TELL ME Design: Protective Behaviour During an Epidemic

Jennifer Badham and Nigel Gilbert
Centre for Research in Social Simulation
University of Surrey
Guildford GU2 7XY
United Kingdom

Abstract

The TELL ME agent based model simulates the connections between health agency communication, personal decisions to adopt protective behaviour during an influenza epidemic, and the effect of those decisions on epidemic progress. The behaviour decisions are modelled with a combination of personal attitude, behaviour adoption by neighbours, and the local recent incidence of influenza. This paper sets out and justifies the model design, including how these decision factors have been operationalised. By exploring the effects of different communication strategies, the model is intended to assist health authorities with their influenza epidemic communication plans. It can both assist users to understand the complex interactions between communication, personal behaviour and epidemic progress, and guide future data collection to improve communication planning.

1 INTRODUCTION

The now completed European funded TELL ME project concerned communication before, during and after an influenza pandemic. Project partners produced materials, such as a guide and online training, to assist health agencies and health professionals to encourage public health behaviours to reduce influenza transmission. As part of TELL ME, a prototype agent-based model was developed that could be used by health agencies to understand the potential effect of different communication plans.

This paper sets out the final design of the agent-based model, describing how psychological theory and epidemiology were operationalised as model

August 2015

rules. The draft design was published by the TELL ME consortium (TELL ME, 2014). Some details were changed during development, particularly agents' perception of social norms in their decisions to adopt (or cease) protective behaviour.

In addition, this paper summarises the results of the calibration process and demonstrates the use of the model with some simple scenarios. Further detail about calibration and model use will be provided in the academic literature.

2 BACKGROUND

Since the focus of the model is the effect of communication, it must connect communication with behaviour. To ensure reasonable model behaviour, that connection should be consistent with both the relevant psychological theories and any empirical data. Evidence shows that a person's decision about whether to adopt protective behaviour depends on both personal factors and the epidemic situation (Bish and Michie, 2010; TELL ME, 2012). Together, these broad requirements established five minimum functional requirements for the model:

1) Communication affects behaviour;
2) Behaviour is based on relevant psychological models;
3) There is appropriate heterogeneity of behavioural response and situational awareness;
4) The epidemic dynamically influences, and is influenced by, personal behaviour; and
5) There is consistency with empirical data, where available.

There are no existing influenza models that comply with more than three of these requirements, and many comply with only one. With respect to item (4), a recent review (Funk et al., 2010) identified 25 theoretical studies that considered the mutual influences of personal behaviour and the spread of infectious disease. Almost all the models reviewed were differential equation based compartment models, a standard mathematical approach to modelling epidemics. This approach creates nominal compartments that count the population in each epidemic state (such as 'susceptible' or 'infected'), and uses equations to control the rates at which people move between compartments. Behaviour is included by increasing the number of compartments and adjusting rates. For example, the 'susceptible' compartment may be split into 'susceptible, good hand hygiene' and 'susceptible, poor hand hygiene' and the rate of infection for the former would be lower than the latter.

However, differential equation compartment models are unable to deal with the heterogeneity requirements of TELL ME. Compartment divisions would be needed not just for behaviour choices, but also for factors that contribute to behaviour such as different levels of perceived risk, geographic proximity to the outbreak, exposure to communication, and relevant demographic features. The most appropriate modelling methodology to allow all these factors to influence behaviour is agent based modelling (ABM), which is 'a computational method that enables a researcher to create, analyse, and experiment with models composed of agents that interact within an environment' (Abdou et al., 2012, pg 141). That is, there are many simulated individuals with different properties (such as geographic location or access to media) who are able to perceive the situation in which they find themselves (including epidemic proximity), and take that situation into account in their decisions to adopt protective behaviour. That behaviour then affects the environment.

Other models deal with different subsets of the five requirements. For example, informal communication is included in two models of the two-way dynamic influence of personal behaviour and epidemic transmission (Funk et al., 2009; Kiss et al., 2010) and there are several models that examine the impact of policy interventions using empirical data from the 2003 SARS outbreak (such as Bauch et al., 2005).

Of most relevance to the TELL ME project is an agent-based model of facemask use during the 2003 SARS outbreak in Hong Kong, the 'first demonstration of a quantitative HBM [Health Belief Model] suitable for incorporation in agent-based epidemic simulation' (Durham and Casman, 2012, pg 567). It at least partially meets three of the five functional requirements. Heterogeneous individual behaviour is modelled using the Health Belief Model, calibrated with published data about facemask use during the outbreak (from Lau et al., 2003), and the modelled facemask adoption occurs in response to dynamic epidemic information about prevalence and deaths. However, the influence is only one-way because epidemic progress is applied as an exogenous factor, and does not respond to model variables such as facemask use. The authors explicitly recognise the model's limitations, arguing that they needed to compromise realism to achieve model feasibility.

The prototype TELL ME model extends this approach. By including communication and mutual influence, however abstractly, the TELL ME model is a substantial second step in modelling protective behaviour and epidemic progress.

3 General Model Structure

The basic structure of the model is determined by its purpose: to compare the potential effect of communication plans on protective personal behaviour and hence on the spread of an epidemic. This requires two linked models: a

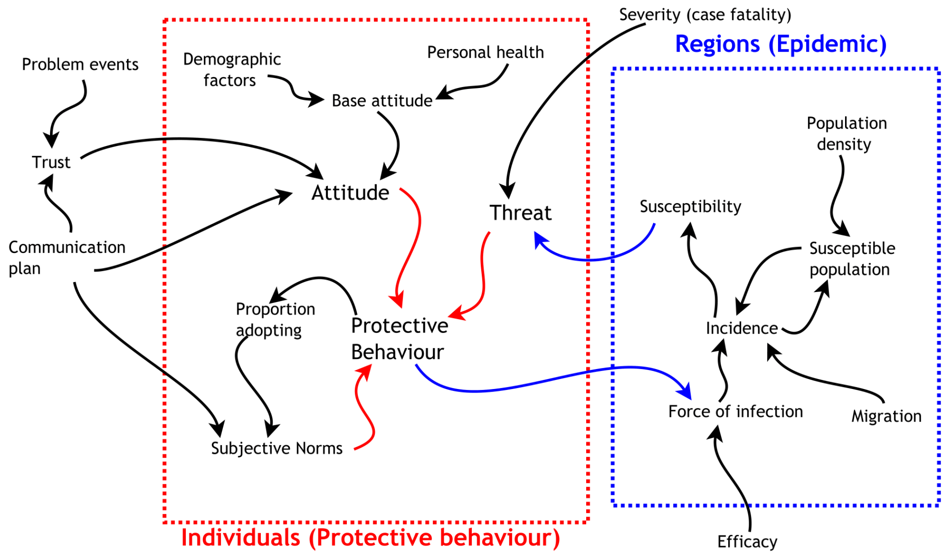

Figure 1. TELL ME model logic, identifying the influences between variables and organised by model entity. The arrows identify the pattern of influences between properties of entities.

