The Design of an Ontology-Driven mHealth Behaviour Change Ecosystem to Increase Physical Activity in Adults

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Abstract. The global pandemic and the resulting lock-downs have indicated the importance of regular physical activity for both mental and physical wellness. Many mHealth applications to increase physical activity exist, they however continue to fail to achieve their objective. The need arises for a more theoretically-grounded approach that considers the dynamic nature of the individual. To create a system that is context-aware and personalised, an interdisciplinary approach is needed and regular input of stakeholders and end-users is of the essence. This expert knowledge is captured into an ontology, centred on the Health Action Process (HAPA) model for behaviour change. This paper describes the requirements for the design of such a mobile health Behaviour Change System for increased physical activity in adults and emphasises the need for personalisation on the level of the user, action and coping planning and motivational level.

Keywords: Knowledge representation · Ontology · Health care · User-centric · Personalisation · Decision support system · Human-computer interaction · Health behaviour change

1 Introduction

The past two years, as we stayed more at home than ever, habits and hobbies had to be replaced and reinvented. Due to the global pandemic and lock-downs, physical activity was reduced to a minimum, as shops and sport centres were closed and working from home became the norm. Nonetheless, physical activity remained important for both mental and physical health [5,8,10]. Non-communicable diseases (NCDs) such as cardiovascular diseases, cancer, chronic respiratory disease, and type-2 diabetes, are worldwide responsible for 41 million

H. Lewy and R. Barkan (Eds.): PH 2021, LNICST 431, pp. 452–468, 2022.
https://doi.org/10.1007/978-3-030-99194-4_28

deaths each year, equivalent to 71% of total deaths [32]. Harmful habits such as physical inactivity, alcohol abuse, and unhealthy diets all increase the risk of dying from a NCD. Now more than ever it is important to form healthy active habits to reduce the risk factors of unhealthy habits. Interventions that aim to reduce these risks can decrease premature deaths by one-half to two-thirds [33].

Mobile health Behavioural Change (hBC) interventions, e.g., to quit smoking or to increase physical activity, have the potential to modify these risks as they have the potential for high reach [33]. As the number of available mHealth applications keeps rising, these applications have yet to reach their full potential to become essential tools for change in the healthcare sector [23]. Mobile health Behaviour Change Support Systems (hBCSS), which have hBC as their objective, often show to be effective, however, comprehensive evaluation of their long-term effectiveness is often lacking and sustained engagement levels outside studies are low [33]. hBCSSs have been successful for e.g., stress, anxiety and promotion of healthier lifestyles [1], but the evidence base for mHealth apps is still in its infancy [23]. Even though these apps can spark interest at first, few manage to retain the attention and are often abandoned after a few uses [27]. Most downloaded mHealth apps are often not even opened, with around 26% that are never used a second time and continued use remains extremely rare [19,23]. Additionally, recent studies show that wearables, e.g., pedometers, are only worn for a limited amount of time: around 32% stop wearing them after 6 months, while 50% stops after 1 year [24]. Another obstacle is that most health apps are disease specific and do not take the needs of diverse stakeholders into account, which could lead to early abandonment if this diversity is not properly addressed [23].

To create an effective mobile hBCSS, it is necessary to go beyond researching the average person in the average context and to take into account some of the basic tenets of human behaviour: individuals are dynamic beings who attune their behaviour as a function of varying contexts. Moreover, because theory-based interventions are more effective than others, it is also recommended to model the knowledge that resides in the theoretical frameworks to drive behaviour change.

This paper presents the requirements for the design of an ontology-driven intelligent Decision Support System for the personalised and context-aware promotion of physical activity in adults. The remainder of this paper will first discuss relevant background information in Sect. 2. Next, in Sect. 3, the interdisciplinary approach to build the ontology and designing the Decision Support System is explained, while underlining the importance of different sources of expert knowledge. Section 4 lists the findings that followed from the several workshops with stakeholders that were organised to date. Following from these findings, requirements for the system and interaction with the end-users were defined, which are detailed in Sect. 4.

2 Background

In order to create an Intelligent Decision Support System to increase physical activity, insight is needed into what theoretical frameworks can be used as the backbone of the system. The following subsections will first elaborate on the added value of ontologies, followed by the chosen model for behaviour change and indication of the significance of previous research.

