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1. Introduction

Physical inactivity is an increasingly serious health problem. On a personal level, it is associated with a higher risk of many non-communicable diseases (such as cardiovascular disease, cancer and diabetes) and it increases the likelihood of developing depression or anxiety. On a societal level, the increased prevalence of physical and mental illness through physical inactivity implies a growing burden on the health care system. The large number and the popularity of health & fitness apps available in the app stores indicate that many people are interested in using such apps to change their lifestyle for the better. The rise of mobile technology and wearables offers new opportunities: to make these apps more informed, more tailored, more adaptive and overall smarter or more ‘intelligent’. The research presented in this thesis investigates different aspects of using technology to stimulate behavior change for physical activity, and it contributes to the development of an intelligent physical activity promotion app.

The remainder of this chapter is organized as follows. Section 1.1 explains the overall motivation behind the research described in this thesis. In Section 1.2, the background to which this research was done is described. Section 1.3 formulates the research objective and research questions. In Section 1.4, the methods applied throughout the chapters of this thesis are outlined. The scientific contributions of the work presented in this thesis are described in Section 1.5. Finally, Section 1.6 explains how the remainder of this thesis is organized.

1.1 Motivation

Physical activity is an important prerequisite for global health. Despite the well-known benefits for both physical and mental health (Eime et al., 2013; I.-M. Lee et al., 2012; Paluska and Schwenk, 2000; Reiner et al., 2013; World Health Organization, 2010), approximately 50% of the adult population in western countries are less physically active than recommended by health authorities (World Health Organization, 2014b). This has serious consequences: insufficient engagement in moderate to vigorous physical activity has been associated with increased risks of cardiovascular diseases, cancer, diabetes and mental illness (I.-M. Lee et al., 2012). Research has shown that physical activity levels decrease with age, in particular when transitioning from adolescence into adulthood (Bell and C. Lee, 2005; Kwan et al., 2012). Therefore, effective and engaging interventions are needed to increase and maintain physical activity levels, with a special focus on young adults.

It is believed that modern (mobile) technology provides an opportunity to support people to become or remain physically active (Knight et al., 2015; Payne et al., 2015). After all, smartphones and smartphone applications (apps) are well intertwined in modern society
(Center, 2016; TelecomNieuwsNet, 2016), always accessible to the user, and they can lower the barrier for people to address their health problems (Griffiths et al., 2006). Also, initial evidence indicates that such mobile interventions are effective (Stephens and Allen, 2013). However, although physical activity can be increased significantly through simple solutions as self-monitoring and the use of pedometers (Bravata et al., 2007; Lubans et al., 2009), it is challenged whether these changes are durable over the long term (Gierisch et al., 2015). Therefore, physical activity interventions based on technological features require a more solid scientific basis in order to yield long-term effects.

It has been established that social processes play an important role in achieving and maintaining a healthy lifestyle (Zimmerman and Connor, 1989). These social influences rely on several motivational mechanisms, such as priming, social norms, observational learning, social facilitation, social support and social comparison (Bandura, 1998; Buunk et al., 2013; Cheng et al., 2014; Festinger, 1954; McNeill et al., 2006). When developing effective physical activity interventions, the potential of such mechanisms should not be overlooked, but exploited in well-advised and effective ways.

The main research objective of this thesis is to explore the field sketched above, which addresses physical activity promotion from an evidence-based perspective, thereby applying techniques from modern (mobile) technology and artificial intelligence as well as scientific knowledge from human-directed disciplines within psychology and social sciences, while taking the importance of social processes into account. Because of its interdisciplinary nature, the subject of this thesis will be addressed from different perspectives and by incorporating various aspects. This way, a broad picture of endeavors to approach this subject will be unfold.

1.2 Context

The research described in this thesis is motivated by both contemporary societal issues, state of the art scientific knowledge about them, and recent advances in technology, which allows a new perspective on ways to solve those issues. In order to position the work in this thesis, it is important to sketch the background to which this research was done. Therefore, this section is devoted to delineating certain aspects of its context.

First, since this work is part of a bigger research project (called Active2Gether), Section 1.2.1 describes the goals of that project in more detail. In Section 1.2.2, the prevalence of physical inactivity in society that partly motivated this research is explained. Then, Section 1.2.3 elaborates on elements that play a role in behavior change. Finally, Section 1.2.4 sketches the developments in the use of computer technology in behavior change initiatives.

1.2.1 Active2Gether project

Active2Gether is a research project financed by the partnership program Healthy Lifestyle Solutions (HLS) of technology foundation STW, the National Initiative Brain & Cognition (Nationaal Initiatief Hersenen & Cognitie, NIHC) and Philips Research (STW, 2012). It aims at developing an innovative solution that supports people to be more physically active. More specifically, the project focuses on young adults, as physical activity levels are known to decline rapidly in this age group (Bell and C. Lee, 2005; Kwan et al., 2012). Two core components of the Active2Gether project are the use of modern mobile technology to unobtrusively monitor the users’ behavior, scientific knowledge about such behaviors and
the employment of social processes to support the users in achieving or maintaining healthy activity levels.

The Active2Gether project is a research collaboration between the Behavioural Informatics group in the Artificial Intelligence section at the Vrije Universiteit in Amsterdam and the Department of Epidemiology and Biostatistics of the EMGO+ Institute for Health and Care Research at the VU Medical Center. The expertise of the two disciplines involved is reflected in the application of principles from artificial intelligence and the focus on evidence-based behavior change techniques.

