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Towards incorporating human behaviour in models of health care systems: An approach using discrete event simulation

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Abstract

Operational Research models are well established as an effective tool for tackling a vast range of health care problems. Many of these models involve parameters which depend on human behaviour, and thus individuals' characteristics or personality traits should be included. In this paper we describe a discrete event simulation model of attendance for screening for diabetic retinopathy, a sight-threatening complication of diabetes. This model takes into account the physical states, emotions, cognitions and social status of the persons involved. The model also uses some ideas from the discipline of health psychology. We believe that this approach provides what is potentially a far more accurate method of modelling patients' attendance behaviour, compared with the standard approach of simple random sampling of patients. However, further empirical work is required, firstly to derive and validate more realistic forms of the model equations, secondly to select the appropriate psychological variables, and thirdly and inevitably to collect data.

Keywords: Health-related behaviour; Modelling; Agent-based simulation; Screening

1. Introduction

Operational Research models in the field of health care often involve parameters which depend on the behaviour of human beings. For example, epidemic models of the spread of HIV/AIDS depend not only on biological and physiological factors, but also on behavioural factors such as condom use, number of sexual partners and needle-sharing (see, for example, Brandeau et al. [7], Kaplan and O'Keefe [20] and Rowley and Anderson [28]). Models for the prevention and treatment of heart disease need to account for variation in smoking, exercise, and dietary habits (see Goldman et al. [13]). Models to evaluate screening programmes for the early detection of disease must include a factor for patients' compliance (the proportion of patients who attend each screen). In fact Davies and Brailsford's model of screening for diabetic retinopathy [9] was highly sensitive to assumptions about compliance. Therefore, from a practical perspective it is very

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important to find an effective way to incorporate these behavioural elements in models which are intended for use in guiding policy decisions in healthcare.

PECS (Schmidt [29]) is a reference model or architecture for modelling human behaviour on an individual level. PECS incorporates state variables belonging to the following four classes: physical state, emotion, cognition and social status. PECS offers two different modes of behaviour for the dynamics of these state variables. These modes are called "reactive" and "deliberative". Reactive behaviour can be determined by the application of a set of rules and is low-level (e.g., instinctive or emotional behaviour), whereas deliberative behaviour is higher-level and involves the conscious pursuit of goals. It becomes clear that for the modelling of health care systems where the individual behaviour of the participants is important, all four classes of state variables and the two modes of behaviour are essential.

The model described in this paper is not an empirical, validated model intended to be applied in practice; its purpose is to show the potential of this modelling approach. Any model is an abstraction and simplification of reality, and just because the real-life phenomenon or situation being modelled is highly complex does not mean that it is impossible to model it. To be of practical use, however, a model must capture the relevant features of the real-world situation, and therefore further empirical work with collaborators from the field of psychology is required, to determine what those features are and how they can best be represented in mathematical or logical terms.

In Section 2 we present a summary of some of the well-known psychological models for health-related behaviour, including the model we use in this paper, the health belief model (HBM). In Section 3 we introduce the PECS architecture and compare it with other choices of architecture. In Section 4 we briefly describe the screening model for diabetic retinopathy, and show how PECS and the HBM are incorporated in it. Section 5 contains a detailed description of the PECS equations. In Section 6 we describe the simulation experiments we performed. Finally, in Section 7 we conclude that the approach is worthy of further investigation, but that the next stage requires empirical research.

2. Psychological models for health behaviour

Research into health-related behaviour has been mainly within the discipline of psychology. Well-known models for health behaviour include Rosenstock and Becker's HBM ([3,25]), Ajzen's theory of planned behaviour [2] and Wallston's health locus of control (HLC) model [30]. The main purpose of these models is to explain rather than to predict, and moreover for most of them it is not immediately obvious how they may be "translated" into OR terminology and implemented in a practical modelling context.

The HBM (Rosenstock [25] and Becker [3]) is the oldest, most widely used and best known of all the models (Conner and Norman [8]). This model is shown in Fig. 1. It has a common-sense operationalisation. In other words its variables are not technical psychological terms, but can be understood by a lay person. It was developed by field workers, so it has face validity, i.e. it makes sense. Its disadvantages include the fact that there is no precise connection among some of the variables, so there is no obvious formal model structure. It also lacks some variables which have been found in practice to be important, e.g. intentions to perform an action and social pressures. However, the four basic constructs (perceived susceptibility, severity, benefits and barriers) are easily understood and interpreted.