2.1 Ontologies

Knowledge can be modelled in various ways [2]. In recent years, behavioural scientist have began to use computerized knowledge-based systems to represent domain-knowledge more formally and to use this knowledge to solve complex problems [15]. A key component in a knowledge-based system is an ontology, which describes concepts in a certain domain, together with their relationships and attributes. This structuring of knowledge facilitates the communication, collaboration and integration of complex problems in a multidisciplinary manner. Furthermore, by combining an ontology with intelligent algorithms, it is possible to reason over the information available in that knowledge domain to gain new knowledge and insights.

2.2 The HAPA Model

Increasing levels of physical activity (PA) is much harder than initially expected [11]. As many mHealth applications remain unsuccessful in creating sustainable behaviour change [14,18], the need arises for more theory-based interventions, both to better understand the processes of behaviour change and to improve the efficacy of the interventions [3,17].

One of the most comprehensive models for behaviour change is the "Health Action Process Approach" (HAPA) model, shown in Fig. 1 [28]. The model describes behaviour change in two layers. On a first stage layer, it distinguishes people based on their intentions and behaviour concerning a specific health behaviour goal: (1) pre-intenders have not yet formed an intention, (2) intenders have formed an intention without acting on it, and (3) actors have formed an intention and translated that intention into action.

The processes that are relevant for each stage and particularly for stage transitions are described in the continuum layer of the model. The HAPA model describes (1) motivational, e.g. risk perception, outcome expectancies, and (2) self-regulatory factors, e.g. action planning, and their role in the process of behaviour change. The two layers of the HAPA make it suitable for both basic research and intervention development [28]. It is also well-grounded in fundamental and experimental research and meets criteria that have been identified as relevant for good theory [6], and a theory diagram has been created for it [12].

Perhaps most importantly, HAPA encompasses the entire cycle of goal-directed action. It includes motivational processes, leading to a behavioural intention, and volitional, self-regulation processes, which bridge the gap between intention and actual behaviour. Research showed that self-regulation strategies, in which participants select their own goals and how to reach them, i.e. action planning, explore solutions for possible obstacles, i.e. coping planning, and keep

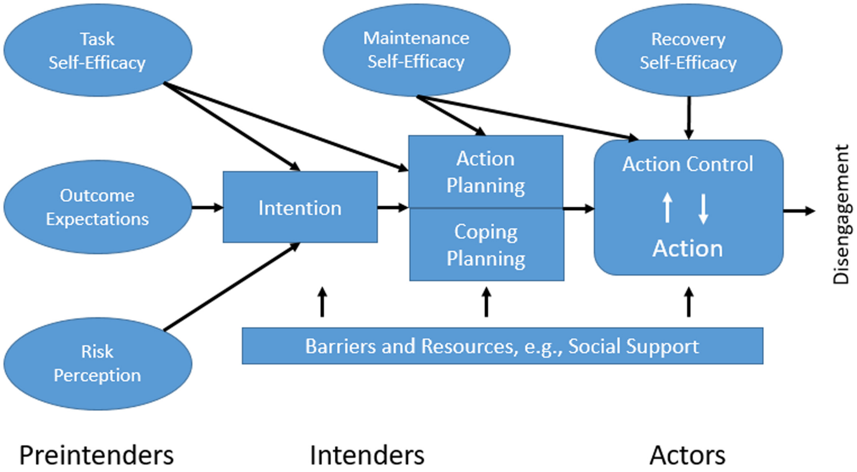

Fig. 1. The Health Action Process Approach (HAPA) model.

track of their change, i.e. action control or self-monitoring, are effective in bridging the intention-behaviour gap [29].

2.3 MyPlan: Action and Coping Planning

As part of previous research, the eHealth interventions, 'MyPlan 2.0' [9] and 'MyDayPlan' [7] support individuals in setting goals and developing and implementing plans for healthy lifestyles. MyPlan 2.0 [9] focuses on creating weekly action plans, while participants using MyDayPlan [7] were asked to create daily action plans. These interventions are based on the HAPA model and investigated the efficacy and processes underlying the promotion of PA in various settings [9,25,31] and various populations [9,16,26,31]. In these interventions, individuals are their own expert: free to set their own goals and formulate their own action and coping plans while being guided by a series of questions and clarifying examples. This approach has proven to be effective but has several disadvantages [7]. The use and quality of the defined plans vary, as users are free to formulate them as they see fit. A plan is considered to be of high quality when it is instrumental to the formulated goal and highly specific [21]. Lower quality of action or coping plans is predictive of less goal attainment [25]. Related, some participants report experiencing difficulties in formulating plans [7]. This indicates the need for more contextualised and personalised support in this planning process.