Altogether, the ingredients of the Active2Gether project were combined in an innovative behavior change intervention. We developed a smartphone app aimed at young adults that coaches them to increase or maintain their physical activity levels in daily life, by incorporating social influences and processes and by using intelligent reasoning mechanisms (including context awareness, personalized feedback, model-based prediction and tailoring). This led to new insights regarding the use of artificial intelligence technology for automated coaching and practical lessons learnt regarding their development and implementation, as well as an extensive and rich dataset that allows us to gain insight in different aspects of physical activity behavior.

1.2.2 Physical (in)activity

Despite the well-known health benefits of physical activity (I.-M. Lee et al., 2012; World Health Organization, 2010), 23 percent of the adult population worldwide did not meet the recommended guidelines in 2010 (World Health Organization, 2014b). Moreover, engagement in moderate to vigorous physical activity decreases with age, in particular when transitioning from adolescence into (young) adulthood (Bell and C. Lee, 2005; Kwan et al., 2012). Systematic reviews reported that levels of physical activity in Europe vary across countries, ranging from 15.6 percent in Israel to 84.8 percent in Slovakia who met the guidelines (Marques et al., 2015). In the Netherlands, approximately one third of the adult population does not meet the Dutch guidelines for healthy physical activity (Wendel-Vos, 2014). Moreover, compared to other European countries, Dutch people lead a relatively sedentary lifestyle, with over 60 percent spending at least 5.5 hours sitting on a usual day and 25 percent at least 8.5 hours sitting on a usual day (TNS Opinion & Social, 2014).

One contributing factor to the increasingly sedentary lifestyles is that people are more inclined to make use of passive modes of transportation. Active traveling modes such as biking and walking can contribute to a healthy level of physical activity (Sahlqvist et al., 2012). Another explanation for sedentary lifestyles is related to the work environment, as many people work in offices and carry out their responsibilities sitting at a desk. Research suggests that having desk jobs increases health risks up to 50 percent. Integrating brief active interruptions in work routines could help to increase physical activity and lower health risks (Levine, 2014).

Insufficient physical activity is one of the leading risk factors for premature mortality and non-communicable diseases as cardiovascular diseases, cancer and diabetes (I.-M. Lee et al., 2012; World Health Organization, 2014b). In addition, physical inactivity is associated with osteoporosis, high blood pressure, high blood cholesterol and obesity (World Health Organization, 2014b). The WHO estimates that a lack of physical activity leads to 3.2 million deaths per year globally (World Health Organization, 2009, 2014b). Related, overweight and obesity cause more deaths today than underweight (World Health Organization, 2004).
On a personal level, the health consequences of physical inactivity may lead to a decrease in quality of life and a decrease in life expectancy. Also, related health care costs may pose a financial burden on patients. For organizations, physical inactivity can have an adverse effect, since it can diminish employee productivity by causing both absenteeism (when employees do not come to work) and presenteeism (when employees come to work, but are not fully functioning). This causes a direct economic loss for employers. On a global level, research has shown that the economic burden of physical inactivity amounted to $67.8 billion in 2013 (Ding et al., 2016). This includes both direct costs for health care expenditure and indirect costs through productivity losses, and because of the conservative methodology of the researchers, it is likely to even be an underestimation.

1.2.3 Behavior change

Since over two-thirds of the total number of global deaths is caused by noncommunicable diseases (World Health Organization, 2014a), healthy lifestyles could contribute significantly to preventing these premature deaths. Therefore, an important effort to control noncommunicable diseases is to focus on modifiable behavioral factors (such as tobacco/alcohol use, excess salt intake and physical inactivity) to decrease the risk of these diseases (World Health Organization, 2014a). This requires a change in behavior, which has shown to be difficult (Bouton, 2014). This section highlights some of the personal, social and environmental factors that play a role in behavior change for physical activity.

Personal factors

Personal characteristics that influence behavior change for healthy lifestyles have been identified and documented in many different theories of behavior change. Some factors appear in multiple theories, whereas some others are more specific to certain theories. This section introduces some of the most prominent relevant personal factors.

Self-efficacy is a construct that is incorporated (in some form) in many theories within the disciplines addressing behavior change, such as the social-cognitive theory, the theory of planned behavior, the health action process approach and the health belief model (Ajzen, 1991; Bandura, 2004; Rosenstock, 1974; Schwarzer, 2002). Self-efficacy represents an individual’s confidence in their own ability to perform a task or to achieve certain goals. It is believed to influence how high people set their goals, but it can also moderate the process of turning intentions into actions. The level of self-efficacy is influenced by prior performance on the same or a related task: a positive evaluation of one’s own behavior helps to build trust in the efficacy, whereas a feeling of failure undermines it. Additionally, feelings of self-efficacy can be influenced by social persuasion or vicarious learning. The health action approach distinguishes different types of self-efficacy for different stages in the behavior change process (Schwarzer, 2002). In the theory of planned behavior, self-efficacy is represented by the concept of ‘perceived behavioral control’ (Ajzen, 1991).

