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Abstract. Behavior plays an important role in managing chronic illnesses, with behaviors such as smoking, unhealthy diet, and physical inactivity often leading to (or worsening) chronic illnesses. To attain long-term healthy behaviors, personalized behavior modification programs are known to be effective. The design of such programs requires (a) developing a patient model that represents the patient’s health needs, behavior challenges and preferences, together with their perceived abilities and motivation; and (b) personalization of standard behavior modification strategies towards the patient model. We argue that, to ensure their effectiveness, the design and personalization of behavior modification strategies should be guided by evidence-based behavioral theory. We present a knowledge-driven, Semantic Web-based behavior modification framework that computerizes core constructs of the Social Cognitive Theory (SCT) into an OWL ontology, called the behavior modification knowledge model. Based on this OWL ontology, concrete patient profiles and behavior modification strategies are instantiated. In line with SCT, our approach formulates behavior modification strategies as a sequence of personalized, short-term action plans, designed to assist the patient to increase their perceived ability to overcome behavior-related barriers. An initial scenario-based evaluation illustrates the system’s ability to personalize action plans towards unique patient-specific profiles and behavioral challenges.

Keywords: personalized health; user modeling; behavioral modification; user personalization.

1 Introduction

The prevalence of chronic diseases is on the rise, which is placing a significant burden on the healthcare system and reducing people’s quality of life [1]. Behavior plays an important role in the prevention and management of chronic diseases, with behaviors such as smoking, unhealthy diet, physical inactivity and alcohol abuse often leading to, or exacerbating, chronic illnesses [2]. Behavior modification is a well-established method to motivate an individual to adopt health-enhancing behaviors, and includes
approaches such as education, positive skill development and emotion management [3–7]. In particular, person-specific behavior modification programs have been shown to be highly effective [8, 9] but are also quite complex, as they require alignment with the individual’s health needs, behavior challenges and preferences, whilst also taking into account factors such as culture, perceived abilities (i.e., self-efficacy), motivation and socio-economic factors [5, 10]. Because of this complexity, designing effective, personalized behavior modification strategies is challenging, and involves a holistic process of: (a) generating an up-to-date patient model, based on questionnaires and health providers’ observations; (b) personalizing standard behavior modification programs based on the patient’s profile; (c) guided by the tailored strategy, delivering timely behavior modification interventions (e.g., educational and motivational messages, activity reminders) to the patient; and (d) monitoring the patient’s compliance to the behavior modification strategy, and adjusting it accordingly [6]. Computerized, person-specific behavior modification programs can be found in the literature, and mostly focus on educational aspects [11–17]. While these works often mention a behavioral-theoretic foundation, to the best of our knowledge, they do not elaborate on a computerized, knowledge-driven behavior modification approach.

In this paper, we present a knowledge-driven behavior modification framework based on Semantic Web technology, which performs patient modeling and personalization of standard behavior modification strategies. The theoretical foundation for our framework is grounded in the Social Cognitive Theory (SCT) [18]. We present a novel approach of computerizing SCT constructs, by (a) modeling the behavioral-theoretic (SCT) knowledge in terms of an OWL ontology, (b) instantiating patient models and standard behavior modification strategies using this ontology, and (c) performing personalization, which involves identifying and ranking strategies suitable for the patient, and allowing patients to fine-tune the activity (e.g., timing) based on their daily schedules. In line with SCT, our approach formulates behavior modification strategies as action plans, designed to assist the patient to increase their perceived ability (i.e., self-efficacy) to maintaining health behavior modification. In this work, we focus on the long-term goal of improving physical activity, although the core knowledge model and framework can be readily extended to manage other behaviors. Our framework is implemented in Java and uses Apache Jena [19] to work with Semantic Web data. It features a front-end Web application for patient interaction.

The paper is structured as follows. In Section 2, we shortly discuss SCT and its application to health behavior modification. Section 3 elaborates on the state of the art in computerized behavior modification. Section 4 details our concrete behavior modification approach. Section 5 provides a scenario-based evaluation of the system. Finally, Section 6 states conclusions and future work.

2 Social Cognitive Theory

Social Cognitive Theory (SCT), as a cognitive behavioral approach, views human beings as self-regulatory systems, characterized by cognitively mediated pro-active and re-active control mechanisms [18]. An important implication of this cognitive aspect is
that, unless there is sufficient motivation, a particular behavior will not be realized. In this vein, Bandura et al. [20] outlined a core set of SCT determinants to promote healthy behaviors by influencing motivation:

- **Knowledge**: knowledge on health risks and benefits of various behavioral practices.
- **Self-Efficacy**: one's perceived ability to perform certain health behaviors.
- **Outcome Expectations**: expectations about cost and benefits of different behaviors.
- **Health Goals**: long-term goals set the course for behavior modification, while short-term goals help people to realize long-term goals over time.