3 Methodology: An Interdisciplinary Approach

This research is part of an interdisciplinary project at Ghent University, Belgium, involving researchers from the field of Computer Science, Health and Behavioural

Sciences and Movement and Sport Sciences. To capture the knowledge in the ontology that drives the context-aware and personalised decision support system, knowledge from these different domains needs to be combined and modelled. Intelligent self-learning algorithms from the field of Computer Science need to be fed expert knowledge from the Health and Behavioural Sciences field.

Figure 2 gives an overview of the process to design the Health Behaviour Change System for increasing physical activity. The ontology and the Decision Support System are designed using an iterative approach. The system will be periodically validated by stakeholders to solve potential gaps and make sure the system is tailored to the needs of the end-users.

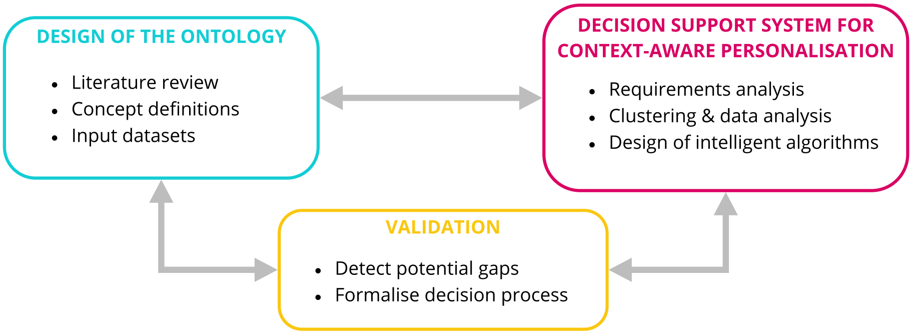

Fig. 2. The Health Behaviour Change Support System is designed using an iterative interdisciplinary approach, exploiting regular validation possibilities to fix potential gaps in the system. Different sources of expert knowledge are consulted during the design of the ontology and the Decision Support System.

The following paragraphs elaborate on the interdisciplinary approach by discussing the different sources of expert knowledge that are consulted during the project.

3.1 Data Analysis

This research aims to use an iterative approach, where close interaction with domain experts and end-users is essential. Information and data collected from previous studies, end-users and stakeholders form a valuable source of information to learn what needs improvement, but also to identify already existing habits or patterns. These existing data sets are thus used for data analysis for both the ontology and the Decision Support System. Moreover, new data collection and data analysis will continue to take place as needed throughout the project.

First, for the design of the ontology, information extracted from the data sets collected from previous studies, such as MyPlan [9] and MyDayPlan [7], has been used to gain insight into action and coping planning. The drafted plans illustrate the types of physical activity people often choose to do, the goals they set, the obstacles they face, and their respective solutions. The data from these studies was used to create a list of necessary concepts and information that needs to be captured in the ontology. Second, a literature review will be conducted to identify and analyse relevant existing ontologies and how they can be integrated in our ontology.

Third, for the design of the Decision Support System, more studies using the questionnaires from MyDayPlan and MyPlan will be conducted. This data contains extensive information of the user, such as a demographic questionnaire and the International Physical Activity Questionnaire- Long Form (IPAQ-LF), which has shown to be a reliable measurement tool for measuring habitual physical activity [4,7,9,13]. New data, together with previously collected data can be fed to clustering algorithms to identify hidden relationships between concepts or profiles of users. This allows users to receive personalised support from the start.

3.2 Panel of Experts

To capture the necessary knowledge from all the involved research domains, a panel of experts from these domains has been composed. The role of the panel of experts has been to help shape the vision of this system from concept to actual requirements, which are translated into an architecture for the system and form the foundation of the ontology.