The HLC model (Wallston [30]) is based on Rotter's original locus of control (LC) model [26,27] which recognised two different psychological frameworks which determine people's behaviour. Internal LC is where an individual believes that events are a consequence of his or her own actions. External LC is where a person believes that events are unrelated to their own actions, and are determined by factors beyond the individual's control. Wallston developed this model in a health context and called it the multidimensional HLC. This measures the likelihood of a given health behaviour along three axes, where the first axis

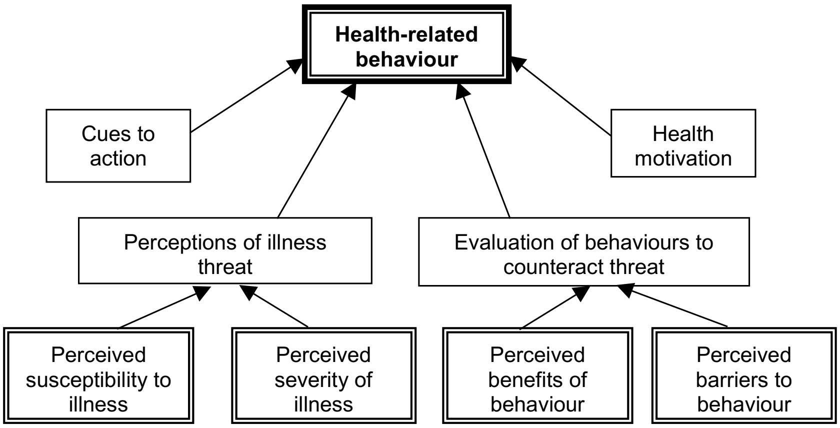

Fig. 1. The HBM (Rosenstock [25] and Becker [3]).

represents internal LC, the extent to which health is under the influence of one's own actions, but external LC is divided into two aspects: "powerful others" and "chance" (fate). The first axis, "internal", is seen as the most important in healthy people. "Powerful others" is mainly seen as an explanation for sick role behaviour, such as compliance with medical advice when a person is ill. Chance, or fatalism, is interpreted as a feeling of lack of control. In practice, this model is a weak predictor of health behaviour, and in studies has been found to account only for a small part of the variance (Conner and Norman [8]). It does not incorporate any concept of the value placed by an individual on their health.

The theory of planned behaviour (Ajzen [1,2]) is an extension of the theory of reasoned action (Fishbein and Ajzen [11]). The model is shown in Fig. 2. Intentions are determined by

- Attitudes (overall evaluations of the behaviour by the individual),

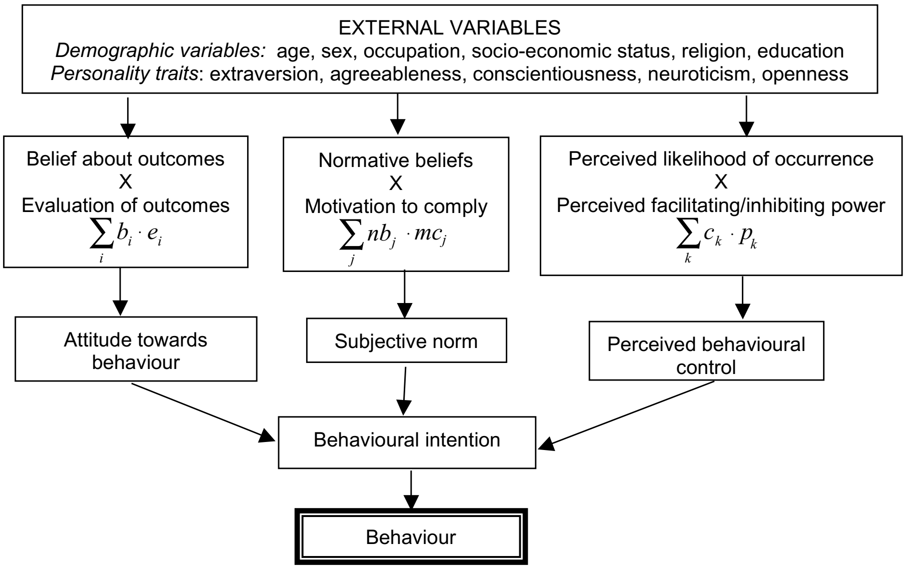

Fig. 2. The theory of planned behaviour (Ajzen [1,2]).

- Subjective norms (do significant others think you should engage in the behaviour) and
- Perceived behavioural control (will this behaviour be easy or difficult?).

The weighted sums in Fig. 2 look very scientific and initially, this model has appeal as having the potential to be modelled mathematically. Fishbein and Ajzen argue that these equations represent the effects of learning; they do not suggest that people actually perform these calculations consciously! According to this model, motivation to behave in a given way is the extent to which a person wishes to comply with the views of referent persons. Therefore, people will behave in a particular way if...

- they believe the behaviour will lead to outcomes which they value,
- they believe that people whose opinions they value want them to do it, and
- they believe they have the necessary resources and opportunities to do it.