One’s intentions are another prevalent personal factor in behavior change. They indicate the extent to which an individual is ready and willing to perform a given behavior. Intentions play a key role in, for example, the health action process approach, the social cognitive theory and the theory of planned behavior (Ajzen, 1991; Bandura, 2004; Schwarzer, 2002), as they are believed to be an immediate antecedent of behavior. One’s intentions can be influenced by many other factors, such as the self-efficacy, perceived barriers and facilitators to perform the given behavior, and social or personal norms.
Another factor that is believed (in some theories) to influence the intentions is the concept of *outcome expectations*. Outcome expectations represent the expected benefits of performing the behavior, whether it is on a personal, physical or social level. In the theory of planned behavior, this notion is represented by the ‘attitude’ towards the behavior (Ajzen, 1991), and the health belief model speaks of ‘perceived benefits’ (Rosenstock, 1974). In addition to affecting the intentions, some of the theories also document another effect of the outcome expectations, such as to the behavior directly (social cognitive theory), to the perceived behavioral control or to the subjective norm (theory of planned behavior).

According to some theories, *perceived barriers* (or *impediments*) and *facilitators* (or *resources*) play a role in the formation of intentions as well (Bandura, 2004; Rosenstock, 1974; Schwarzer, 2002). Although these factors are quite often external phenomena (for example, impediments such as foul weather, lack of time, inept opening hours of some facility), it is the individual’s *perception* of how insurmountable they are that determines their influence on the behavior change process. The perception of barriers is again influenced by the self-efficacy: the more confident people are, the more likely they will assess their inhibiting conditions as surmountable. Facilitators work in the exact opposite direction, with a stronger perception of facilitators leading to easier execution of the behavior.

An important step in achieving behavior change is the translation of intentions into actual behavior, and thereby overcoming any perceived barriers. This requires *self-regulation skills* (Bandura, 1991; Baumeister and Heatherton, 1996). In the health action approach, a distinction is made between action planning and coping planning skills (Schwarzer, 2002). The former is related to initiating behavior, whereas the second represents one’s ability to overcome obstacles. In the self-regulation theory, four different components of self-regulation are distinguished: *standards* of some desirable behavior, *monitoring* by comparing the self to the standard, a source of self-regulatory strength (i.e., *willpower*), and *motivation* to meet the standards (Baumeister and Vohs, 2007).

**Social factors**

Personal factors are not the only determinants of behavior, as attitudes and behaviors are also influenced by interactions with other people. Therefore, social processes play an important role in achieving and maintaining a healthy lifestyle, and should not be overlooked when investigating behavior change (Zimmerman and Connor, 1989). Many mechanisms that underlie such social factors have been identified (e.g., Bandura, 1998; Cheng et al., 2014; McNeill et al., 2006), and it is beyond the scope of this chapter to discuss them all. Therefore, this section highlights a number of social factors that are relevant to behavior change.

*Social norms* are the expectations for a certain behavior that are formed by interactions with other individuals. These norms can influence one’s behavior through both social and self-evaluation (Bandura, 2004). Complying with normative behavior leads to social acceptance and praise, which reinforces the behavior. In contrast, deviating from the norms leads to social disapproval. Similarly, meeting social standards for behavior gives a positive internal reaction, whereas violating the norms leads to negative self-evaluation, thereby reinforcing or undermining certain behavior.

*Social facilitation* is the tendency for certain tasks or behaviors to be easier in the presence of others (Harkins, 1987). The effect occurs when being observed while performing a task (especially when the task is simple) (Bond and Titus, 1983), or when carrying out a task together. Therefore, it may be easier to adopt and internalize new behavior when doing
it together than when trying to achieve behavior change alone.

Adopting new behavior is also easier when people feel supported by their social environment. Such social support exists in different forms (Langford et al., 1997). For instance, instrumental support encompasses very practical support to help others to achieve their goals, for example by providing financial aids or material goods. Informational support can also be practical, but relates to offering useful information, advice and guidance, rather than tangible help. A third form is emotional support, which stands for expressions of empathy and encouragement.

Another mechanism that plays a part in behavior change is social comparison (Buunk et al., 2013; Festinger, 1954). Social comparison is the act of comparing one’s own behavior (or behavioral outcomes) to another individual. It exists in two variants: downward social comparison and upward social comparison (Festinger, 1954), depending on whether the target (with whom one compares oneself) performs worse (i.e., downward) or better (i.e., upward) than the individual. Both variants can be effective and encouraging, for instance by boosting one’s self-view or by motivating improvement, but also counter-effective and discouraging, for instance by advocating inferior standards or by threatening the self-view (Corcoran et al., 2011). The strength of the effect of social comparison depends on several factors, including one’s closeness and similarity to the other individual, or one’s closeness to some relevant performance metric (for example, number one position) (Garcia et al., 2013). When designed carefully and applied correctly, social comparison can be an effective tool for empowering people to achieve behavior change.

In addition to the specific mechanisms discussed above, we can also look at the effect of the social environment from a social network perspective. It is known that emotions, attitudes and behaviors can spread through social networks via network ties, by means of a process called social contagion (Christakis and Fowler, 2013). Even though it also works for less desirable phenomena, such as obesity (Christakis and Fowler, 2007) and violence (Fagan et al., 2007), social contagion can also play a role in beneficial health behaviors. When trying to achieve behavior change, focusing on changing the behavior of specific actors in a social network could lead to a more widespread change in the network, for example because these actors have a large number of connections (Valente and Pumpluan, 2006), or because they hold key positions in the network, thereby strongly influencing the diffusion to other parts of the community (Borgatti, 2006).