First, for the design of the ontology, assignments and workshops have been held to help identify the necessary concepts and topics that need to be captured in the ontology. These topics range from general concepts, such as time, to domain-specific information, such as the medical background of the user. For example, if you want to provide personalised suggestion for an individual with chronic back pain, information regarding physical activity for patients with low back pain needs to be captured within the ontology. To create the ontology, the co-design method by F.Ongenae et al. [20] is applied. Via role-playing and decision-tree workshops ontology concepts and rules or axioms are defined.

Second, for the Decision Support System, intelligent algorithms that are able to make personalised suggestions to the user are embedded into the system. But before these can be created, the requirements of the system need to be defined. To do so, the required functionality of the system was defined during multiple Requirement Analysis workshops with the panel of experts. During these workshops the experts were asked to define how the user can interact with the application and why. This was done by defining user stories in the form of *As a user I want to be able to ... as to ...* These workshops resulted into use cases that define the interaction of the user with the system. A concrete example of some of these use cases was illustrated in the scenario in Sect. 5.1.

3.3 Focus Groups

Finally, for the validation of both the ontology and the Decision Support System, different focus groups, consisting of end-users and other stakeholders, will be composed. Workshops and interviews with the focus groups are essential to evaluate the completeness of the ontology or system. Moreover, as the ontology takes shape and the functional requirements are defined, workshops with focus groups are held to formalise the decision processes that drive the personalised and context-aware Decision Support System.

4 Findings

This section gives an overview of our findings to date. These findings are the result from (1) the data analysis that has been conducted on the collected data sets from the MyPlan [9] and MyDayPlan [7] studies and (2) the workshops that were held so far with the panel of experts on the concepts of the ontology and the requirements analysis of the Decision Support System. First, the conclusions that can be made regarding the ontology are presented. Next, an overview of important decisions made during the requirement analysis is given. Finally, several opportunities for personalisation are discussed.

4.1 Building the Ontology

The studies regarding MyPlan [9] and MyDayPlan [7] have shown that to form action or coping plans with enough instrumentality and specificity, more support is needed in the form of personalised suggestions regarding the user's current context. Daily, users were prompted to fill in a questionnaire, which guided them through the process of creating action and coping plans. However, they did not receive any guidance or support as to what the content of those plans could or should be. No suggestions were made and all questions were free-text format, which often resulted in action and coping plans that remained too vague or were irrelevant. The objective of the system is to counteract this by making suggestions for their plans that make sense for that specific user on that specific moment. However, providing these personalised suggestions is not an easy feat, as the meaningfulness can change in function of time, context or person.

Formalisation of the HAPA model as a generic model exists and an ontology has been built, which is used as the starting point for the ontology [12]. As the concepts defined in the HAPA model, such as action and coping planning, remain vague and limited, the ontology will need to be extended to take into account the profile and context of the user to make meaningful suggestions. For example, Fig. 3 shows a part of the HAPA ontology extended with an example of some domain-specific concepts and concrete instances on the lowest level of the ontology. These HAPA concepts, such as *action* and *coping planning* remain vague and need to be defined further to be used for personalised support. The example shows a possible action plan of a person, Ada, to go biking and indicates possible barriers for this plan could be rain or fatigue. To define these domian-specific concepts and instances, existing ontologies such as ACCIO [20], modelling basic to psychological, sociological to biological profile information