The model has been widely tested and successfully applied (Conner and Norman [8]). It incorporates many important cognitive variables: intentions, outcome expectancies and perceived behavioural control. It also incorporates social pressures and makes clear causal links between variables and behaviour. However, the model was developed outside the health arena, and thus it does not include health threat.

To summarise, the most widely used model appears to be the HBM, although the theory of planned behaviour appears possibly the best candidate for quantitative modelling. Janz and Becker [19] carried out a quantitative review of 46 applications of the HBM using its four main constructs: perceived susceptibility of the individual, the severity of the disease, the health benefit to be gained by the behaviour and barriers to performing this behaviour. This review looked at studies of two types of health behaviour, preventive behaviours and sick-role behaviours, and used a vote count procedure to determine the proportions of studies in which each of the four constructs was found to be significant (Table 1).

Table 1
Percentage of 46 studies using the HBM in which each construct was found to be a significant predictor

Type	Susceptibility	Severity	Benefit	Barriers
Preventive	86	50	74	93
Sick-role	77	88	80	92
Overall	81	65	78	89

This review was criticised for ignoring the size of the studies in a further review by Harrison et al. [16]. Harrison initially considered 234 studies but had very strict inclusion rules, and finally only used 16. He suggested that all four components had small but significant effects, and also that the effects should be combined and that the combined effect was greater than the sum of its parts. He did not, however, suggest how they should be combined. A key issue for the modeller is how to combine the various HBM constructs in a mathematical or logical way. One possible formulation was suggested by Lewis [22] in his Ph.D. thesis:

$$\text{Threat} = \text{susceptibility} + (\text{susceptibility} \times \text{severity}). \qquad (1)$$

Lewis also argued that the barriers to performing health behaviours were easily quantifiable and immediate, whereas the benefits are more hypothetical and long-term. This is certainly the case in screening for diabetic retinopathy. The costs of screening (both the financial costs of the screening process and the costs in terms of the patient's time and possible anxiety) are measurable and are incurred at the time of screening, but the benefits are often not apparent for many years, if at all (Gold et al. [12]).

3. The PECS architecture

PECS is based on the view that human beings are "psychosomatic units with cognitive facilities embedded in a social environment", and that all these aspects (physical, emotional, cognitive and social) need to be taken into account in a model of human behaviour. Although PECS is a theoretical architecture, it was first implemented in an agent-based simulation framework and has been used to

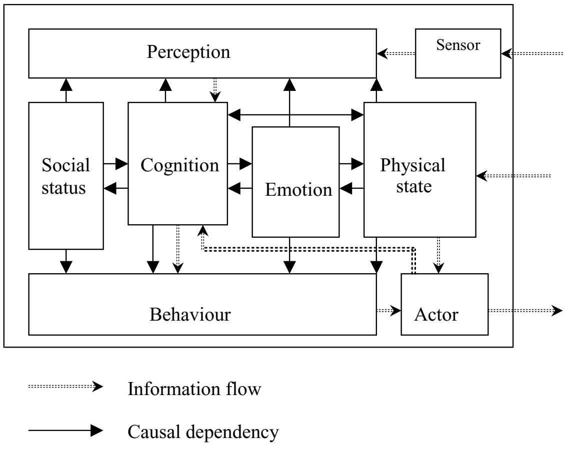

Fig. 3. The basic structure of a PECS agent.

identify emergent patterns of behaviour: see, for example, Schmidt [29].

Fig. 3 shows a simplified version of the structure and the internal organisation of a PECS agent. The area outside the box represents the environment. The basic agent structure consists of input, internal states and output. The upper level, the components sensor and perception, corresponds to the input. These components are responsible for the reception and initial processing of information from the environment. The middle four components, i.e. status, cognition, emotion and physical state, contain the agent's state variables and their changes of state. The two components at the bottom of the figure, behaviour and actor, are responsible for the output. The behaviour component contains a set of rules which form the basis for issuing "execution orders". An execution order is an instruction to perform a specific behaviour. These are passed on to the actor, which is then responsible for carrying them out.

The scientific literature contains a multitude of agent architectures for describing and modelling human behaviour. In order to assess these approaches and compare them with the PECS architecture, we use the following evaluation criteria:

- The existence of a theoretical basis, and a well-structured design, based on a modular, hierarchical methodology.
- The ability of the internal conceptual model to represent the external world.
- Mechanisms for behaviour control, especially reactive, deliberative and reflexive behaviours.
- The range of potential internal states for the agents, e.g. physical, emotional, cognitive and social.
- The number of action-classes an agent has at its disposal; and
- domain-independence; i.e., the ability of the architecture to be used in different application areas.