behaviour model that responds to communication, and an epidemic model. The key entities are:

- *Messages*, which together form communication plans;
- *Regions*, which hold information about the local epidemic state; and
- *Individuals*, who receive communication and make decisions about whether to adopt protective behaviour.

The broad model logic is at Figure 1. The major flow of influence is the effect that communication has on attitude and hence behaviour, which affects epidemic transmission and hence incidence. Incidence contributes to perceived risk, which influences behaviour and establishes a feedback relationship.

Two types of protective behaviour are included in the simulation: vaccination and non-vaccination behaviours. The latter represents hand hygiene, wearing face masks, social distancing and other personal behaviours. This separation allows simulated individuals to, for example, adopt increased hand hygiene and social distancing while simultaneously being unwilling to be vaccinated.

4 INDIVIDUAL PROTECTIVE BEHAVIOUR

The model includes a few thousand agents (exact number depends on the country modelled and the resolution) representing individuals with characteristics that are important for protective behaviour and communication. These characteristics include membership of some nominal target group or being a healthcare worker. Individuals perceive the epidemic state of their local region, the content of messages directed to them, and the behaviour of other nearby individuals. These individuals adopt or abandon protective behaviour according to their particular situation.

4.1 Psychology of Health Behaviour

There are several well established models from psychology that aim to predict or explain behaviour and change in behaviour on the basis of other psychological constructs such as attitude or perceived risk. Three of these are particularly important. The Theory of Planned Behaviour is the dominant general purpose behaviour model in psychology. The Health Belief Model and the Protection Motivation Theory are also popular in the health behaviour literature.

There is no agreement on which of these psychological models is most suitable for any specific type of behaviour, and there is insufficient detail about parameters that may be appropriate for epidemic influenza. Thus, they cannot be directly applied to determine protective behaviour for simulated individuals in the TELL ME model. Nevertheless, they provide guidance on the factors that should be included in the simulation model. Some of the explanatory factors are common to more than one theory, and there have been attempts to develop a theory that combines the strengths of each.

4.1.1 Theory of Planned Behaviour

The Theory of Reasoned Action asserts that intention is the best predictor of behaviour, and that intention is predicted by three factors (Fishbein, 1995). According to this theory, intention is increased in the presence of:

- attitude: favourable evaluation about the specific behaviour;
- subjective norms: perceived social pressure to perform the behaviour, or approval from other people; and
- behavioural control: perceived ease of undertaking the behaviour.

The Theory of Planned Behaviour extends this understanding by including perceived behavioural control as a predictor of behaviour, in addition to its role in predicting intention (Ajzen, 1991). This extension was introduced to recognise that many factors can interfere with intended behaviour, and that perceived control is one way to estimate the likely impact of these factors.

The model does not simply identify the important contributing factors but also prescribes the way they are combined. In particular, intention is a linear combination (weighted sum) of attitude, norms and control. However, the parameter values associated with each explanatory variable depend on both the behaviour to be predicted and the situation (Ajzen, 1991). Predictive power varies considerably, with a major review of 185 empirical studies finding that, on average, 27% of the variation in behaviour is explained by the proposed explanatory variables (Armitage and Conner, 2001). Thus, although the structure can be adapted for the TELL ME model, there is limited guidance on the values to use in rules to control behaviour.

4.1.2 Health Belief Model

For preventative health behaviour, an important alternative to the general Theory of Planned Behaviour is the Health Belief Model (Rosenstock, 1974). This asserts that behaviour arises from two dimensions that motivate action—susceptibility and severity—and two that determine the action to be taken—benefits and barriers. There is also some underlying 'cue to action' or trigger (such as symptoms or exposure to media) to stimulate the need for a decision.

There is some evidence that the model has only limited predictive power (Janz and Becker, 1984). This is at least partly because the model is primarily descriptive; there are no standards about how to measure each of the four input factors or how to combine them into a prediction of behaviour, and only limited research about the triggers. Two specific reviews (Harrison et al., 1992; Carpenter, 2010) found that published studies do not support the use of the Health Belief Model as a predictive model.

4.1.3 Protection Motivation Theory

Protection Motivation Theory (Maddux and Rogers, 1983), together with related theories such as the Extended Parallel Process Model (Witte, 1992), focusses on the role of threat in explaining preventative health behaviour. They argue that fear motivates intent, but appropriate behaviour only occurs if there is an effective remedy available. If threat is high but capacity to cope low, Protection Motivation Theory suggests that denial or other maladaptive behaviour will occur instead.

There are six explanatory variables, divided into two groups: appraising threat and coping strategy. Threat combines vulnerability (perceived likelihood that the threat personally applies), severity (perceived seriousness of consequences of the threat) and fear arousal (level of worry about the threat). Capacity to cope comprises response efficacy, self-efficacy (perceived ease of undertaking the behaviour) and the absence of costs or barriers that interfere with undertaking the behaviour.

There is empirical support that the framework is useful in explaining existing ongoing behaviour, but less support for its use in predicting future behaviour (Milne et al., 2000). In particular, the threat appraisal elements are only weakly predictive, but this could be due to difficulties in varying perceived severity in an experimental setting.