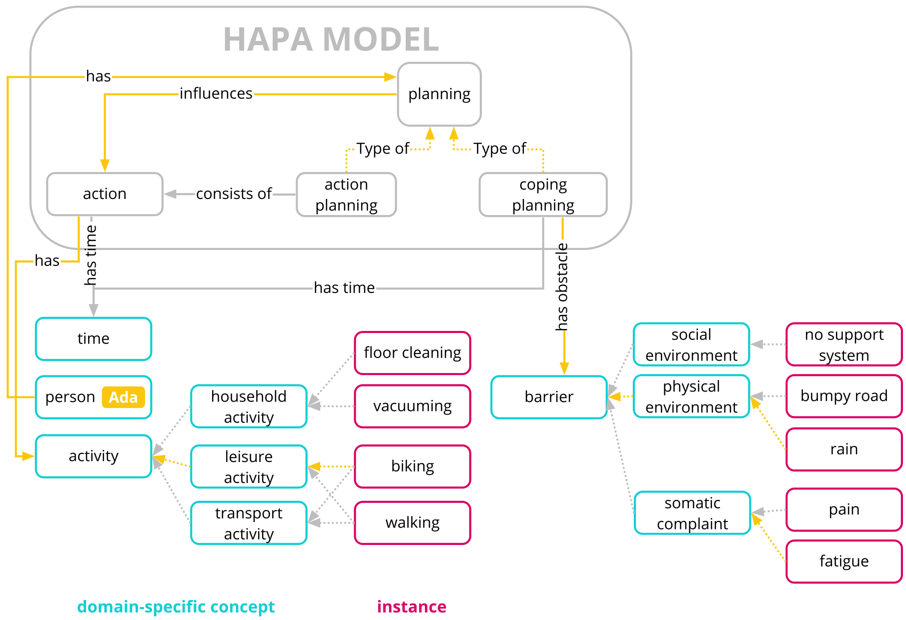

Fig. 3. An example of the HAPA model ontology (partial) extended with domain-specific concepts and instances necessary to formulate a possible action plan for the specific person, Ada. A relevant action plan to suggest to Ada is a leisurely bike ride. Possible barriers for her not to go on a bike ride, are fatigue and rain. The yellow arrows indicate the concepts and relationships necessary to suggest this plan.

or the PACO ontology [22], modelling physical activity are researched to be integrated into our ontology.

Furthermore, the panel of experts was responsible to identify these topics that needs to be modelled in the ontology. Together with the results of the data analysis, this information is used to extend the ontology to create an ontology that can provide this level of personalised support, is future-proof, and in the long run, can support all types of end-users.

4.2 Requirements Analysis

During the Requirement Analysis workshops, the panel of experts defined how the user can interact with the system by defining user stories. These workshops uncovered several important design decisions that impact the ontology and Decision Support System.

First, not all physical activities are deemed equal when it comes to planning. Certain activities require to be planned more in advance than others, based on the necessary preparation time, transport, duration or other factors. For example, an activity such as swimming requires that you have your swimming gear on you and it takes time to get to the pool. Moreover, people might prefer to plan activities in advance if they take a significant amount of time out of your schedule. For example, a mother of two young children might need to schedule time to exercise in advance, so other tasks can be planned around it. Therefore the need arises for a distinction between a weekly plan and daily plans. At the start of each week, the user is prompted to create their action plans for the week and each morning, the user is reminded of what they planned for the day and receive the suggestion to make additional action plans for that day. The weekly plan forms the backbone of the system, whereas the usage of daily action plans keeps the user "on track" to reach their weekly goal.

Second, although the aim is to create a personalised and context-aware system, the user still makes the final decision. Multiple suggestions for action and coping plans are offered to the user based on their current context and history, but in the end the user decides which of the suggestions they want to focus on. Similarly, for the weekly plan, suggestions are made regarding timing and types of action plans, but the user has the autonomy to decide when and what activities to add to their schedule.

Finally, people are unique and context changes over time. Whereas the action and coping planning can support the user as they start the process of behaviour change as an intender, this might not be the case when a habit starts to form. Therefore, there is a need to include other techniques to motivate the user throughout the entire process, such as gamification. As people are unique, multiple opportunities arise to extend the personalisation to different levels of the system, which will be explained in the next subsection.

4.3 Levels of Personalisation

Multiple levels of personalisation are needed: First, the system needs to keep track of the progress or regress of behaviour change within the entire cycle of goal-directed action. Any techniques or support delivered to the user should be tailored to the phase to which the individual belongs, i.e., pre-intender, intender, or actor. Often, this type of personalisation occurs only once, namely at the beginning of the intervention, i.e. static tailoring. As the individual will change their behaviour during the intervention, i.e. increase or decrease their physical activity, the system should be able to dynamically adapt to the shifting phases of the individual.

In such a complex intelligent Decision Support System, many opportunities for personalisation arise. To exploit these opportunities, several levels of personalisation are provided, as shown in Fig. 4. To validate their impact on the system and the user's behaviour change process, multiple user studies will be conducted, to incrementally test the influence of a more personalised support system.