Clearly, these determinants are interrelated: e.g., motivation can be supplied by positive outcome expectations, which is itself influenced by increasing knowledge on the pros and cons of health behavioral practices. Self-efficacy plays a central role, as the patient’s perceived ability to complete the action influences expectations about outcome and the feasibility of health goals. Bandura et al. identified 4 sources of information (or modes) [21] that inform one’s self-efficacy, in order of importance:

- **Mastery Experience**: appraisal of one’s own performance at performing an action. Experiencing success enhances one's self-efficacy, and failure reduces that sense. Overcoming some barrier through sustained effort will realize a more resilient appraisal.
- **Social Modeling**: seeing others succeed, who are comparable to one's own situation and physical characteristics, increases one's perceived ability to perform the activity.
- **Social persuasion**: persuading others to believe in themselves may be effective in increasing their self-efficacy.
- **Control over physical/emotional states**: even if one possess the necessary skills, some emotional states (e.g., anxiety) will likely result in a low self-efficacy.

By maximizing one or more of these modes, self-efficacy can be increased, which, as mentioned, is a pivotal factor in promoting healthy behaviors.

### 3 Computerized Behavior Modification Programs

A number of works computerize certain behavior modification theories to effect sustained behavior modification [11–16]. However, these studies do not present a detailed, re-usable and knowledge-driven approach to behavior modification, as is done in our paper. Secondly, most of these studies only include an educational aspect, meaning they also differ in scope. Real-time behavioral interventions help patients to apply health-related skills and behaviors in natural settings, instead of clinical environments, to improve long-term health behavior [22]. SMS-based solutions involve sending text messages with relevant educational materials at certain points during the day, to support smoking cessation [16] or to sustain recent weight loss [17]. Other solutions utilize more advanced technology: e.g., King et al. [23] used a PDA to support activities such as timely goal setting, progress feedback and assessment of barriers. As mentioned before, while these works mention the application of behavior modification theories, none of them present a detailed, grounded behavior-modification approach and framework.

In previous work, we introduced an SCT-based self-management framework to increase patient self-efficacy [6], which focused on delivering personalized educational
and motivational messages. Later efforts extended this work with a mobile messaging platform [24], and applied it in practice to achieve behavior modification for diabetes [25]. This paper significantly extends this previous work, with action planning capabilities for behavior modification.

4 Behavior Modeling and Personalization Approach

Given the centrality of Self-Efficacy within SCT, and the modes readily available to positively influence it (Section 2), our approach focuses on increasing Self-Efficacy. For this purpose, we target its most influential mode [21], namely Mastery Experience. To support Mastery Experience, we adopt a goal-setting and action-planning approach, which consists of setting a series of achievable, short-term goals in the form of action plans. Each action plan assists the patient in overcoming a personal barrier, which is inhibiting their ability to achieve a long-term goal (e.g., regular physical activity). As per SCT, progressively achieving action plans, each overcoming a non-trivial barrier, increases a patient’s self-efficacy in overcoming barriers to long-term behavior change. By targeting short-term (limited to a week) and achievable action plans, we ensure minimal likelihood of failure and loss of motivation. To further maximize the chances of success, action plans are pre-selected and ranked based on their suitability.

Our framework includes the following major components to implement our personalized action-planning approach. (Two other components, monitoring and messaging components, are left out as they are not the focus of this paper.)

- A Knowledge Model modeling the necessary behavioral-theoretic (SCT) knowledge, including:
  - Patient Model: personal attributes and perceived barriers to healthy behaviors.
  - Action Plan Suggestions (ActiPS): action plan templates based on validated medical content, relevant to certain user attributes and barriers.
- The Action Planning Component selects and ranks ActiPS based on their descriptions and the patient’s profile, preferring plans with high likelihood of success.
- The Personalization Component allows the patient to tailor an ActiPS, 1) choosing timings and frequencies based on personal constraints to increase chances of success; and 2) indicating their confidence, thus reflecting their current self-efficacy.

4.1 Knowledge Model

The Knowledge Model, implemented as an OWL ontology, incorporates the necessary knowledge for effecting personalized behavior modification, based on Social Cognitive Theory (SCT). By encapsulating this information in an ontology, we decouple action plan processes (see Section 4.2) from knowledge representation, and thus allow any kind of analysis to be performed to inform long-term behavior modification.