4.1.4 Combining psychological theories

In a 1992 workshop sponsored by the (US) National Institute of Mental Health, leading supporters of different theories discussed the overlap and reached consensus on eight important factors that explain variations in behaviour (Fishbein, 1995). For the purpose of operationalising behaviour in a simulation model, the consensus recognition that some of the explanatory factors included in separate models are essentially the same is particularly relevant. For example, the attitude measure from the Theory of Planned Behaviour is very similar to the combination of benefits and barriers from the Health Belief Model. While Protection Motivation Theory was not included in this reconciliation, it overlaps substantially with the Health Belief Model with, for example, threat appraisal adding only the emotional aspect of worry to the motivation factors of severity and susceptibility.

At least three studies (Oliver and Berger, 1979; Zijtregtop et al., 2009; Myers and Goodwin, 2011) have tested influences from both the Theory of Planned Behaviour and the Health Belief Model for predicting the uptake of vaccination against an influenza epidemic. All found that attitude and subjective norms from the Theory of Planned Behaviour are important predictors and that predictive power increased with the addition of variables from the Health Belief Model, but did not agree on the particular additional variables. Systematic reviews of psychological factors associated with vaccination against epidemic influenza using the framework of Protection Motivation Theory (Bish et al., 2011; TELL ME, 2012) found similar results, with evidence supporting that the threat appraisal variables of susceptibility and severity are associated with vaccination.

4.2 Operationalising Individual Behaviour

The TELL ME model focusses on attitude, subjective norms and threat as the key inputs to protective behaviour decisions. Threat is modelled as a combination of recent local incidence and a ‘worry factor’. These factors are

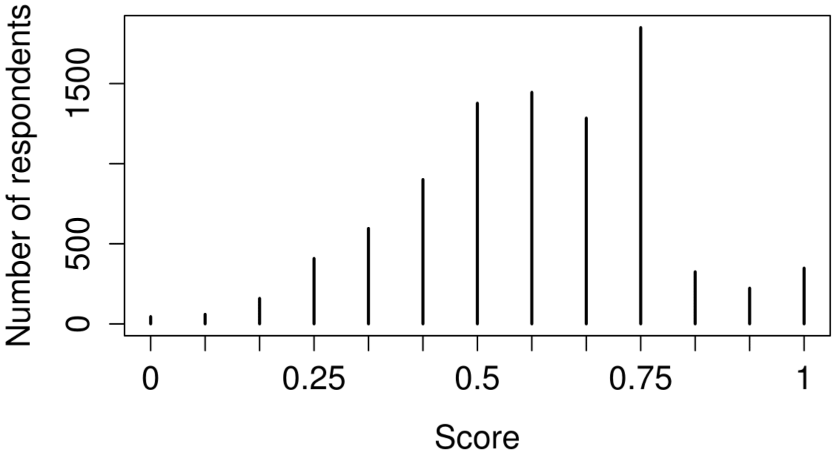

Figure 2. Distribution of 9,033 responses to four questions about hand hygiene behaviour in the past three days in Hong Kong during the 2009 H1N1 epidemic (Cowling et al., 2010, supplementary information). The questions asked about covering mouth when coughing or sneezing, washing hands, using liquid soap, and avoiding directly touching common objects such as door knobs. The responses were coded 1 (Always) to 4 (Never), resulting in a score of 4 to 16 (and excluding those who reported 'Don't know' on any of the four questions). The score was reversed and rescaled to the interval [0,1] for the figure and the TELL ME model.

included in the decision rules of individuals because they are important in the psychological literature and they are dynamic, potentially changing during an epidemic simulation.

Simulated individuals within the model are assigned an initial attitude for each behaviour (vaccination, other) with a value between 0 and 1. Attitude scores are updated during the simulation in response to messages created as part of the input communications plan that are received by the individual (see section 5) and gradually revert to their initial values.

For nonvaccination behaviour, the initial attitudes are drawn from a triangular distribution with mode 0.75, a simplification of hand hygiene behaviour survey responses during the 2009 H1N1 epidemic in Hong Kong (supplementary information from Cowling et al., 2010, see Figure 2). For vaccination, the initial attitude is drawn from a triangular distribution with mode of 0.25 or one with mode 0.75, with the former selected according to the proportion of the population who oppose vaccination (a model parameter controlled by the user).

Personal characteristics such as age or health status are known to be associated with willingness to adopt protective behaviour (TELL ME, 2012). Although the model does not include these characteristics explicitly as agent properties, their influence is represented through the empirically based distribution used to assign initial attitude values. One characteristic that is explicitly included as an agent property is that of 'target group membership'. This can indicate different subpopulations that may be targeted during communication, such as older people or those with poor health status. The initial attitude can be adjusted to introduce a difference in the mean attitude by target group membership, with the size of the difference and the proportion of the population in the target group both set as model parameters by the user.

Subjective norms describe how a person believes family, friends and other personally important people expect them to behave and the extent to which they feel compelled to conform. In the TELL ME model, norms are operationalised as the proportion of the individuals (agents) in the same or nearby regions that have adopted the behaviour.

Perceived threat reflects both perceived susceptibility and the consequences of becoming infected (severity plus an emotional fear element). Following the method of Durham and Casman (2012), susceptibility is modelled with a discounted cumulative incidence time series. In the TELL ME model, however, only nearby cases are included in the discounted cumulative incidence rather than the national incidence used by Durham and Casman (2012). This approach allows perceived susceptibility to increase as the epidemic approaches an individual's location but then gradually fade away after the peak has passed. That is, perceived susceptibility will generally be higher for the simulated individuals who are close to the new cases than for those further away.

Threat includes not just susceptibility, but also the perceived consequences of becoming infected. The model includes an arbitrary 'worry' multiplier, that is intended to capture some combination of severity and fear arousal relative to the base case of 2009 H1N1 influenza.