Environmental factors

Although some behavior change theories do lightly touch upon external factors that influence behavior change (through perceived barriers and facilitators or social influences), human behavior might be more influenced by environmental factors than these theories suggest. The ANGELO framework proposed by Swinburn et al. (1999) distinguishes four types of environmental factors: physical, economical, political and sociocultural (Swinburn et al., 1999). Examples of social influences are described in the previous section, although sociocultural factors – as the name suggests – also comprise more abstract cultural influences, such as parenting styles or religious viewpoints.

The physical environment refers to the accessibility of resources and opportunities to perform a given behavior. In the domain of physical activity, it includes, for example, the availability of sports clubs in the neighborhood, the presence of safe and well maintained bike lines, and a building layout of the workplace that encourages walking, for example to
the copier. The physical environment can play a role in nudging people to make healthy lifestyle choices, for example when an entrance naturally leads to a staircase, and the elevators can be found around the corner. The health belief model incorporates such (and other) stimuli as ‘cues to action’ (Rosenstock, 1974).

The economical environment concerns the financial costs associated with performing a desirable behavior. When considering physical activity, one could think of the costs for memberships of sports clubs or fitness centers, for sports equipment, and for example the costs of purchasing and maintaining a bike (as compared to the costs for traveling by car or public transport). In addition, people’s incomes also form part of the economical environment, as well as the overall economic situation of a country or municipality.

The fourth type of environmental influence, the political environment, refers to laws, regulations and policies that enable or facilitate the desirable behavior. In case of physical activity promotion, this could include an employer’s incentive for the employee to bike to work (for example through a program that allows employees to advantageously purchase a bike), or (a discount for) a fitness membership included in the collective labor agreement. Policies on national level could stimulate healthy behavior in a similar manner, or indirectly through making such corporate programs and policies attractive to employers.

In addition to the four types of environmental elements, the ANGELo framework also distinguishes different levels of environmental size, namely the microenvironmental settings (e.g., homes, schools, workplaces) and the macroenvironmental sectors (e.g., media, transport systems, sports/leisure industry) (Swinburn et al., 1999). Other researchers have identified three levels: the micro level, which represents the actual surroundings of the behavior (such as homes, workplaces); the meso level, which comprises the characteristics of the neighborhood, community and organizations (such as availability of bike lines); and the macro level, which refers to the societal system that can influence behavior through policies, cultural norms, et cetera. (Booth et al., 2001; Brug et al., 2007).

1.2.4 Computer technology and behavior change

As introduced in Section 1.1, the advances in (mobile) technology have lead to many new opportunities to support behavior change. Not only has the transition from traditional face-to-face coaching sessions and print-based interventions to Internet-based interventions increased the reach of interventions to the masses, it has also opened up possibilities to provide coaching at any time and any place. The advantages of smartphones, smartphone apps and wearables as mobile coaching systems for physical activity (or any other health behavior) are in line with that trend, as they are well intertwined in modern society, always accessible to the user, and because they can lower the barrier for people to address their health problems (Griffiths et al., 2006; Pantelopoulos and Bourbakis, 2010).

Using computer technology in behavior change interventions has many benefits. First of all, smartphones and wearable devices allow for continuous monitoring of users through their built-in sensors. This leads to a theoretically complete picture of the individual’s behavior, as well as the possibility to respond to certain events immediately when they take place. In the domain of physical activity, the most relevant sensors in such devices are accelerometers or pedometers, heart rate sensors and location measurements (such as GPS, or location detection through cell towers of Wi-Fi signals). In addition, online data can be used to enrich the context information about the user. For example, current and forecast weather predictions in the user’s area can be retrieved online, as well as traffic conditions
and travel routes. Also, the user’s location information can be enriched with GIS data to understand the type of location (e.g., sports club, shopping area, public transport hub).

Second, the computing power of mobile devices (and/or remote systems) enables more intelligent interpretation of the sensor data. For example, interpretation of data from one or a combination of sensors could be used for the detection of activities (such as walking, biking or driving a car). Both Android and iOS nowadays offer built-in mechanisms to detect important locations and travel modes (Apple Inc., 2017; Google LLC, 2017), and some physical activity promotion apps are based on this principle as well (Human.co, 2016).

In addition to sensing and interpreting the user’s behavior, administering a behavior change intervention through the smartphone allows for tailoring of the coaching. This could entail simple personalization features, such as greeting the users with their own name or providing a type of coaching based on a user categorization. However, advances in artificial intelligence provide opportunities for far more complex tailoring. Rather than providing a one-size-fits-all approach, where all (categories of) users receive the same type of feedback and advice, sophisticated reasoning mechanisms can be used to decide which support action to perform for a specific user. The reasoning mechanism could be based on, for example, agent-based models, bayesian inference or rule-based systems. Such underlying models can be developed top-down, from theories and available literature, or in a bottom-up manner, by applying machine learning techniques to collected data.

Continuous information about the user can be used for continuous adaptation of the coaching to the users as well. For example, if (global or personal) parameters play a role in a reasoning mechanism as described above, the available data can be used to tune the parameter values over time, in order to match the users’ behavior as closely as possible.

Finally, the smartphone opens up the possibility to use online social networks as a new source of information and to influence on behavior change. Through online friendship connections, the user’s social environment can be investigated, and it can be used to steer social processes that play a role in behavior change (see also Section 1.2.3).

1.3 Research objective and research questions

The aim of the research presented in this thesis is to investigate and develop methods that can be used to counteract physical inactivity, by combining evidence-based intervention design with principles from artificial intelligence. More specifically, the overall research question addressed in this thesis is as follows:

*How can mobile technology and artificial intelligence techniques be applied in the design of a behavior change system that aims to increase physical activity levels in young adults?*

This overall research question is expanded into four subquestions. These questions are stated below, accompanied by a brief explanation.