First, on the level of the user, the distinction is made between person-similar and person-specific personalisation. For the former, users receive personalised support based on information extracted from users with a similar profile. The latter is implemented on the level of the individual by using reinforcement learning which is capable of making suggestions based on the individual's previous

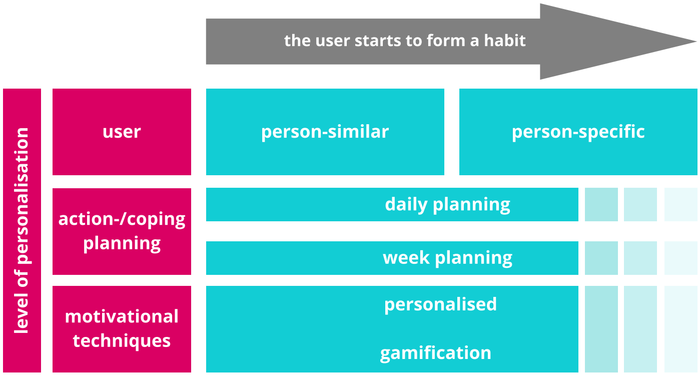

Fig. 4. The system should adapt to the user as they evolve or relapse throughout the process. To do so, personalisation is offered on (1) the level of the user, offering person-similar and person-specific personalisation, (2) the level of the action and coping planning by introducing a fade-out of support and (3) the level of motivational techniques in the form of personalised gamification.

actions. At the start of the process, when the user starts using the system, person-similar personalisation allows the user to receive personalised support from the start. As they progress and the system learns who the user is, more person-specific personalisation will be applied.

Next, personalisation is provided on the level of action and coping planning. Users will be supported during the drafting of these plans providing personalised suggestions for these plans based on their current context. An example is explained in Sect. 5.1 Scenario. Moreover, the use of action and coping plans should fade out as the user progresses or be reinstated if the user relapses.

Finally, applied motivational techniques, such as gamification should be personalised as the system detects if the user is in a slump and requires extra motivational support. The Hexad Player Type [30] model defines the player type of the user and what gamification elements they might respond to. Nevertheless, the used gamification should be dynamic and allow the user to change player types throughout the process and therefore offer different game elements or fade-out when support becomes less essential.

5 System Design

Based on the findings from the workshops with the panel of experts and the data analysis of previously collected data sets, requirements of the system were defined. First, the ontology that will be build needs to contain enough detail to provide meaningful suggestions to specific users. Next, the distinction between weekly and daily plans is made, giving the user autonomy over the final decision to include specific action or coping plans. Finally, multiple levels of personalisation will be realised to offer continued support to the user throughout the entire behaviour change cycle.

The following paragraphs will first discuss an example scenario that shows how this support will be offered. To conclude, a high level overview of the system's most important building blocks will be given.

5.1 Example Scenario

The following paragraphs describe a scenario to illustrate how the future system can support the user by providing personalised suggestions for action and coping plans. The scenario indicates how personalised support is provided weekly as well as daily, based on the user's current context information, such as calendar or weather and many more.

Profile. Margaux is a 28-year-old female living in the centre of Ghent with her boyfriend. She has a sedentary office job, which requires her to unexpectedly work late on some days. During the weekends she likes to visit museums or exhibitions but has otherwise mostly sedentary hobbies, such as reading and board games. She is generally in good health. To stay active, she cycles to work, but as this is only a short trip, she likes to increase her daily physical activity.

She has been using the Intelligent Decision Support System for a few weeks to help her formulate action and coping plans to increase her physical activity. Her current goal is to achieve around 60 min of physical activity a day.

Scenario. On Sundays, she uses the system to help her make a plan for the coming week, using that week's agenda as a starting point. The system learned from her behaviour during the previous weeks that Tuesday afternoons, Saturday, and Sunday mornings are moments she often succeeds in pursuing her plans. Based on this knowledge and her preferences, the system suggests to go swimming twice this week and to take a few walks. Margaux agrees with this suggestion, as shown in Fig. 5, without adding extra activities.