These factors are combined to determine whether an agent's protective behaviour. For a given individual i able to see region r, their behaviour score (B_i) at time t is given by the weighted average of these three elements (see equation 1, with A, N, W and I representing attitude, norms, worry and incidence respectively). The behaviour score is compared to a threshold and behaviour is adopted or dropped accordingly. Both weights and thresholds are potentially different for the two behaviours: vaccination and other behaviour. Once vaccinated (that is the individual has a high enough behaviour score to seek vaccination and the vaccine is available), vaccination cannot be dropped.

$$B_i = \omega_A A_i + \omega_N N_r + (1 - \omega_A - \omega_N)\, W \sum_{j=0}^{t} \delta^{t-j} I_{t-j,r} \tag{1}$$

5 Communication and its Effect

As described above, an agent's decision concerning adoption of protective behaviour is based on its attitude, perception of norms and threat. Health authority communication is operationalised through its effect on these decision inputs, thereby influencing the agent's behaviour indirectly. This communication is provided by the model user as a set of messages (for further details, see the model User Manual: TELL ME, 2015).

The set of messages is described to the model with properties and specific values based on the transmission oriented communication framework (Lasswell, 1948; Shannon and Weaver, 1949): Sender, Message, Channel, Receiver, and Effect. Modern understanding of communication is more nuanced, recognising that the impact of communication depends on many contextual factors that influence how a message is encoded by the sender and decoded by the receiver (Hall, 1980). But this nuanced understanding is neither feasible nor desirable for the simulation, which is focussed on the more fundamental question of whether the message is received at all, applying a similar effect for each relevant person exposed.

The 'Sender' is the health authority and does not change, so is not explicitly provided to the model. The 'Effect' is also not part of the inputs, because it arises from the model rules. The remaining three properties make up the communication input, together with timing and triggering properties for coordinating the communication plan. The transmission framework variable of 'Message' is coded in two properties: Behaviour and Content. Behaviour identifies whether the message is directed to vaccination, non-vaccination or both. Content specifies the type of information that the message is intended to convey, such as epidemic status updates or the benefits of the promoted behaviour. 'Channel' is operationalised directly, as the delivery mechanism for the message. This is combined with the Target property to specify the 'Receivers' of the message. The properties of the messages are used to identify which simulated individuals receive the messages and the type of information that they receive.

The effect of receiving a message is derived from the message Content, which can take the values of:

- promoting benefits, which influences attitude;
- epidemic status information, which increases trust;
- emphasising norms, which increases the perceived social norm to adopt the behaviour; and
- recommend adoption, which leads the individuals to reassess the situation as if the threat was high.

The first two message content types lead to a permanent change in a person's attitude and trust values respectively. The other two content types temporarily increase other factors that contribute to behaviour, and consequently the likelihood of adoption of that behaviour.

5.1 Attitude and trust

If the Content promotes the benefits of the behaviour, the effect will be a change in attitude with the size of the change moderated by trust. Social Judgement/Involvement Theory (Sherif et al., 1965) asserts that the change in attitude induced by communication depends on two key factors: the position of the communication and the latitude of acceptance for the receiver. Conceptually, attitudinal positions have a value over some range. Both the person receiving the message and the message itself have positions. The attitude of the person receiving the message changes toward the position of the message, but only if the message has a sufficiently similar position to not be rejected (in the agent-based modelling literature, this idea is referred to as bounded confidence, as in Hegselmann and Krause (2002)). The latitude of acceptance refers to the range of positions that are considered and integrated into the receiver's updated attitude. In the model, only positive changes in attitude are made in response to received messages because it assumes that the communication planners are effectively promoting protective behaviour.

For messages within the latitude of acceptance, the amount of change is proportional to the discrepancy between the individual's existing attitude position and the position of the message. Thus, a greater difference in position will result in more change. In addition to the evidence directly supporting Social Judgement / Involvement Theory, there is empirical support for change in attitude proportional to discrepancy (Anderson, 1971; Danes et al., 1978).

The induced attitude change is moderated by trust in the sender (or health authority). Trust can be increased (to a maximum of 1) with messages that provide epidemic status information, thereby leading to greater attitude change from future messages that promote benefits.

More formally, if A_0 is the attitude prior to the communication and A_m is the attitude position of the message, the revised attitude (A) depends on trust in message source (τ), the size of the latitude of acceptance (θ) and some constant of proportionality (α) as follows:

$$A = \begin{cases} A_0 + \tau\alpha\left(A_m - A_0\right) & A_0 \le A_m \le A_0 + \theta \\ A_0 & \text{otherwise} \end{cases} \tag{2}$$

The attitude value for messages promoting benefits is set to 0.9 for general messages and 0.3 for those targeted to people with views opposing vaccination.

That is, the model assumes that the messages targeted to people opposing vaccination will be designed in such a way as to recognise their concerns and be attractive to at least some of those people.

5.2 Temporary influences on behaviour

Messages with a Content type of 'Emphasise norms' or 'Recommend adoption' do not affect the properties of the individuals who receive the message, but instead change the way in which they calculate behaviour for several timesteps using equation 1. An 'Emphasise norms' message will increase the value of N, adding a bonus to the population of nearby individuals who have adopted the behaviour. A 'Recommend adoption' message will lead to the individual using the maximum discounted cumulative incidence across all regions rather than the one that applies in their own region. That is, such a message is interpreted as an assertion by health authorities that all individuals are at risk from the epidemic.

6 Epidemiology

The final group of operationalisation decisions concerns how to model the spread of influenza, which affects the agents' perceptions of threat, but is also necessary to forecast the effect of a communication effort. For both behaviour and communication, the operationalisation was guided by relevant theory but with only limited modelling experience to draw from. In contrast, there are well established methods to simulate influenza transmission and substantial empirical evidence with which to set parameter values.