Most of the architectures proposed in the literature for modelling human behaviour are highly domain-dependent and were designed to tackle very specific problems. Moreover, some of them do not satisfy the above criteria. Therefore, in the following we only describe the three architectures which are most closely comparable with PECS.

The BDI architecture (Rao and Georgeff [24]) is one of the most widely used architectures for the structuring of autonomous agents. It has technical origins, but its sound theoretical basis and its clearly structured design have made it attractive for the modelling of human behaviour as well. The BDI architecture concentrates on rational and cognitive aspects of human behaviour. The internal mental state of a BDI-agent consists of beliefs, desires and intentions. *Beliefs* represent an agent's conceptual model. These will be influenced or changed by incoming "percepts" from the environment. *Desires* are the states of the environment the agent wants to achieve by means of his actions. The cognitive process generates plans which enable the agent to reach his goals. *Intentions* are the plans which the agents choose to execute and which trigger the corresponding actions. Fig. 4 gives an overview of the general architecture of a BDI-agent.

The fundamental shortcoming of the BDI-architecture is the fact that it is restricted to cognitive processes. The integration of physical, emotional or social processes and their interactions are not taken into account. This means that essential aspects which determine human behaviour are not included. The BDI architecture is valuable for technical applications like robotics. However, it is unsuitable for the modelling of human behaviour.

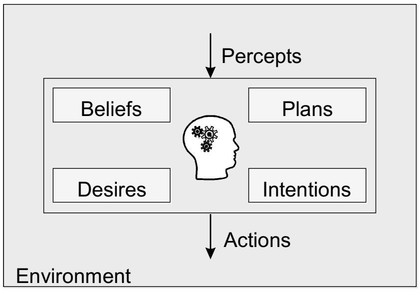

Fig. 4. The basic structure of a BDI-agent.

The architecture of Wright, Sloman and Beaudoin's cognition and affect project [32] avoids this restriction to cognitive processes, and includes emotions and their influences. This architecture integrates three modes of human behaviour control. It identifies reactive, deliberative and reflexive layers. This third layer is perhaps the most interesting as it incorporates reflexive aspects such as faculties for self-reflection, self-evaluation and self-control. The main advantage of this architecture, compared with the BDI architecture, is the inclusion of *facts*, a highly relevant feature for human beings and their unique capabilities. Fig. 5 gives an overview of the general structure of a cognition and affect project-agent.

Unfortunately, the whole concept remains rather vague. The architecture lacks clarity and a well-structured design. It is not clear what the actual functions of the various subcomponents are, nor is it clear how they interact. The multitude of arrows in Fig. 5 is not an adequate substitute for a well-structured model specification. Therefore, although this architecture provides some good suggestions about the direction in which the design of agents to mimic human behaviour should go, it is only of limited value as a reference model or as a general design pattern.

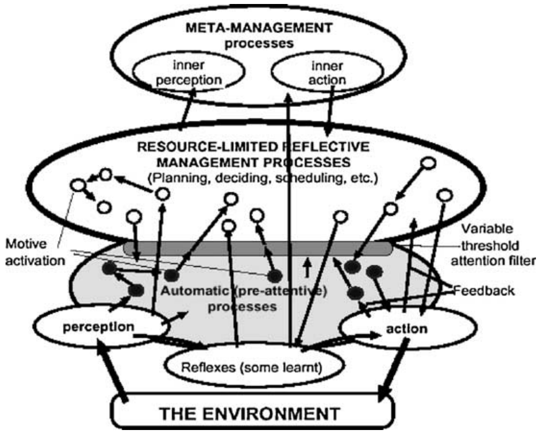

Fig. 5. The basic structure of a cognition and affect-agent.

Dörner's **Ψ** architecture [10] is based on the assumption that it is not sufficient to consider cognition, emotion and motivation in isolation. An integrated methodology is required, which can combine these three aspects and describe their interactions. In this respect Dörner's **Ψ** shares some common ground with the cognition and affect project architecture. The basic elements in the **Ψ** architecture are motives which compete with each other. The strength of each motive changes over time and is determined by physical, emotional and cognitive state variables. The motive with the greatest strength becomes "action leading". The architecture selects the actions which belong to this motive and which lead to a final satisfaction of this motive.

We consider the **Ψ** architecture to be one of the best architectures available for modelling individual human behaviour. However, it has two drawbacks. Firstly, it suffers from the fact that the publications about it are only in German, and therefore it is relatively unknown. Secondly, this approach entirely ignores sociological factors, such as the importance of social norms, adaptation to group behaviour, compliance with social expectations, and the need for social contact.