Fig. 1 shows a high-level EER diagram of the Knowledge Model OWL ontology. The Patient subclass represents the Patient Model. It keeps a set of profile attribute values (ProfileAttribute) describing the patient’s current situation, physiological properties and relevant medical issues. A ProfileAttribute has subclasses for each attribute type, which themselves have a discrete set of values (e.g., young, adult). Secondly, the
Patient Model keeps the patient’s perceived barriers, which are obtained by filling out a Self-Regulatory Efficacy Questionnaire (SREQ) comprising a set of SREQ Questions, each of which pertain to a Barrier. Answering these questions enables the patient to self-identify personal barriers to be overcome (identified property).

An ActionPlanSuggestion is a standard behavior modification strategy, and is related to a set of barriers that it can help to overcome, as well as profile attribute values to which it is relevant, with associated relevance scores (0 < score < 1). For instance, the ActiPS brainstormProjectIdeasWhileWalking tackles barriers tooMuchWorkload and oftenFeelTooTired; and is relevant only to people who are employed (fulltime or part-time; relevance of 1) and considered less relevant to people with high time availability (since better ways of increasing physical activity exist in that case; relevance of 0.5).

For our work, we re-used the physical activity SREQ from Bandura et al. [26] and included its barriers in our Knowledge Model. Furthermore, for each barrier, a health expert extracted a set of ActiPS from well-known health-related sources, including WebMD, MayoClinic, CDC and the American Heart Association, which were integrated into the Knowledge Model.
4.2 Action Planning

Action planning involves finding and ranking suitable ActiPS, based on information from the knowledge model. To calculate the suitability of an action plan AP for patient P, we apply the suitable function:

1. function suitable(P, AP)
2. \( sim_{barr} := (barr_{curr}(P) \in barr(AP)?1:0) \)
3. \( sim_{attr} := 0 \)
4. foreach \( A_p \in attr(P) \)
5. \( A_{AP} := attr(AP)[A_p] \)
6. if \( rel(A_{AP}) = 0 \)
7. \( sim_{attr} := 0 \)
8. break loop
9. end if
10. \( sim_{attr} := sim_{attr} + rel(A_{AP}) \)
11. end for
12. \( sim_{attr} := sim_{attr}/|attr(P)| \)
13. if \( sim_{barr} = 0 \lor sim_{attr} = 0 \)
14. return 0
15. return \( sim_{barr} \times weight_{barr} + sim_{attr} \times weight_{attr} \)

First, the function checks whether the patient’s current barrier is tackled by the action plan (line 2). Then, it checks the relevance of the patient’s profile attributes w.r.t. the action plan (lines 3-12). If one of the patient’s attributes has 0 relevance, the overall attribute score will be 0 as well (e.g., an action plan unsuitable for the disabled will have a 0 relevance for the disabled attribute) (lines 6-9). Then, the attribute score is normalized by the total number of profile attributes (line 12). If either of the individual scores is 0, an overall suitability score of 0 is returned (lines 13-14). If not, a weighted sum of both scores is returned (line 15).

Utilizing the suitable function, the findMatches function performs action planning by selecting and ranking ActiPS for a patient, based on their Patient Model:

1. function findMatches(P)
2. matches := ∅
3. foreach \( A_P \)
4. score := suitable(P, \( A_P \))
5. if \( score > threshold_{suitable} \)
6. match := (plan:\( A_P \), suitable:score, done: followed(P, \( A_P \)))
7. matches := matches \cup match
8. end if
9. end for
10. rank(matches)
11. return matches

The function calculates the suitability of each ActiPS for the patient (lines 3-4), keeping only action plans with scores above a configured threshold (lines 5-7). For ranking purposes, it also collects whether and how often the patient already followed the action plan (done attribute). Finally, the rank function ranks the ActiPS, with the number of times the patient followed the action plan being the first sort criterium (ascending) and the suitability score the second sort criterium (descending).
4.3 General Behavior Modification Process

In our behavior modification framework, the patient follows an overall process that was inspired and adapted from the Chronic Disease Self-Management Program (CDSMP [27]), which has been shown to be effective in follow-up clinical trials [28, 29]. We summarize the full process below (the messaging step is not presented in this paper):