In the TELL ME agent-based model, the epidemic is managed by regions rather than individual agents. Their properties include population density and the proportion of the population in specific epidemic states such as 'infected'. The most appropriate standard model for influenza transmission is the SEIR model: People start in the susceptible (S) state, become exposed (E) but not yet infectious, then become infectious (I) and are eventually removed from calculations (R) because they either recover and become immune or they die. Assuming that those who have recovered from the infection are fully immune and ignoring the relatively slow processes of births and deaths from non epidemic causes, the SEIR model is given by the following set of differential equations (Diekmann and Heesterbeek, 2000):

$$\begin{aligned}\frac{dS}{dt} &= -\beta SI \\ \frac{dE}{dt} &= \beta SI - \lambda E \\ \frac{dI}{dt} &= \lambda E - \gamma R \\ \frac{dI}{dt} &= \gamma R\end{aligned} \tag{3}$$

The process of transitions through states is simulated by stepping through discrete time. At each time step, the equations describe a change in the proportion of the population in each state, governed by transition rate parameters (β for $S \to E$, λ for $E \to I$, and γ for $I \to R$). The transition rate parameter from S to E (β) incorporates contact rate and the probability of transmission given contact. This is the point at which the behaviour of individuals influence the epidemic spread. In each region, the value is reduced as given in equation 4 in accordance with the proportion of individuals in that region who have adopted protective behaviour (P_r) and the efficacy of the behaviour (E). This leads to a reduction in incidence (equation 4).

$$\beta_r = \beta\left(1 - P_r E\right) \tag{4}$$

Each region is updated separately. Population density is based on GIS information (obtained from Population Density Grid Future collection held by Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2013) and the transition rate parameters are identical in each region apart from the impact of personal behaviour. To allow the epidemic to spread, a proportion of the new exposures generated by the infectious population in a region are actually created in neighbouring regions.

7 Calibration

There are many parameters in the model. Some are directly available from previous research, such as the basic reproduction ratio, plausible values for the efficacy of protective behaviour and access to different types of media. Others must be calibrated, selecting values such that the model generates results that are consistent with empirical data. However, relevant data that can be compared to model output is not available for all parameters. The lack of data is particularly severe for the effect of communication.

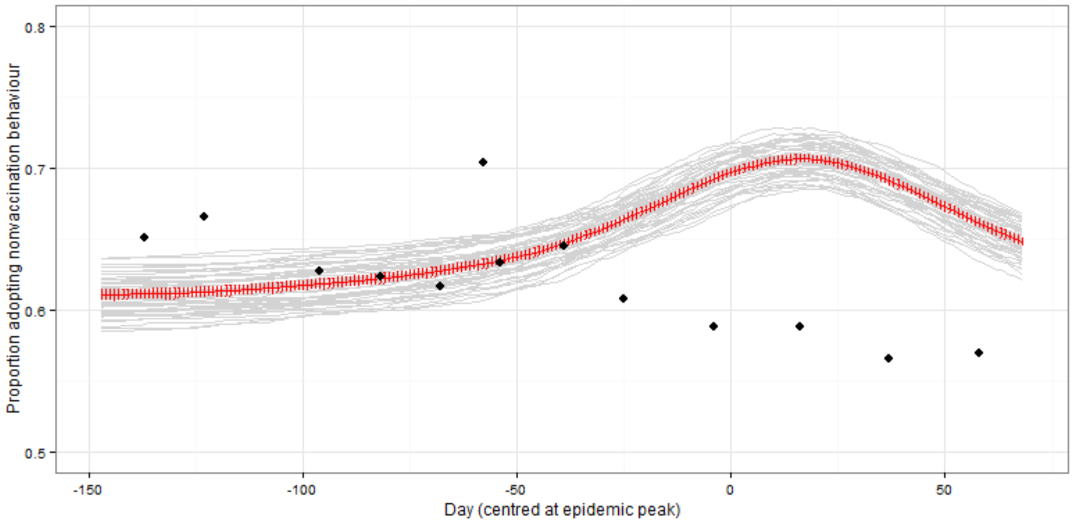

Figure 3. Fifty simulation runs with the best fit parameters for proportion adopting hand washing behaviour during the 2009 H1N1 epidemic in Hong Kong. Parameter values are: 0.35 for attitude weight, 0.1 for norms weight, 0.55 for threat weight, 0.18 discount in cumulative incidence, and 0.25 for threshold. Empirical behaviour values, (extracted from Cowling et al., 2010, supplementary information), are shown with dots.

Calibration therefore focussed on the core parameters of behaviour adoption (equation 1): weights, incidence discount and behaviour threshold. Even so, it is reasonable to expect that parameters would vary by (at least) disease, culture, and behaviour type. To fit these parameters, longitudinal data that include both behaviour and epidemic progress are required.

The comparison data were drawn from Hong Kong hand washing (Cowling et al., 2010), and French (Vaux et al., 2011) and Italian (Ferrante et al., 2011) willingness to vaccinate during the 2009 H1N1 epidemic. Fit was assessed using three criteria: minimum mean squared error between the actual and simulated proportion of the population adopting protective behaviour, minimum difference between actual and simulated maximum adoption, and minimum difference between the actual date that maximum occurred and the simulated date (relative to the epidemic peak date). Minimum mean squared error is a standard approach to measuring the fit of a model against several data points. The other two criteria were included to assess the appropriateness of the shape of the behaviour adoption curve.

Fit was generally poor. The simulation results for the best fit parameters for Hong Kong, France and Italy are shown in Figures 3, 4 and 5 respectively.

The Hong Kong data is particularly suggestive as to one potential reason.

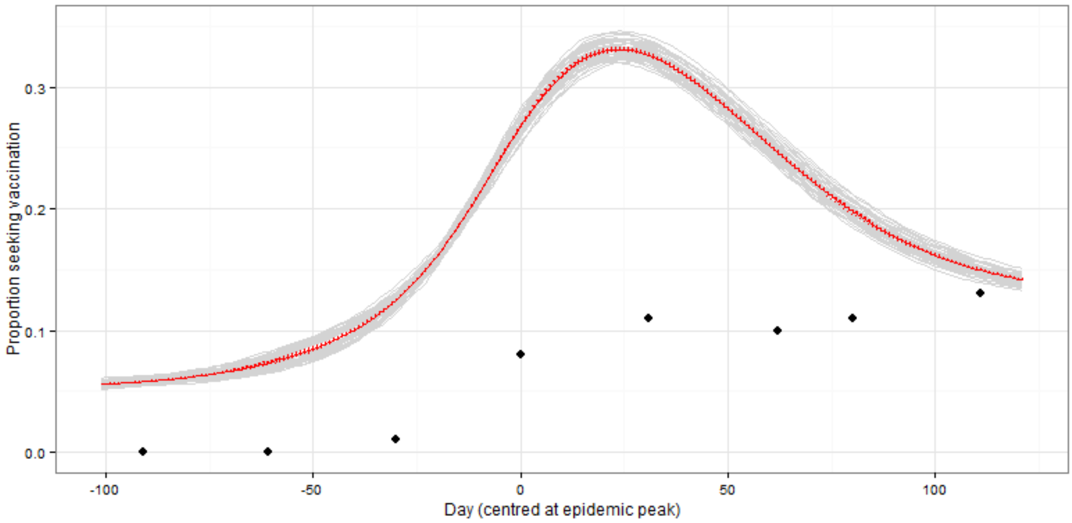

Figure 4. Fifty simulation runs with the best fit parameters for proportion willing to vaccinate during the 2009 H1N1 epidemic in France. Parameter values are: 0.45 for attitude weight, 0.1 for norms weight, 0.45 for threat weight, 0.04 discount in cumulative incidence, and 0.4 for threshold. Empirical behaviour values, (extracted from Vaux et al., 2011), are shown with dots.