Compared with BDI (Rao and Georgeff [24]), PECS is not just restricted to rational decision-making and to cognitive processes. In this respect PECS is broadly similar to the approaches of Wright et al. [32] and Dörner [10]. Wright et al.'s approach does not appear to be well structured, and thus it is almost impossible to apply this architecture to new application areas. PECS claims to be a reference model as it has the ambitious aim of being applicable to almost any problem. PECS has many similarities with Dörner's **Ψ**, but PECS has greater scope, as it allows the possibility of modelling social processes as well.

4. The NIDDM screening model with PECS

The model described in this paper was based on Davies and Brailsford's model for screening for diabetic retinopathy in people with non-insulin dependent diabetes (NIDDM). This model has been described in detail elsewhere (Brailsford et al. [5] and Davies et al. [9]). For the purposes of this paper, the original model has been somewhat simplified, and compliance with screening has been modelled using a combination of the HBM and the PECS architecture.

Retinopathy is one of the most serious complications of both types of diabetes: insulin-dependent (IDDM) or Type 1 diabetes, more common in younger people, and non-insulin-dependent or Type 2, which mainly affects older people (Klein et al. [21]). It can lead to blindness if untreated, but can, if detected sufficiently early, be successfully treated by laser. The patient is often unaware of the early signs of diabetic retinopathy, so screening and timely treatment can be very effective in the prevention of blindness. Currently many different screening modalities are in use, with no clear consensus about the ideal setting (e.g., hospital clinic, high-street optometrist, primary care), the ideal screener (e.g., specialist ophthalmologist, diabetic consultant, general practitioner) or the ideal interval between screens. The original model was designed to investigate these different modalities and make recommendations about good practice.

One of the interesting findings of this work was the key role played by patient compliance with screening. Compliance is defined as the probability that a person will attend for screening when invited on a given occasion. This result led Davies and Brailsford to recommend that screening methods which achieve a high compliance level are desirable. The data used in published versions of this model was obtained from O'Neill et al. [23], the Leicester University Diabetic Retinopathy Audit (Grimshaw et al. [14]) and from James et al. [18] and showed compliance to be fairly high, averaging over 80%.

There are two types of sight-threatening retinopathy, known as proliferative diabetic retinopathy (PDR) and clinically significant macular oedema (CSMO). People progress through different stages of retinopathy, either starting with background diabetic retinopathy (BDR), then PDR, then blindness; or starting with diabetic macular oedema (DMO) to CSMO to blindness. It is possible to have both types of retinopathy, although PDR is more common in IDDM, and CSMO is more common in NIDDM. Therefore people will continue to be screened for the other form of retinopathy, even after they have been treated for one form. The simplified version of the screening process used in the current model is shown in Fig. 6. "OP" denotes a visit to a hospital out-patient clinic, where a positive test result is confirmed before treatment is given. False positive screening results are identified at this stage.

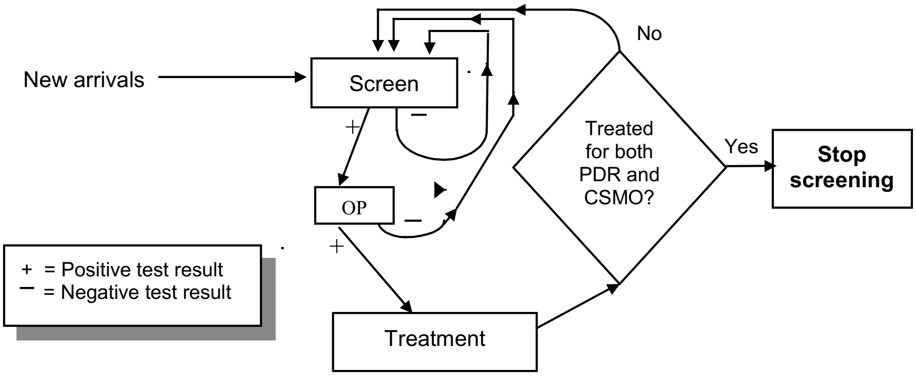

Fig. 6. Simplified model of the screening process.

In the original model, compliance was a constant (85%) for everyone. This meant that for every person, the probability of attending was 0.85 each time they were invited for screening. In practice, people who fail to attend on a given occasion are likely to be followed up and invited to attend again shortly after their missed appointment. Previously published versions of the original models allowed for this, although the model described in this paper does not. The original models were also used to study the effects of varying coverage. Coverage refers to the proportion of people who are screened at least once in their lifetime. Coverage of less than 100% means that some people are never screened at all, which is more serious than just randomly failing to attend on a given occasion. The original model was sensitive to both coverage and compliance. In practice, in a health behaviour model, coverage is also an important issue because it is likely that persistent non-attenders are people who are at additional risk for a variety of reasons. If people do not consider screening important, they may equally well not consider other health-related behaviours important, such as diet and exercise. Their diabetic control may not be good, their living conditions may be poor, and they may have more serious socio-economic problems such as homelessness and alcoholism. Harris and Lynn [15] discuss the importance of health beliefs and compliance with medical advice in general in the control of diabetes.

