | $(j=4)$   |
| Mean       | -5,780    | -7,117      | -6,360  | -7,522    |
| SD         | 5,201     | 5,480       | 5,840   | 6,113     |
| Median     | -3,620    | -3,991      | -3,631  | -6,072    |

Momentary utility is measured relative to the maximum of utility derived from physical social contacts under normal conditions (absent pandemic), $\max_{c,t} u^c(c_{jt}) = 1$. Present values are obtained applying the weekly discount factor for the baseline calibration, $\delta = 0.995$. 
S4 Table. Effects of the contact ban announcement.

|                          | Motivation                  | Contacts                       |
|--------------------------|-----------------------------|--------------------------------|
|                          | Protect me (1)              | Protect family & friends (2)   | Protect others (3) | Past week (4) | Less than required (5) | As required (6) | More than required (7) |
| Post ban announcement    | 0.976 (0.825)               | -0.875 (0.613)                | -0.101 (0.570)    | -0.422***     | -0.016***                | 0.086***          | -0.070***               |
| Age                      | 0.218*** (0.028)            | -0.107*** (0.021)             | -0.110*** (0.020) | -0.012**      | -0.002***               | -0.003***          | 0.005***               |
| Female                   | 0.961 (0.839)               | 0.697 (0.625)                 | -1.658*** (0.582) | -0.966***     | -0.054***               | -0.027             | 0.081***               |

**Education**

- University degree
  - -2.277 (4.506) 10.760* (6.460) -8.483 (6.026) 0.909 (1.682) 0.061 (0.068) -0.018 (0.155) -0.043 (0.167)
- A-levels/vocational training
  - -2.650 (4.478) 11.943* (6.449) -9.292 (6.007) 0.840 (1.682) 0.037 (0.068) -0.051 (0.155) 0.015 (0.167)
- Secondary school
  - 1.460 (4.442) 10.378 (6.435) -11.838** (5.987) 0.819 (1.679) 0.052 (0.068) -0.054 (0.154) 0.002 (0.167)
- Secondary general school
  - 0.473 (4.474) 10.688* (6.443) -11.161* (5.988) 1.114 (1.682) 0.045 (0.068) -0.032 (0.154) -0.013 (0.167)

**Household income**

- 1,500 – 3,000
  - 0.000 (1.203) 0.579 (0.879) -0.579 (0.771) 0.013 (0.201) -0.043** (0.019) -0.008 (0.027) 0.051* (0.028)
- 3,000 - 4,000
  - -0.940 (1.286) 1.044 (0.949) -0.104 (0.877) -0.277 (0.221) -0.081*** (0.019) -0.027 (0.030) 0.107*** (0.031)
- ≥ 4,000
  - 0.350 (1.433) 0.201 (1.040) -0.551 (0.949) -0.624*** (0.233) -0.057*** (0.021) -0.070** (0.031) 0.127*** (0.033)

Observations: 3481 3481 3481 3478 3483 3483 3483

Notes: OLS estimations for a weighted sample. Respondents before the ban are reweighted to match the mean values in age, gender, education, and income of those after the ban. Standard errors in parentheses. * p < 0.1, ** p < 0.05, *** p < 0.01

S2 Fig. Correlation between survey responses and cell phone movements.

Plot shows the correlation between the average survey responses and reductions in cell phone movements per county.
S4 Appendix  Numerical solution method and AMPL programming code

Numerically, the problem to solve the set of dynamic equations that describe epidemiological dynamics, and the optimality conditions, (1), (10a), (10b), and (11), along with initial conditions for the number of susceptibles, infected, and recovered from all groups of individuals, and transversality conditions, is usually a more difficult task than solving an optimization problem. In our numerical approach to compute the utilitarian optimum, we thus use the following lemma:

**Lemma 1.** The social optimization problem (9) is equivalent to

\[
\dot{W} = \max_{\{c_{jt}\}} \sum_j \sum_{t=0}^T \delta_t^j \left( (S_{jt} + I_{jt}) u^e_j(c_{jt}) + I_{jt} \delta_j \theta_j V^q_{jt} \right) \quad \text{subject to (1),}
\]

where \( c_{jt} \) is the individual choice of physical social contacts in Nash equilibrium and \( V^q_{jt} \) is the individual present value of becoming a COVID-19 patient, \( V^q_{jt} \), as determined by (5).