According to Google Trends data (Google Trends, 2014), the peak media interest occurred in the week ending 2 May 2009 (117 headlines), with smaller peaks in the weeks of 20 June (47) and 15 August (33), whereas the peak incidence occurred almost five months later on 29 September (day 0 in Figure 3) and peak protective behaviour near 18 July. That is, the media responded much more strongly to the initial reports from Mexico than to the local epidemic. The TELL ME model is based on psychological theory, with behaviour determined by a weighted combination of epidemic spread, attitude and existing behaviour. These factors cannot be combined to reproduce a pattern with peak protective behaviour occurring before the epidemic peak.

The best fit parameter values for the French and Italian data highlight the difficulty of finding appropriate values that can be applied generally. Both datasets concern willingness to vaccinate. However, the calibration results are very different, suggesting there is no 'right' answer that can be used as the default values for the model. That is, each health authority would need a local dataset in order to determine suitable behaviour parameters for their own situation.

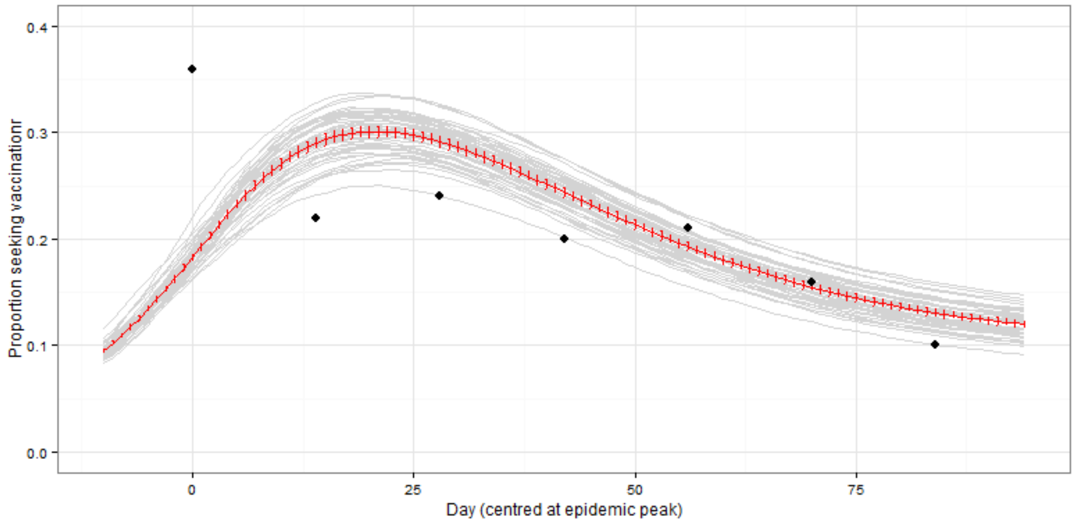

Figure 5. Fifty simulation runs with the best fit parameters for proportion willing to vaccinate during the 2009 H1N1 epidemic in Italy. Parameter values are: 0.3 for attitude weight, 0.15 for norms weight, 0.55 for threat weight, 0.08 discount in cumulative incidence, and 0.3 for threshold. Empirical behaviour values, (extracted from Ferrante et al., 2011), are shown with dots.

8 Model Results

As the focus of this paper is the model design, a full set of scenarios is outside its scope. However, three simulations are required to demonstrate that the model achieved the five functional requirements intended. In particular, appropriate scenarios are required to demonstrate that communication affects behaviour and that the behaviour influences the epidemic. For ten different epidemics, the same random seed was used for three different conditions:

- **Baseline:** No communication and any adopted behaviour has no effect;
- **Communication:** Basic communication plan with two messages - one at day 20 to promote the benefits of nonvaccination, and the other at day 40 emphasising norms for vaccination, with ineffective behaviour; and
- **Influence:** Same basic communication plan as above, with 25% efficacy for nonvaccination protective behaviour and 60% for vaccination.

The simulation was run using Spain with epidemic parameters of 2 for basic reproduction ratio (R_0), 2 days for the latency period, and 5 days for the recovery period of 5 days. All non-experimental parameter values were set to their defaults. The results are shown in Figure 6.

Compared to the baseline scenario (blue), the two scenarios with communication (green and red) show an increase in nonvaccination protective behaviour at day 20 (top panel). For the scenario with effective behaviour (red), there is a clear impact on the epidemic, delaying and reducing the peak prevalence. The vaccination behaviour (middle panel) is more complex. Compared to the baseline scenario, communication has induced additional vaccination at day 40 where protective behaviour is ineffective (green). However, with effective behaviour (red), the epidemic is less threatening and vaccination is actually lower than occurs in the baseline scenario. This interaction of personal and epidemic behaviour highlights the difficulty in estimating the effects of proposed actions in a complex system, and the importance role for models in understanding such systems.

9 Conclusion

This paper describes the implementation of personal protective behaviour in the TELL ME agent-based model. Simulated individuals respond to communication with attitude change or temporary behaviour incentives and to perceived threat based on local epidemic progress. Their attitude, perceived subjective norms (based on observed behaviour of others) and perceived threat are used to determine their protective behaviour: seeking vaccination, adopting other protective measures or ceasing protective measures. That protective behaviour influences the epidemic progress.