1.3.1 Research question 1

*What are requirements for mobile behavior change interventions for physical activity based on the state of the art of such interventions and user preferences of the target population?*

This research question is made up of two parts: in order to contribute to the current offer of behavior change interventions for physical activity, it is important to have an
understanding of both the state of the art of such interventions and the intended users’ preferences. With respect to the state-of-the-art physical activity promotion apps, it is interesting to know to what extent existing mobile interventions apply behavior change techniques. Also, the extent to which technological features are applied provides relevant information about the current offer of such interventions. In both cases, exploring this leads to insights about gaps in the state of the art and therefore opportunities to develop an intervention that goes beyond existing interventions. On the other hand, knowledge on user preferences is important to be able to respond to their needs and wishes for such an application, and to thereby improve user engagement and adherence.

1.3.2 Research question 2

What role can dynamic computational models play in the development of an intelligent mobile intervention for physical activity?

This research question focuses on one area of artificial intelligence, i.e. dynamic computational modeling, and how it can be applied in the domain of behavior change systems. A first step is to actually develop such a dynamic computational model of influences on physical activity behavior, based on theoretical and empirical evidence found in literature. Especially when aiming to deploy such a model in a real-life behavior change intervention, it is important to investigate the validity of the model’s simulation outcomes. However, more practical considerations also come into play, for example whether the simulation outcomes also meet other requirements than validity only.

1.3.3 Research question 3

How can an individual’s social network be used to influence his/her physical activity behavior?

As explained in Section 1.2.3, social processes (e.g., social contagion, social comparison) play an important role in behavior change. This research question focuses on the analysis of such processes and the development of methods to employ social influences to support behavior change. Analysis of social processes, for example by comparing interventions with or without a social component or by explaining behavioral patterns in data with models of social influence, leads to better understanding of the dynamics involved. A thorough understanding of these dynamics is essential when trying to influence social processes for the benefit of behavior change.

1.3.4 Research question 4

To what extent can the answers to the questions above be used to design, implement, exploit and evaluate a personalized mobile intervention for physical activity promotion?

As one of the objectives of the Active2Gether project (see Section 1.2.1) is to develop and evaluate a behavior change intervention for physical activity, exclusively theoretical endeavors do not suffice to achieve this goal. This raises a number of different questions and challenges, specifically with respect to practical considerations of designing, implementing and exploiting such an innovative behavior change system. Also, evaluating both the effectiveness and user appreciation reveals important lessons learnt and directions for future research and improvement.
1.4 Methods

The broad scope and the interdisciplinarity of the work presented in this thesis also implies a wide range of different methods applied. Among these are methods that are traditionally typical for social sciences and methods that are more related to computer science. The sections below give an overview of the methods applied throughout this thesis.

1.4.1 Systematic reviews

Systematic reviews are a very suitable means to investigate the state of the art of mobile interventions for physical activity (see research question 1). One option would be to analyze the literature on this topic, but that is still only sparsely available. Therefore, analyzing the actual offer of physical activity apps provides a more insightful overview of the characteristics of currently available apps.

When conducting the review of the selected apps, the information in the app description in the app stores provides a good starting point for the analyses. However, additionally downloading and exploring the apps leads to more complete and more reliable findings. In the reviews in this thesis, the apps are scored on two different aspects: the application of evidence-based behavior change techniques (such as self-monitoring, providing feedback, etc.) and the use of technological features (such as using built-in or external sensors, visualizing aggregations of data, etc.). In the former case (Chapter 2), the scoring is based on an existing taxonomy of behavior change techniques (Abraham and Michie, 2008), slightly adapted to fit the scope of mobile rather than traditional interventions. In the other case (Chapter 3), a custom framework of technological features is devised.

These systematic app reviews serve different purposes. In the first place, the reviews aim to sketch the landscape of currently available apps for physical activity promotion, whether the focus is on the number of evidence-based behavior change techniques implemented or the extent to which technological features are incorporated. At the same time, the findings reveal opportunities for improvement for the next generation of physical activity apps. Lastly, the scores obtained from the review combined with meta information about the apps (for example, its price) allow for identification of connections between certain aspects, which can provide additional insight in the characteristics of these apps.

1.4.2 Qualitative interviews

To investigate the user preferences for physical activity promotion apps (as required to answer research question 1), qualitative interviews provide rich information, that would arguably be hard to obtain from quantitative research methods. While a continuum of interview types are available (i.e., from structured to unstructured), focus group interviews are especially suitable. Since the interviews take place in a group setting, interactions between participants may help to stimulate creativity and to bring new ideas to the surface.

In this thesis, focus group interviews are conducted to assess user preferences (i.e., their requirements and wishes) for physical activity coaching apps. The results are described in Chapter 4. In this case, the interview sessions are preceded by a three-week period in which the participants used an existing physical activity promotion app, in order to give them some relevant experience and as a stimulus to jump start the discussions. In addition, a discussion guide with open-ended questions and a number of prompt statements are created to streamline the discussions and to provoke the participants to share their views. In order
to prevent information getting lost due to participants not willing to share their opinion on a certain topic in the group, they are asked to for written comments at the end of the discussion.