In our model we identified a number of factors known to affect attendance. For example, in screening for breast cancer it is known that the number of previous attendances is a key factor in predicting future attendance (Weinberg et al. [31]), and we therefore decided to include this factor in our model. Health motivation in general was selected for the reasons outlined above. These factors are listed below:

- Number of previous attendances.
- Health motivation (defined as good, medium or poor).
- Perceived physical state (patient's known stage of retinopathy).
- Emotion (anxiety).
- Perceived susceptibility to disease.
- Cognition.
- Knowledge about the disease, and belief about disease prevalence, and
- Status: educational level.

These are linked together to form the HBM constructs, shown in Fig. 7 below, in which the PECS elements are shown in shaded boxes which influence the various constructs within the HBM. For example, a person's emotional state will influence their own perceived susceptibility to illness; a nervous, anxious person will worry about going blind and will think it is likely to happen to them. Similarly, a well-educated person is more likely to make a rational judgement, based on medical evidence, about the value of attending for screening. The connections between the elements in Fig. 7 are specific to diabetic retinopathy. A different application might require different interpretations of the relationships between the PECS components and the HBM constructs.

The assumptions underlying the selection of the PECS components for diabetic retinopathy were as follows:

- *Physis*: the physical state—the stage of retinopathy may affect people's attendance; being diagnosed in the early stages of disease could act as a "cue to action", reminding people that they already have potential sight problems.
- *Emotion*: Anxiety, and individual perceptions of the overall threat of blindness, will together influence a person's perceived susceptibility to becoming blind themselves. We assumed that highly anxious people are more likely to attend for screening.
- *Cognition*: Knowledge about the facts of diabetic retinopathy, screening and treatment will influence a person's perceptions about the severity of the disease and his/her evaluation of the benefits of screening to counteract the threat of blindness. A person's belief about the prevalence of retinopathy could also affect their understanding of their own risk of getting it.
- *Status*: a person's educational level is likely to determine his/her ability to evaluate behaviours to counteract the threat of blindness, and also his/her perceptions of the threat itself. We as-

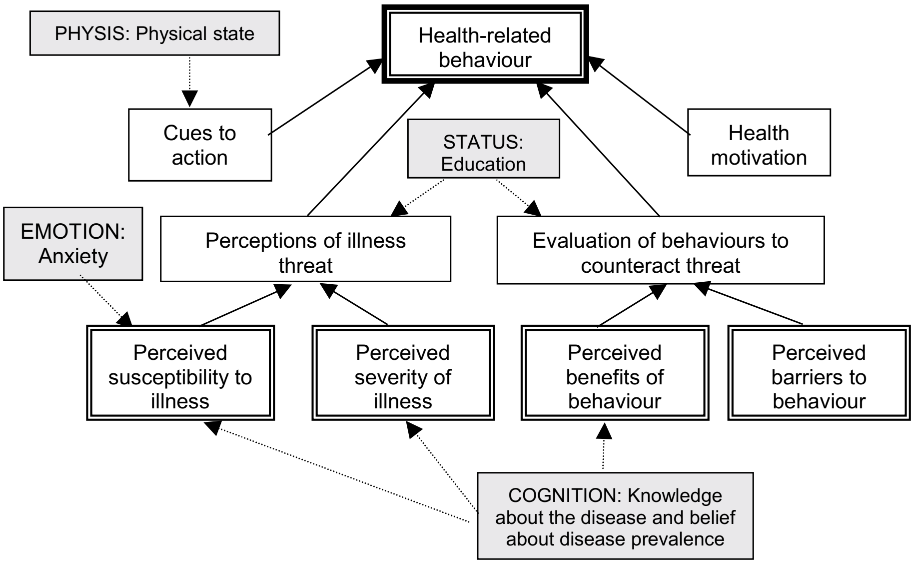

Fig. 7. The PECS architecture combined with the HBM constructs.

sumed that the better educated a person is, the more likely s/he is to attend.

5. Implementing the model

We embedded a subset of the PECS components from Fig. 3 inside the entities in a discrete-event simulation. Our approach did not use the full PECS agent structure, in that our "patient" entities had no sensor or perception components. Our entities had a behaviour component to calculate the probability of attending for screening, and an actor component to execute the behaviour, i.e., either to attend for screening, or not.