The model therefore meets all five functional requirements, which is a significant step beyond the existing models of personal behaviour during an epidemic. However, this advance has come at the cost of only limited success in fitting model parameters to replicate observed behaviour.

The purpose of the TELL ME model is to compare the effect of different communications plans. These plans are compared to each other, on the assumption that all other effects are equal. Thus, the difficulties with the fit (whether due to media visibility or for other external reasons) are of less importance than they would be in a predictive model. In particular, the model represents the theoretical understanding of the mutual influence between communication, behaviour and epidemic spread and can therefore assist planners in understanding these relationships and the potential consequences of different options.

One consequence of the relatively poor fit is that the model highlights the inadequacies of the theoretical understanding. There are clearly other factors that must be included in any hypothetical predictive model. Furthermore, the TELL ME model highlights the information that must be collected during an epidemic for such a model to be calibrated. In particular, longitudinal information is required concerning the effect of communication activities on

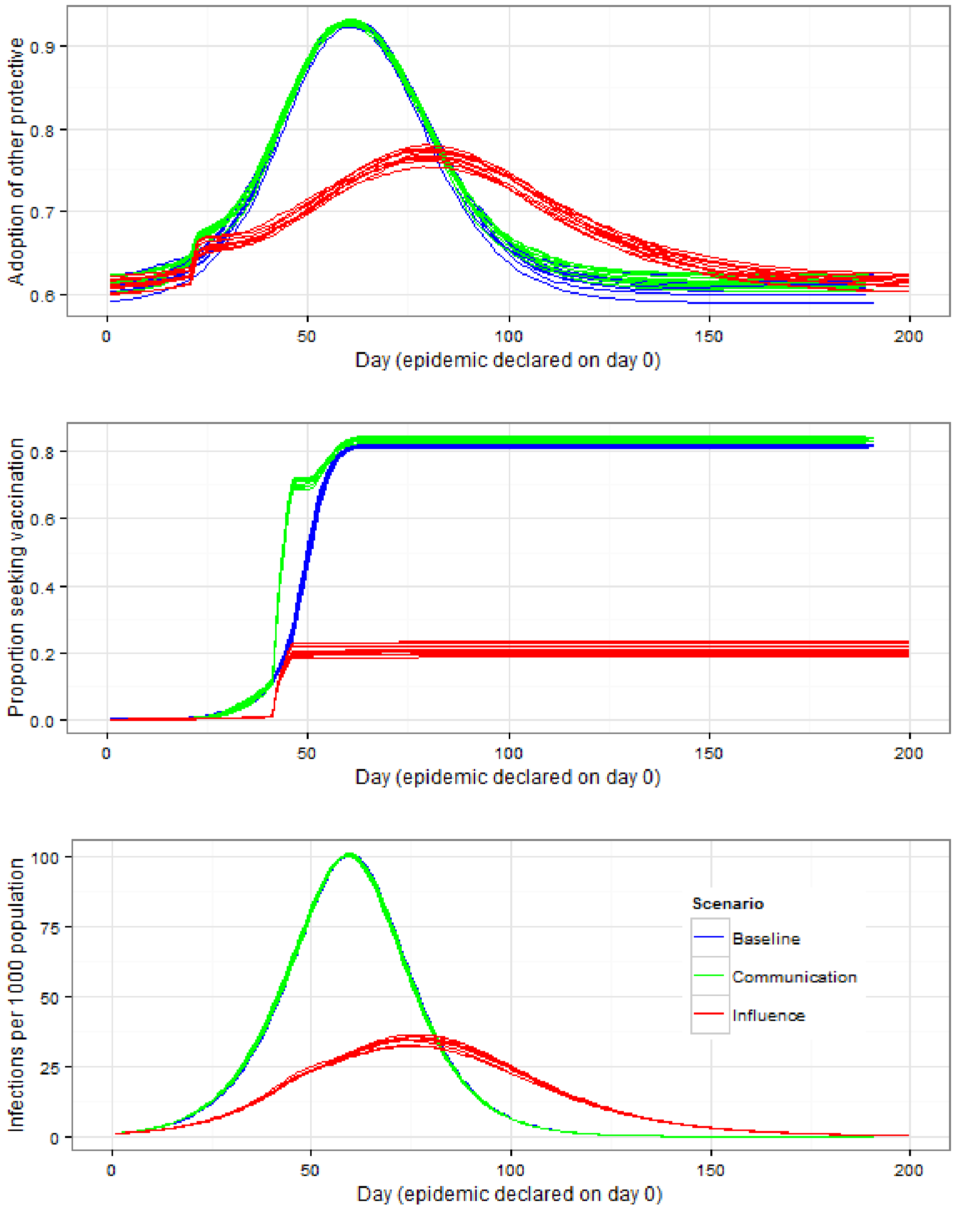

Figure 6. Ten simulation runs with the same behaviour parameter values for each of three scenarios. Baseline scenario has no communication and ineffective behaviour. Communication scenario has two messages, promoting nonvaccination (through attitude) at day 20 and promoting vaccination (through norms) at day 40. Protective behaviour is effective in the Influence scenario, so that adoption delays the peak of the epidemic and reduces its impact.

attitudes and behaviours, as well as additional datasets that capture changes in behaviour as an epidemic progresses.

10 Acknowledgements

This research has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013), Grant Agreement number 278723. The full project title is TELL ME: Transparent communication in Epidemics: Learning Lessons from experience, delivering effective Messages, providing Evidence, with details at http://tellmeproject.eu/.

References

Abdou, M., L. Hamill, and N. Gilbert (2012). *Designing and Building an Agent-Based Model*, pp. 141–165. Dordrecht: Springer.

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes 50*(2), 179 – 211.

Anderson, N. H. (1971). Integration theory and attitude change. *Psychological Review 78*(3), 171.

Armitage, C. J. and M. Conner (2001). Efficacy of the theory of planned behaviour: A meta-analytic review. *British Journal of Social Psychology 40*(4), 471–499.

Bauch, C. T., J. O. Lloyd-Smith, M. P. Coffee, and A. P. Galvani (2005). Dynamically modeling SARS and other newly emerging respiratory illnesses: Past, present, and future. *Epidemiology 16*(6), pp. 791–801.