Upon collection of the interview data, the discussions are transcribed verbatim. From these reports, relevant fragments (based on the discussion guide) are selected and various codes and subcodes are created. After further review and rearranging the codes, general themes are identified and organized in a tree diagram. This process enables the discovery of overall patterns in the sizeable set of individual opinions and statements, and thereby facilitates forming a coherent picture of the target users’ preferences. This is an important base when developing a physical activity app, so engagement is not threatened by unfulfilled expectations.

1.4.3 Computational modeling

One of the techniques from artificial intelligence that is studied in this thesis, is dynamic computational modeling. It refers to the use of computer systems to simulate behavior of complex systems, in order to study, predict and better understand them. Research question 2 focuses on different aspects of using computational models in the development of mobile physical activity promotion interventions.

In the creation of computational models, four iterative stages can be distinguished. First, the conceptualization stage deals with identifying relevant concepts and relationships between concepts from literature. In the formalization stage, these concepts and relationships are defined in more detail. For the concepts, this amounts to deciding on a operationalization of the variable (e.g., qualitative or quantitative, range of possible values). For the relationships, the formalization step consists of describing the influences between the concepts over time mathematically. It is understandable that the conceptualization and formalization processes go hand in hand.

The third and fourth stages, simulation and evaluation, are also closely connected. Through simulations of the formalized model, simulation traces are obtained. These simulations can be initialized based on available data or on carefully devised scenarios. Evaluation can be done in different ways. For example, reviewing the simulation traces on face validity provides a first indication of the model’s correctness. In addition, verification of expected patterns in the simulations through so-called ‘property checking’ is a more structured approach. Also, the model can be validated by comparing its simulation outcomes with empirical data.

In this thesis, a computational model of influences on physical activity behavior, together with a preliminary verification, is presented in Chapter 5. Chapter 6 provides an in-depth evaluation of (an updated version of) that same model. A further analysis, taking other evaluation measures than goodness of fit to empirical data into account, is described in Chapter 7. At the same time, Chapter 7 is also a proof-of-concept for a new application of parameter tuning techniques, namely the evaluation of model behavior.

1.4.4 User studies

As the work in this thesis builds towards a practical application, it is important to set up real-life test scenarios to review intermediate design choices, to validate assumptions or models, and eventually to evaluate the final product. Consequently, experiments and user
studies play a substantial role in answering research question 2, research question 3 and research question 4.

In each of these experiments, data is collected from a number of participants (ranging from ten to more than a hundred). Depending on the research question at hand, several types of data are collected. Data is collected unobtrusively where possible, i.e. without the participants’ interference. This increases user friendliness and allows for more continuous data collection, since participants don’t have to actively provide the data. In the scope of this thesis, unobtrusive data collection is achieved, for example, by collecting location information through an app on the smartphone and activity data through an activity tracker (e.g., Fitbit One).

However, some notions are difficult to measure directly. Especially for such types of data, questionnaires are appropriate means to collect information. This is, for example, the case with psychological states, such as one’s feelings of self-efficacy or beliefs with respect to outcome expectations. For the assessment of such constructs, validated questionnaires are used where possible. The same holds for subjective information, for example regarding the participants’ opinions. A third category of data to be collected through questionnaires is information that is technically difficult to measure. In the scope of this thesis, this concerns for example transportation modes (e.g., walking, biking, car, bus, train) and sports participation (e.g., swimming). In order to increase user friendliness, the (short) questionnaires to collect this information are presented conveniently on the smartphone and where possible based on triggers.

During the development of this thesis, several smaller intermediate or pilot experiments were conducted. In Chapter 7, user data is used to analyze the behavior of a computational model of influences on physical activity behavior. Chapter 9 describes a validation of a computational model of social contagion based on collected empirical data. In Chapter 12, data is collected to test a design principle related to social comparison. In addition to the intermediate experiments, a final experiment was conducted in which the Active2Gether intervention was tested. Chapter 15 describes the analyses of the effectiveness of the intervention and an evaluation of the user experiences is presented in Chapter 16. The data collected in this final experiment is also used in Chapter 6 to validate a computational model of influences on physical activity behavior.

1.4.5 Data analysis

In the experiments described in the previous section, many different types of data were collected to answer various research questions. As a consequence, a wide variety of data analysis approaches are required. The most suitable type of data analysis depends heavily on the research question at hand, as well as on the available data. This section illustrates a number of different data analysis approaches applied throughout this thesis.

One important objective pursued with data analysis is model validation. Validation of computational models, as briefly introduced in Section 1.4.3, can be approached in many different ways. This thesis contains two validations of a computational model of social contagion (in Chapter 9 and Chapter 11), and a validation of a computational model of influences on physical activity behavior (in Chapter 6). These chapters present a wide range of tests for the models’ validity (depending on the available data and the focus of the validation), for each of which a suitable statistical approach was selected. Among those are a Mann-Kendall correlation test between predicted and empirical data, a Mann-Whitney test
to compare error sizes between two models, and a Spearman rank correlation test between predicted and empirical changes.

In addition to using data analysis for model validation, this thesis also contains applications of data analysis for other purposes. For each task, appropriate statistical tests are conducted, among which regression models (in Chapter 10), Mann-Kendall tests for significance of trendlines (in Chapter 9 and Chapter 12), a log-rank test on Kaplan-Meier survival curves (in Chapter 16), Anova or Krukal-Wallis tests and Tukey or Mann-Whitney post-hoc tests to examine differences between conditions (in Chapter 16).