A similar format to that of the equations in the theory of planned behaviour model (Ajzen [1,2]) was used to construct equations for the behaviour component to calculate the compliance. This format was based on a very simple exploratory model developed by one of Schmidt's students, Birkle [4]. Birkle's model calculated the average compliance with one-off screening for a hypothetical disease in a population of N people. Every person was assigned a value of 1, 2 or 3 for each of the PECS components, representing a score of low, medium or high on that factor. A standardised weighted average of these PECS values was then rounded to zero or one to give a binary "attend/not attend" measure for each patient.

Birkle's approach [4] was refined and extended to incorporate the HBM constructs shown in Fig. 7, and was embedded in Davies and Brailsford's discrete-event simulation model for diabetic retinopathy screening. The model used data derived from the literature for the population prevalence of the stages of retinopathy and the natural history of disease. For full details of the original model and the data, see the University of Southampton's retinopathy website (Brailsford and Davies [6]).

In the DES model a population of diabetic patients is tracked over time; during this period some patients will die and some new patients will be diagnosed. Each patient is an individual entity in the model, with his or her own characteristics, such as their history of disease and record of attendance for screening. The HBM/PECS approach was implemented in this model by assigning numerical attributes, representing the various psychological characteristics, to the patient entities. The stage of retinopathy was already known for every person in the simulation, and the number of previous screening attendances was recorded for each patient. Anxiety, perceived susceptibility, knowledge of disease, belief about disease prevalence, health motivation and educational level were all defined as low, medium or high, and given values between 0 and 1. The four PECS components were then calculated from these attributes as follows:

- *Physis* = stage of retinopathy = 0.7 for None, 0.9 for BDR or DMO, and 1.0 for all other states, reflecting our assumption that people with background retinopathy are aware they have potential sight problems and are thus more likely to attend for screening.
- *Emotion* = anxiety × perceived susceptibility where both take one of the three values 0.8 (low), 0.95 (medium), 1.0 (high).
- *Cognition* = knowledge of disease × belief about disease prevalence where both take one of the three values 0.8 (low), 0.9 (medium), 1.0 (high).
- *Status* = educational level takes one of the three values 0.8 (low), 0.95 (medium), 1.0 (high).

Each time an individual was invited for screening, their compliance was calculated (by the behaviour component) using the following equation:

$$\text{Compliance} = v \times m \times p \tag{2}$$

where

$$v = \text{visits} = 1 - (0.1)^{\text{number of previous visits}}, \tag{3}$$

$$m = \text{motivation} = 0.6 \text{ (low)}, 0.9 \text{ (medium) or } 1.0 \text{ (high)}$$

and

$$p = \text{PECS} = \left\{ \frac{\text{physics} + \text{emotion} + \text{cognition} + \text{status}}{4} \right\}. \tag{4}$$

Eq. (3) models the "visits" component as an increasing function of the number of previous attendances. Eq. (2) yielded a value C between 0 and 1, interpreted as the probability of attending on that occasion. A uniform random number u was then sampled, and if C was greater than u then the patient attended (corresponding to the actor component).

Table 2
Calculated values of the compliance for different parameter settings

	Compliance
All PECS parameters low, no previous visits, no retinopathy	0.375
All PECS parameters medium, 5 previous visits, BDR	0.802
All PECS parameters high, 15 previous visits, PDR	1.000
All PECS parameters medium, 5 previous visits, no retinopathy	0.756

The parameter values used in this model were obtained (on a trial and error basis) by a systematic series of calculations for all combinations of the parameters, in order to obtain a plausible range of values for the compliance compared with known estimates of population compliance with screening derived from the literature (O'Neill et al. [23], Grimshaw et al. [14], and James et al. [18]). Table 2 shows a few of the calculated values for different values of the parameters. The multiplicative form of the PECS components, the additive way in which they were combined in Eq. (3) to give p, and the multiplicative form of the main equation (1), were chosen arbitrarily, and there is clearly scope here for further research to derive a more empirical basis for both the choice of form of these equations, and for the parameter values.

6. Simulation experiments

The model was run for 10 different scenarios for a population of 1000 diabetic patients. These 10 scenarios were chosen as follows. In order to investigate the effects of extreme values, in the first scenario all the parameters were set to low, and in the second scenario all the parameters were set to high. To investigate the relative effects of three of the PECS components, the next six scenarios were obtained by setting the three PECS parameters emotion, cognition and status in turn to low and then high, meanwhile keeping all the other parameters fixed at medium. Since the physis