On Monday morning, Margaux receives a notification with her scheduled activities for the day, as shown in Fig. 6. Planned for today is a short lunch walk. The system asks her if there are possible obstacles that might stop her from going on a walk. As the weather forecast said to expect rain and Margaux has been indicating that she failed to exercise due to too little time, the system suggests these as possible hindrances. Margaux thinks the rain might be her biggest obstacle today, to which the system suggests to take an umbrella with her to work or to schedule another indoor activity for today. Margaux feels brave today, so she takes an umbrella to work. Luckily, the brisk walk in the rain under her umbrella cleared her head during an otherwise stressful day at work.

By Thursday, her week has been so hectic she had to cancel swimming and failed to do any exercise apart from her short lunch walk on Monday. As usual, in the morning, she receives a notification with her plans for the day, as shown in Fig. 7. The system knows she has not been reaching her set goals and apart from the already planned lunch walk, suggests some more action plans for that day. Margaux decides to try and be more active throughout the day by taking

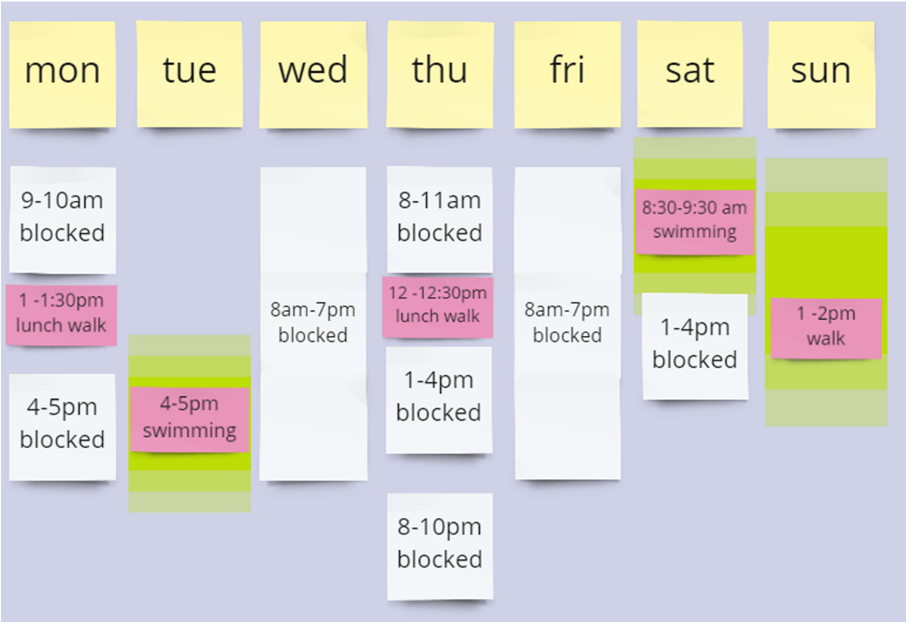

Fig. 5. Based on Margaux's calendar of the coming week (white) and information on her behaviour previous weeks, the system knows what moments are ideal for exercising (green). The system uses this information to make several suggestions for physical activities in this week (pink). (Color figure online)

the stairs when possible. To shake off the stressful week, she decides to do yoga in the evening. She adds coping plans for the selected action plans and starts her day.

5.2 Overview

The effectiveness or relevance of different instantiations of action or coping plans may vary widely as a function of the person, context and time. In other words: what works for one person might not work for another. The constructs in theoretical models, such as the HAPA model remain generic and abstract and thus require specific operationalisation or instances that work for the individual. For example, the instance of an action plan "During lunch, I will take a walk outside" should be accompanied by an instantiation of a coping plan that makes sense for this specific action plan, such as "if it rains, I will use an umbrella". The intelligent decision support system will support the user in this process by providing personalised suggestions based on the individual's current context and history.

The system shall consist of 3 major components, as shown on Fig. 8: a mobile application that supports the user in formulating their own action and coping plans. Next, an ontology that captures relevant concepts and their relationships.