1.4.6 Development and implementation

In addition to the scientific methods described in the previous sections, a considerable part of the work behind this thesis consisted of the development and implementation of the Active2Gether system. The challenges that come into play when actually developing such a system are covered by research question 4. The design and development of the intervention is described in Chapter 13, and Chapter 14 describes the technical aspects of the development of the Active2Gether system in detail.

From a technical perspective, the Active2Gether system includes four main components. First, a MySQL database is used to store relevant user data, such as activity data, important locations and their characteristics, assessments of psychological constructs, etc. Second, a set of Python scripts, together called the ‘reasoning engine’, read the database contents to decide on the system’s next actions (e.g., sending the user a supportive coaching message). Third, a Java-based program regularly checks the availability of relevant messages or questions, and takes care of sending them to the user. Fourth, the interaction with the users is done through an Android app: it shows a dashboard with recent activity data, it collects location data, and it presents the questions and messages to the user.

The development of the Active2Gether system required careful formalization of conceptual ideas and integration of its various components, and above all thorough testing and debugging.

1.5 Contributions

The scientific contributions of the research presented in this thesis will be elaborated on in the Discussion & Conclusion (Chapter 17). This section briefly outlines the overall foreseen contributions that warrant the added value of this thesis.

As explained in Section 1.1, the overall aim of the work described in this thesis is to contribute to the field of study that pursues healthy lifestyle promotion by combining knowledge and methods from (health) psychology and artificial intelligence. The integration of these two disciplines implies an interdisciplinary approach, in which each of the perspectives is reflected accurately.

Although the combination of (health) psychology and artificial intelligence is not unique, its application to the actual development of a behavior change intervention for physical activity is relatively unprecedented. To this purpose, a variety of techniques that aim to promote physical activity by using ‘intelligent’ approaches are (developed and) investigated. This produces many insights in the added value of such techniques and their advantages and disadvantages. Some of these insights contribute to the understanding of human behavior and dynamics underlying behavior change, whereas others provide practical directions
for the development of physical activity interventions. One can imagine that some of the investigated techniques should be relatively easily transferable to other aspects of healthy lifestyle (such as sleeping, nutrition, smoking habits and alcohol intake), thereby extending the scientific value to beyond physical activity only.

The interdisciplinary nature of this thesis, as well as the wide variety of techniques investigated on their ability to contribute to behavior change, goes hand in hand with a wide range of methods to approach the overall research objective. As Section 1.4 exemplifies, these include methods that are traditionally typical for social sciences and methods that are more related to computer science.

Finally, another important contribution is the collection of several rich datasets regarding physical activity behavior and a diversity of related factors. These datasets form the basis for answering specific research questions in some of the chapters of this thesis, but the variety of information stored in these datasets allows for a wide range of further analyses. Therefore, various interesting research questions that were beyond the scope or time limit of this work will still be able to be investigated based on this data.

1.6 Thesis organization

This section delineates the structure of this thesis. First, Section 1.6.1 explains the type of this thesis. Then, Section 1.6.2 describes the thesis’ different parts. Finally, each of the chapters (and the publications they are based on) are briefly outlined in Section 1.6.3.

1.6.1 Thesis type

This thesis is a cumulative thesis, which means that it is composed of a collection of independent articles. As some elements had to be explained in multiple papers, this implies that certain notions or ideas are repeated in more than one chapter and therefore some parts may show some overlap. However, this also implies that each of the chapters can be read as a standalone narrative.

1.6.2 Thesis outline

This thesis consists of six parts in total, including the Introduction (Part I) and the Discussion & Conclusion (Part VI). The core of this thesis is organized into four parts (Part II – Part V), each consisting of multiple chapters. Each of these four parts addresses one of the research questions introduced in Section 1.3. Below, the remaining five parts and the overall contents of their chapters are outlined.

Part II: Investigating the state of the art and user preferences

Part II provides an answer to research question 1, as introduced in Section 1.3. It first presents an overview of the state of the art of behavior change interventions that promote a physically active lifestyle. This is done through two systematic reviews and content analyses: one focusing on the use of behavior change techniques (in Chapter 2) and one focusing on the application of technological features (in Chapter 3). In addition, the results of exploring user preferences regarding such interventions through focus group discussions are presented in Chapter 4.
Part III: Modeling influences on physical activity

Part III contributes to answering research question 2. Chapter 5 presents a dynamic computational model of influences on physical activity behavior. Chapter 6 provides a preliminary validation of a refined version of this model, based on empirical physical activity data. In Chapter 7, it is investigated how parameter tuning techniques can be used to get more insight in the behavior of such a computational model. The latter is especially useful when employing a computational model in a real-life application, as in the Active2Gether intervention.

Part IV: Using the social environment to influence behavior

Part IV deals with research question 3. It contains four chapters that—each from a different perspective—focus on the role of social influences on physical activity behavior. Chapter 8 investigates how interventions in the structure of social networks can lead to improved behavior, and how the best locus of such interventions can be identified. In Chapter 9, a computational model that describes contagion of behaviors, attitudes and emotions through a social network is validated using real-life data. Chapter 10 demonstrates the effect of online communities in a corporate physical activity promotion program, and Chapter 11 investigates the role of social contagion in explaining changes in physical activity in the same dataset. Finally, Chapter 12 investigates the relation of social comparison implementations with the users’ preferences.