- **Identification of the Problem**: the patient fills out a Self-Regulatory Efficacy Questionnaire (SREQ) related to the long-term goal. Based on the questionnaire results, the system obtains a ranked list of barriers currently perceived by the patient.
- **Goal Selection**: the collected barriers are presented as short-term goals, and the patient is prompted to select one of them.
- **Listing of Action Plan Suggestions**: based on the Knowledge Model, the action planning step (Section 4.2) computes a filtered and ranked list of suitable ActiPS.
- **Tailoring the Action Plan**: after choosing an ActiPS, the patient tailors the frequency and intensity of the activity, and indicates their confidence in completing it (1-10). (If this confidence is below 7, the patient is suggested to revise.)
- **Messaging**: during the action plan, the system sends educational and motivational messages to the patient.
- **Monitoring**: at the end of the week, the patient is asked to report on the degree of success (1-10). In case of failure (success < 5), the patient is advised to try out a different ActiPS for the barrier.

5 Scenario-based Evaluation

This section illustrates the usage of our behaviour modification approach, targeted towards physical activity. Below, we introduce a relevant patient profile and follow the overall process flow to guide the patient towards long-term behavior change.

5.1 Patient Profile

Jane is an older home-maker living in the suburbs, with plenty of free time. She currently does not participate in sports and has no gym membership, but she has training equipment at home. She currently has a musculo-skeletal condition, and is on steroid medications that keeps her condition under control.

5.2 Process Flow

Below, we show each patient going through the main process flow steps: i.e., problem identification, goal selection, and listing of ActiPS.

**Identification of the Problem**: by filling in the SREQ questionnaire, the patient self-identified the following barriers to behaviour change: Jane often feels too tired to engage in physical activities, due to her musculo-skeletal condition, and cannot go outside due to bad weather.

**Goal Selection**: the system presents these self-identified barriers to the patient, who chooses to overcome her weather-related barrier.
Listing of ActiPS: based on the selected barrier and the patient's personal profile, the system selects and ranks a top-5 list of ActiPS for Jane:

1. Exercise while you watch TV: score 1.0
2. Do mall walking when you drop family off at shopping mall: score 1.0
3. Get up and move around (e.g., inside house) for a few minutes / hour: score 1.0
4. Visit local shopping mall and walk (30 min.): score 1.0
5. Move around while making phone call: score 1.0

(Note that these plans all have a suitability score of 1; we address this in our Conclusion.) In the Knowledge Model, these action plans are related to Jane's chosen barrier of not being able to go outside due to bad weather (all activities can be performed indoors). Concerning suitability towards her profile, we note that no typical homemaker activities (e.g., cleaning the house, ironing clothes, etc.) were suggested, since her profile indicates she is a homemaker and thus likely performs them already. In the Knowledge Model, these kinds of homemaker activities are related to homeMakerOccupation (an instance of Occupation, which is a subclass of ProfileAttribute) with a 0 relevance. Since Jane has plenty of time, the system also suggests more time-consuming (indoor) activities, including visiting the local shopping mall (4). Since Jane does not have a gym membership but does have equipment at home, the system also suggests exercising while she watches TV (1). To support this matching, the Knowledge Model relates the ActiPS to relevant attributes with a \( > 0 \) relevance: e.g., mallWalking is related to highTimeAvailability, and tvExercising is related to homeEquipmentAvailability. Finally, the activity already tried by Jane, namely (5), is ranked lowest.

6 Conclusion

We presented a behavior modification framework based on validated behavioral theory (i.e., SCT), which is driven by a Knowledge Model that encodes behavior-theoretic constructs and includes an elaborate Patient Model. Our novel approach involves (a) modeling the SCT knowledge in terms of an OWL ontology, (b) instantiating the ontology with patient profiles and standard behavior modification programs, and (c) applying action planning processes to personalize these strategies. To effect resilient behavior modification, our action-planning and goal-setting approach focuses on maximizing the pivotal Self-Efficacy determinant by improving Mastery Experience. To that end, the patient completes a personalized sequence of short-term action plans, targeted to overcome non-trivial barriers. Our initial, scenario-based evaluation shows that our approach is able to cope with patients' unique barriers and restrictions.

Future work involves studying how the Social Modeling mode, whereby one's perceived ability is influenced by the achievements of similar people, can be utilized to further increase Self-Efficacy. For instance, by keeping the collective achievements of patients using the system, ActiPS suggestions may be accompanied by the success rates of similar patients. Further, this mode may influence the ranking of ActiPS as well, which would help choosing between ActiPS with very similar suitability scores (e.g., see evaluation). We also aim to incorporate an educational and motivational messaging component, to yield a holistic behavioral modification process.
References