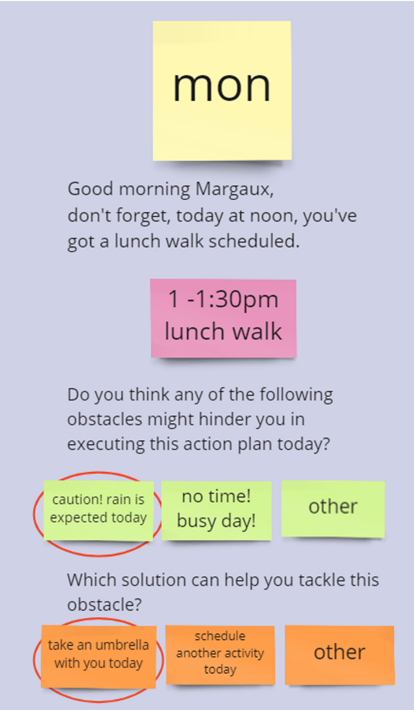

Fig. 6. Margaux receives a notification with today's plans (pink). The system suggests possible obstacles that could hinder her in completing those plans (green) based on her current context. Next, the system suggests possible solutions for the chosen obstacle (orange). (Color figure online)

Fig. 7. By Thursday, Margaux has failed to keep up with the activity goal, so the system suggests some more action plans (pink) that can help her be more active throughout the day. (Color figure online)

The ontology, centred on the HAPA model, forms the backbone of the system, supporting the user in formulating personalised and context-aware action and coping plans. The final component, the Decision Support System, forms the connection between the ontology and the application. It has the responsibility, based on the user's profile information and current context information, to decide which information, extracted from the ontology, is best used at that moment to provide personalised suggestion to the user for finalising their action or coping plan.

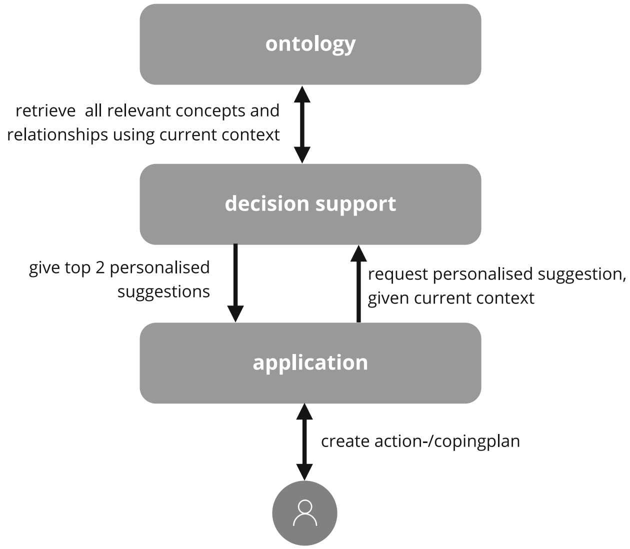

Fig. 8. The system consists of 3 major components: an ontology, modelling the expert knowledge, the decision support module that decides which information from the ontology is currently relevant and finally, an application that interacts with the end user by gathering context data and offering personalised suggestions to the user while making action or coping plans.

6 Conclusions

Mobile health Behaviour Change Support Systems show the potential to alter unhealthy habits that increase the risk of non-communicable diseases. However, they lack long-term effectiveness and sustained user engagement as these intervention fail to consider the dynamic nature of their target audience.

We propose an ontology-driven Intelligent Decision Support system, that uses the theoretical HAPA framework as backbone to increase physical activity and form a healthy sustainable habit. To design the system, an interdisciplinary approach is taken, combining knowledge from the field of Computer Science and Health and Behavioural Sciences.

From the workshops and data analysis of previously collected data sets, several requirements for such a system were defined. For the ontology, we learned that there is a need to model information on the level of the individual, i.e. the instances, to be able to formulate action and coping plans tailored to specific individuals. These plans should be offered to the user as suggestions, giving the user freedom in the final decision. To create sustainable behaviour change, the distinction is made between a weekly plan, to encourage the user to be physically active regularly and a daily plan, to keep the user on schedule to reach their weekly goal. Finally, to sustain the motivation of the user, there is a need for personalisation on multiple levels of the system. On the level of the user, person-similar personalisation is supported by person-specific personalisation as the user progresses, taking into account groups of similar users as well as the personal growth of the individual. Throughout this progress, action and coping planning should be tailored to the user's current context, fading out support as the user starts to form a healthy habit. Finally, motivational techniques such as gamification should be personalised to the user to detect possible slumps or should fade when support is not needed.

Acknowledgements. This research is funded by an interdisciplinary research grand of the Special Research Fund of Ghent University, Belgium (BOF-IOP, BOF.24Y.2020.0012.02).

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