**Proof.** The optimality conditions for (22) can be written as

\[
\begin{align*}
\dot{u}_j^e(c_{jt}) + \delta_j \frac{S_{jt} + I_{jt}}{S_{jt} + I_{jt}} \beta I_t \left( \lambda^s_{jt} - \lambda^i_{jt} \right) &= 0 \\
\dot{u}_j^e(c_{jt}) - \lambda^s_{jt,t-1} + \delta_j \left( 1 - \beta c^s_{jt} I_t \right) \lambda^s_{jt,t-1} + \delta_j \beta c^s_{jt} I_t \lambda^i_{jt} &= 0 \\
\dot{u}_j^e(c_{jt}) + \delta_j \theta_j V^q_{jt,t-1} - \lambda^s_{jt,t-1} + \delta_j (1 - \theta_j) \lambda^i_{jt} + \delta_j \theta_j \lambda^q_{jt} &= \sum_i \delta_i \beta c^i_{jt} S_{jt} \left( \lambda^s_{jt} - \lambda^i_{jt} \right) \\
-\lambda^q_{jt,t-1} + \delta_j (1 - \gamma^q_{jt} - \alpha^q_{jt}) \lambda^q_{jt,t} + \delta_j \gamma^q_{jt} \lambda^q_{jt,t} + \delta_j \alpha^q_{jt} \lambda^d_{jt,t} &= 0 \\
-\lambda^r_{jt,t-1} + \delta_j \lambda^r_{jt,t-1} &= 0 \\
-\lambda^d_{jt,t-1} + \delta_j \lambda^d_{jt,t-1} &= 0,
\end{align*}
\]

with transversality conditions \( \lambda^h_{jt} = V^h_j \) for \( h \in \{s, i\} \) and \( \lambda^h_{jT} = 0 \) for \( h \in \{q, r, d\} \). The transversality conditions together with (23a), (23c) and (23d) imply \( \lambda^s_{jt} = \lambda^r_{jt} = \lambda^d_{jt} = 0 \) for all \( t \) in this auxiliary problem. Equations (23a) and (23b) are identical to (10a) and (10b). Using the above result \( V^q_{jt,t-1} = \lambda^q_{jt,t} \), equation (23c) is equivalent to (11). \( \square \)

In the online Supporting Information we provide the AMPL code for computing the utilitarian optimal epidemiological dynamics, as shown in Figure 1.

To compute the Nash equilibrium with selfish individuals, we solve the system of equations (7), (8) and epidemiological dynamics (1) for \( t = 0, \ldots, T \) with \( T = 20 \) weeks. This is done by means of a code similar to the one below, except that the objective function (9) is dropped (i.e. there is no optimization) and that equations (7) and (8) are imposed as conditions.

The number of contacts chosen by imperfectly altruistic individuals is computed from the optimal number of contacts and the number of contacts in the Nash equilibrium with selfish individuals, using these results in equation (13). Using the resulting number of contacts in (1), we simulate the resulting epidemiological dynamics and welfare in the Nash equilibrium with imperfectly altruistic individuals.

The codes used for computing the results for the other figures are all based on modifications of this code and are available upon request.
References

1. Robert Koch Institut. Fallzahlen in Deutschland; 2020. Available from: https://npgeo-corona-npgeo-de.hub.arcgis.com/datasets/dd4580c810204019a7b8eb3e0b329dd6_0.

2. Pinotti F, Di Domenico L, Ortega E, Mancastroppa M, Pullano G, Valdano E, et al. Lessons learnt from 288 COVID-19 international cases: importations over time, effect of interventions, underdetection of imported cases; 2020. Available from: https://www.medrxiv.org/content/10.1101/2020.02.24.20027326v1.full.pdf

3. Rothe C, Schunk M, Sothmann P, Bretzel G, Froeschl G, Wallrauch C, et al. Transmission of 2019-nCoV infection from an asymptomatic contact in Germany. New England Journal of Medicine. 2020;382(10):970–971.

4. Boldog P, Tekeli T, Vizi Z, Dénes A, Bartha F, Röst G. Risk Assessment of Novel Coronavirus COVID-19 Outbreaks Outside China. Journal of Clinical Medicine. 2020;9(2):571.

5. Ferretti L, Wymant C, Kendall M, Zhao L, Nurtay A, Abeler-Dörner L, et al. Quantifying SARS-CoV-2 transmission suggests epidemic control with digital contact tracing. Science. 2020;368(6491).

6. an der Heiden M, Buchholz U. Modellierung von Beispielszenarien der SARS-CoV-2-Epidemie 2020 in Deutschland. Robert Koch Institut; 2020.

7. Read JM, Bridgen JR, Cummings DA, Ho A, Jewell CP. Novel coronavirus 2019-nCoV: early estimation of epidemiological parameters and epidemic predictions; 2020. Available from: https://www.medrxiv.org/content/10.1101/2020.01.23.20018549v2

8. Maier BF, Brockmann D. Effective containment explains subexponential growth in recent confirmed COVID-19 cases in China. Science. 2020;368(6492):742–746.

9. Rocklöv J, Sjödin H, Wilder-Smith A. COVID-19 outbreak on the Diamond Princess cruise ship: estimating the epidemic potential and effectiveness of public health countermeasures. Journal of Travel Medicine,. 2020;forthcoming.

10. Baud D, Qi X, Nielsen-Saines K, Musso D, Pomar L, Favre G. Real estimates of mortality following COVID-19 infection. The Lancet infectious diseases. 2020;.