Part V: Combining all components of the Active2Gether intervention

Part V covers the topics raised in research question 4. It combines the components that were investigated in each of the previous parts. First, Chapter 13 describes the stepwise approach of the overall design of the Active2Gether intervention. Then, Chapter 14 provides more detail on the technical development of the Active2Gether intervention and its underlying system. In Chapter 15, the results of a user study on the effectiveness of the Active2Gether intervention are presented. Finally, Chapter 16, discusses the results of a user evaluation study of the Active2Gether intervention, in which the experiences of users with the system are investigated.

Part VI: Discussion and Conclusion

The final chapter of this thesis (Chapter 17) provides a discussion of the results obtained in each of the parts, reflects on ethical issues, and looks ahead at future work related to the currently presented ideas and endeavors.

1.6.3 Chapters

Most of the chapters of this thesis appeared as peer-reviewed published articles, one is still under review and one will be submitted for publication. This section provides an overview of the articles that the chapters were based on, together with a brief explanation of my individual contributions to each piece of work.

My personal contributions included conceiving the review setup, collecting the app data, conducting the review, providing intellectual input to the review and manuscript, and approving the final version of the article.

**Chapter 3** has been published as: **Julia S. Mollee**, Anouk Middelweerd, Robin L. Kurvers, and Michel C.A. Klein (2017). “What technological features are used in smartphone apps that promote physical activity? A review and content analysis”. In: *Personal and Ubiquitous Computing* 21.4, pages 633–643. ISSN: 1617-4917.

My contributions included conceiving the review setup, co-supervising the student having the lead in the review, conducting the review, performing the analyses, writing most of the manuscript and incorporating feedback in the final version of the article.


My contributions to this work included providing intellectual input, co-supervising the students having the lead in the focus group interviews, assisting with the focus group discussions, providing feedback on the manuscript, and approving the final version of the article.


The authors can be regarded to have made equal contributions to the work and are therefore in alphabetical order. My personal contributions included exploring relevant literature, co-designing and co-implementing the computational model, running a substantial part of the simulations, writing a substantial part of the manuscript and incorporating feedback in the final version of the article.


My contributions included co-designing the experimental setup, conducting a substantial part of the data collection, performing the analyses, writing most of the manuscript and incorporating feedback in the final version of the article.

**Chapter 7** has been published as: **Julia S. Mollee**, Eric F. M. Araújo, and Michel C. A. Klein (2017). “Exploring Parameter Tuning for Analysis and Optimization of a

My contributions included co-designing the experimental setup, conducting a substantial part of the data collection, performing the analyses, writing most of the manuscript and incorporating feedback in the final version of the article.


The authors can be regarded to have made equal contributions to the work and are therefore in alphabetical order. My personal contributions included co-designing the experimental setup, implementing part of the software, performing part of the analyses, writing a substantial part of the manuscript, providing feedback on the manuscript and incorporating feedback in the final version of the article.


My contributions included co-designing the experimental setup, co-supervising the student in charge of conducting the experiment, providing feedback on the analyses and the manuscript, and approving the final version of the article.


My contributions included co-designing the experimental setup, providing feedback on the analyses and the manuscript, and approving the final version of the article.


My contributions included co-designing the experimental setup, co-performing the analyses, writing most of the manuscript, incorporating feedback on parts of the manuscript, providing feedback on parts of the manuscript, and approving the final version of the article.

**Chapter 12** has been published as: Julia S. Mollee and Michel C. A. Klein (2016). “The effectiveness of upward and downward social comparison of physical activity in an

My contributions included co-designing the experimental setup, co-supervising the student in charge of conducting the experiment, exploring relevant literature, performing the analyses, writing most of the manuscript, and incorporating feedback in the final version of the manuscript.

Chapter 13 is based on the article that is conditionally accepted for publication as: Anouk Middelweerd, Saskia J. te Velde, Julia S. Mollee, Michel C.A. Klein, and Johannes Brug (2018). “Development of Active2Gether: An app-based intervention combining evidence-based behavior change techniques with a model-based reasoning system to promote physical activity among young adults”. In: Journal of Medical Internet Research.

My contributions included co-designing the intervention, co-designing the experimental setup and co-conducting the intervention study, providing feedback on the manuscript and approving the final version of the article.

Chapter 14 has been published as: Michel C. A. Klein, Adnan Manzoor, and Julia S. Mollee (2017). “Active2Gether: A Personalized m-Health Intervention to Encourage Physical Activity”. In: Sensors 17.6, pages 1436–1451.

The authors can be regarded to have made equal contributions to the work and are therefore in alphabetical order. My contributions included co-designing and implementing a substantial part of the proposed system, writing a substantial part of the manuscript, providing feedback on the manuscript, incorporating feedback in the final version of the manuscript.

Chapter 15 is based on the manuscript of the article that will be submitted as: Anouk Middelweerd, Julia S. Mollee, Michel C.A. Klein, Adnan Manzoor, Johannes Brug, and Saskia J. te Velde (2018). Exploring use and effects of an app-based intervention to promote physical activity: Active2Gether.

My contributions included co-designing the intervention, implementing a substantial part of the intervention, co-designing the experimental setup and co-conducting the intervention study, assisting in the data preprocessing, providing feedback on the manuscript and approving the final version of the article.


My contributions included co-designing the experimental setup, co-conducting the data collection study, performing the analyses, writing most of the manuscript, and incorporating feedback in the final version of the article.

Additional publications

In addition, the following four articles have been written in the context of the creation of this thesis, but are not included.


*The authors can be regarded to have made equal contributions to the work, and are therefore in alphabetical order.
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