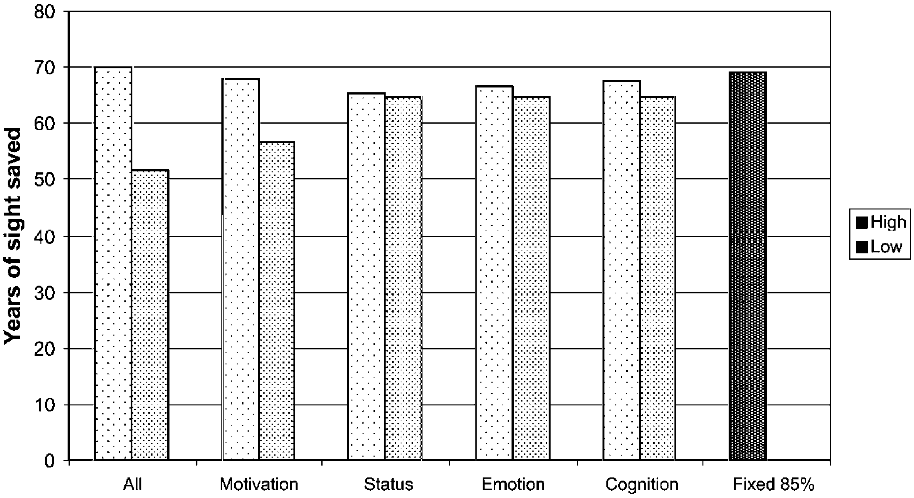

Fig. 8. Total years of sight saved over a 10-year period in a population of 1000 diabetic patients.

parameter depended solely on the stage of retinopathy, as described above, physis was not varied but was calculated in the same way in all the scenarios. The final two scenarios were chosen to investigate the effect of the motivation parameter *m*.

Screening in each case was offered at annual intervals. The screening test considered was a moderately accurate test, with sensitivity 61% and specificity 85%. Sensitivity refers to the ability of the test to correctly identify positive cases, whereas specificity refers to its ability to correctly identify negative cases. In fact, this is the accuracy of screening carried out by a van-mounted mobile camera, taking one photograph, subsequently reviewed by a diabetologist (Hutchinson et al. [17]).

Each scenario was run for 10 years with a run-in of 5 years, and was averaged over 200 iterations. This number of iterations was required to ensure that the 95% confidence limits were within 5% of the estimated mean. The selected output measure was the total years of sight saved in a population of 1000 diabetic patients. These 10 scenarios are compared, in Fig. 8 below, with the results of using a fixed probability of attendance of 0.85 for all patients, derived from the literature (O'Neill et al. [23], Grimshaw et al. [14], and James et al. [18]), and shown in the column on the right.

One of the key findings of Davies and Brailsford's work [9] was that the simulation results were highly sensitive to assumptions about compliance. The compliance was varied from 40% to 100% and the years of sight saved were closely correlated with the compliance. The results presented in Fig. 8 suggest that using a fixed value for everyone in the population may tend to overestimate the attendance. However, the results are merely artefacts of the form of the compliance equation (2), and so we do not claim that this is likely to be true in practice. For example, the impact of "health motivation" appears greater than that of the other four PECS components, simply because this factor has four times the weight of the individual PECS constructs in Eq. (2). Nevertheless, the results illustrate the impact of changes in behaviour on a measurable outcome, years of sight saved by screening and treatment. The results demonstrate how compliance can be made to vary in different circumstances—for example, if a public health awareness campaign increased people's knowledge about the disease in a section of the population. Such a model would have great potential value as a policy analysis tool.

7. Conclusions

This implementation of the PECS architecture was developed within a conventional discrete-event simulation model. PECS had not previously been applied in a discrete-event mode, but it was found to be very easily implemented by adding additional fields for the PECS attributes to the entity record. The entities (patients) were given numerical attributes, calculated using a simple arithmetic formula, which determined a key aspect of their health behaviour: compliance with screening. The results showed the possibility of capturing the determinants of this behaviour sufficiently accurately to enable policy decisions aimed at increasing compliance to be made. No existing models in the literature have used this approach. The standard method is simply to assume a certain (fixed) percentage of the population will fail to attend when invited for screening. Our new approach is capable of utilising a number of measurable personality traits in order to obtain a more accurate model for attendance at screening. Collaboration with psychologists is required to develop the underlying behavioural model further, to refine the PECS equations, and to collect empirical data. The key benefit of this approach will be that it will enable health planners and policy-makers to design more efficient and effective screening programmes, in order to attract non-attenders and improve the overall health of the population.

We have shown that modelling human behaviour is possible … up to a point. Capturing the full complexity of the human personality in a computer programme still remains a topic for philosophers rather than operational researchers. However, the ability of agent-based simulation to model systems of patients in a more sophisticated way, incorporating not only their interactions with each other, but also with health care professionals and with the environment, gives rise to exciting prospects. This approach has the potential to be applied not just to screening for diabetic retinopathy, but to many other health arenas.

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