Bish, A. and S. Michie (2010). Demographic and attitudinal determinants of protective behaviours during a pandemic: A review. *British journal of health psychology 15*(4), 797–824.

Bish, A., L. Yardley, A. Nicoll, and S. Michie (2011). Factors associated with uptake of vaccination against pandemic influenza: A systematic review. *Vaccine 29*(38), 6472 – 6484.

Carpenter, C. J. (2010). A meta-analysis of the effectiveness of health belief model variables in predicting behavior. *Health Communication 25*(8), 661–669. PMID: 21153982.

Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT (2013). Gridded population of the world, version 3 (GPWv3): Population density grid, future estimates (2015).

Cowling, B. J., D. M. Ng, D. K. Ip, Q. Liao, W. W. Lam, J. T. Wu, J. T. Lau, S. M. Griffiths, and R. Fielding (2010). Community psychological and behavioral responses through the first wave of the 2009 influenza A (H1N1) pandemic in Hong Kong. *Journal of Infectious Diseases 202*(6), 867–876.

Danes, J. E., J. E. Hunter, and J. Woelfel (1978). Mass communication and belief change: A test of three mathematical models. *Human Communication Research 4*(3), 243–252.

Diekmann, O. and J. Heesterbeek (2000). *Mathematical Epidemiology of Infectious Diseases*. Wiley Chichester.

Durham, D. P. and E. A. Casman (2012). Incorporating individual health-protective decisions into disease transmission models: a mathematical framework. *Journal of The Royal Society Interface 9*(68), 562–570.

Ferrante, G., S. Baldissera, P. F. Moghadam, G. Carrozzi, M. O. Trinito, and S. Salmaso (2011). Surveillance of perceptions, knowledge, attitudes and behaviors of the Italian adult population (18–69 years) during the 2009–2010 A/H1N1 influenza pandemic. *European journal of epidemiology 26*(3), 211–219.

Fishbein, M. (1995). Developing effective behavior change interventions: some lessons learned from behavioral research. *NIDA Research Monograph 155*, 246–261.

Funk, S., E. Gilad, C. Watkins, and V. A. A. Jansen (2009). The spread of awareness and its impact on epidemic outbreaks. *Proceedings of the National Academy of Sciences 106*(16), 6872–6877.

Funk, S., M. Salathé, and V. A. A. Jansen (2010). Modelling the influence of human behaviour on the spread of infectious diseases: a review. *Journal of The Royal Society Interface 7*(50), 1247–1256.

Google Trends (2014). Headlines with H1N1 or flu, Hong Kong 2009.

Hall, S. (1980). Encoding/Decoding. In S. Hall, D. Hobson, A. Lowe, and P. Willis (Eds.), *Culture, Media, Language: Working Papers in Cultural Studies, 1972-79*, pp. 166–176. Hutchison.

Harrison, J. A., P. D. Mullen, and L. W. Green (1992). A meta-analysis of studies of the health belief model with adults. *Health Education Research 7*(1), 107–116.

Hegselmann, R. and U. Krause (2002). Opinion dynamics and bounded confidence: models, analysis and simulation. *Journal of Artificial Societies and Social Simulation 5*(3), 2.

Janz, N. K. and M. H. Becker (1984, Jan). The health belief model: A decade later. *Health Education & Behavior 11*(1), 1–47.

Kiss, I. Z., J. Cassell, M. Recker, and P. L. Simon (2010). The impact of information transmission on epidemic outbreaks. *Mathematical Biosciences 225*(1), 1 – 10.

Lasswell, H. D. (1948). *The structure and function of communication in society* (2nd ed.)., pp. 117–130. Urbana: University of Illinois Press.

Lau, J., X. Yang, H. Tsui, and J. Kim (2003). Monitoring community responses to the SARS epidemic in Hong Kong: from day 10 to day 62. *Journal of Epidemiology and Community Health 57*(11), 864–870.

Maddux, J. E. and R. W. Rogers (1983). Protection motivation and self-efficacy: A revised theory of fear appeals and attitude change. *Journal of Experimental Social Psychology 19*(5), 469 – 479.

Milne, S., P. Sheeran, and S. Orbell (2000). Prediction and intervention in health-related behavior: A meta-analytic review of protection motivation theory. *Journal of Applied Social Psychology 30*(1), 106–143.

Myers, L. B. and R. Goodwin (2011). Determinants of adults' intention to vaccinate against pandemic swine flu. *BMC Public Health 11*(1), 15.

Oliver, R. L. and P. K. Berger (1979). A path analysis of preventive health care decision models. *Journal of Consumer Research 6*(2), pp. 113–122.

Rosenstock, I. M. (1974). The health belief model and preventive health behavior. *Health Education & Behavior 2*(4), 354–386.

Shannon, C. and W. Weaver (1949). *Mathematical Theory of Communication*. University of Illinois Press.

Sherif, C., M. Sherif, and R. Nebergall (1965). *Attitude and Attitude Change: The Social Judgment-Involvement Approach*. Philadelphia: W.B. Saunders Publishing Company.

TELL ME (2012). *D1.1 Systematic Review Report*. TELL ME Project.

TELL ME (2014). *D4.2 Software Design*. TELL ME Project.

TELL ME (2015). *D4.3 Prototype Software (Documentation)*. TELL ME Project.

Vaux, S., D. Van Cauteren, J.-P. Guthmann, Y. Le Strat, V. Vaillant, H. de Valk, and D. Lévy-Bruhl (2011). Influenza vaccination coverage against seasonal and pandemic influenza and their determinants in France: a cross-sectional survey. *BMC Public Health 11*(1), 30.

Witte, K. (1992). Putting the fear back into fear appeals: The extended parallel process model. *Communications Monographs 59*(4), 329–349.

Zijtregtop, E., J. Wilschut, N. Koelma, J. Van Delden, R. Stolk, J. Van Steenbergen, J. Broer, B. Wolters, M. Postma, and E. Hak (2009). Which factors are important in adults' uptake of a (pre) pandemic influenza vaccine? *Vaccine 28*(1), 207–227.