Original Article

Formal, dynamical systems modelling to advance health psychology theories: Interdisciplinary working where psychology meets mathematics

Olga Perski
Tampere University, Finland & University of California, San Diego, USA
Jim Allen
Glasgow University, UK

Background

We health psychologists spend much of our time building, testing and refining theories because they are powerful tools for predicting, understanding and influencing empirical phenomena of interest (e.g., habit formation, behaviour change initiation and maintenance). However, many dominant health psychology theories have mostly been developed under a 'low-resolution measurement paradigm' (e.g., questionnaires administered several weeks or months apart) and therefore tend to incorporate time in a coarse way (Chevance et al., 2021; Scholz, 2019). For example, according to the Transtheoretical (Stages of Change) Model, the behaviour change process for a given individual, from initiation to maintenance, is made up of discrete motivational and behavioural phases (e.g., precontemplation, contemplation, etc), with each phase lasting up to several months. Although the Stages of Change Model has been critiqued for several reasons (West, 2005), recent observations from Ecological Momentary Assessments in people's daily lives fundamentally question its temporal propositions, with many studies finding large within-person fluctuations in stress, affect, motivation and health behaviours over time (Chevance et al., 2021). The same critique applies to many other popular health psychology theories.

In addition, most health psychology theories are ambiguously described and require several additional assumptions about, for example, appropriate measures and study designs, to be specified in order to generate testable hypotheses (Eronen & Bringmann, 2021; Guest & Martin, 2021; Oberauer & Lewandowsky, 2019). As an example, the Control Theory (also known as the Self-Regulation Theory) proposes that behaviour change occurs as the result of a feedback loop. The person sets a goal, monitors (or allows someone else to monitor) their behaviour in relation to the desired goal state and subsequently shifts their behaviour or adjusts their goal based on the detected goal-behaviour discrepancy (Carver & Scheier, 1982). However, the Control Theory is not very precise about how rapidly this process plays out over time and within individuals, or how to measure the different constructs.

Taken together, we and others have argued that the abovementioned issues stifle progress within our field, as they hinder the adjudication between competing theoretical explanations and the development of potent interventions which take time into account (Perski et al., 2023).

A way forward

A potential solution to the abovementioned issues is to use 'formal modelling' to make our theories more precise (Eronen & Bringmann, 2021; Guest & Martin, 2021). Formal modelling involves translating a theory's structure into a mathematical framework (e.g., a series of equations or logical propositions). The formal model then acts as the theory's 'empirical interface' and can be directly tested against empirical observations (Guest & Martin, 2021). Typically, the formal model is also translated into a computational model – i.e., computer code using R or python – which enables the system behaviour to be easily simulated and visualised under different conditions. Dynamical systems models are a specific type of mathematical framework that can be used, which have the benefit of accommodating non-linearities and feedback loops, using a single framework to represent many different behavioural patterns. For example, one can easily get increases, decreases or cyclical behaviour in a dynamical systems model, using the same underlying model structure. As dynamical systems can quickly become complex, it can be difficult for the theorist to track the consequences of different theoretical principles. Hence, it is important to implement the formal model in mathematical software or a computer and visualise the system behaviour when developing and refining theories.

Many scientific disciplines, including physics, engineering, biology, neuroscience and public health, have a long tradition of using formal and computational modelling. Recently, health psychologists and engineers have translated the Theory of Planned Behaviour and subsequently the Social Cognitive Theory into formal, dynamical systems models (Martín et al., 2018; Riley et al., 2016). However, our recent scoping review found that efforts to formalise existing, or using formal modelling to develop new, health psychology theories are still few and far between (Perski et al., 2023).

In the next sections, we dig deeper into how we embarked on a joint, interdisciplinary project to develop a formal, dynamical systems model to more precisely predict and explain when and why lapse and relapse occur when people try to stop smoking (project 'COMPLAPSE'; https://www.olgaperski.com/research/complapse). Our project is still ongoing, so rather than presenting the results, our intention here is to begin to open up the 'black box' of formal and computational modelling practices, which are typically not well-described in the literature. Although there are many important aspects worth highlighting – notably the participatory involvement of different stakeholder groups – we focus here on the interdisciplinary collaboration between health psychologists and modellers in our project, including where points of tension may arise during the collaborative modelling process. We aim to develop more in-depth tutorials targeting health psychologists in future writings.

Developing a formal model and the need for interdisciplinary collaboration

Since different scientific disciplines have developed formal and computational models, they each take slightly different approaches to their development. For example, useful guiding frameworks have been developed within engineering, neuroscience and public health (Hammond, 2015; Ljung & Glad, 1994; Wilson & Collins, 2019). However, the goal of the modelling typically differs between disciplines and projects. For example, formal modelling is sometimes used to improve the shared understanding of a problem space or to predict, rather than causally explain, events of interest. It is useful to be aware of these different modelling goals when approaching potential collaborators to ensure goal alignment. Given our goal of theory development/refinement in project COMPLAPSE, after searching the literature, we landed on using a recent guiding framework which was generated specifically for the construction of explanatory psychological theories. The Theory Construction Methodology (Borsboom et al., 2021) suggests five broad methodological steps for theorists, including: i) the identification of relevant phenomena which the theory seeks to explain; ii) the formulation of a 'prototheory' which causally explains how the phenomena are produced; iii) the translation of the phenomena and prototheory into a formal and computational model; iv) the checking of the formal model's explanatory adequacy, including if it can produce the phenomena of interest in computer simulations; and v) the assessment of the theory's overall 'goodness', including its coherence, plausibility and predictive power.

In addition to drawing on the Theory Construction Methodology, we took a participatory approach in our project, conducting interviews with stakeholders to elicit their mental models of when and why smoking lapses occur during a quit attempt. We summarised the findings in a conceptual map, which was subsequently translated into a series of equations implemented in R. Rather than working with off-the-shelf equations or statistical software packages, formal and computational models tend to be bespoke. Therefore, for health psychologists, developing formal models typically requires collaboration with applied mathematicians. OP and JA met at the inaugural EHPS Winter School in Leuven and identified a shared interest in formal and computational modelling to advance health psychology theories. OP has a background in health psychology/addiction research and has prior experience of applying complex analytical techniques (e.g., multilevel modelling, machine learning) to intensive, longitudinal data and writing R code. JA has a background in dynamic models of social processes across a range of systems. We then initiated a collaboration, which, in our project, required frequent discussion to combine our knowledge of health psychology, addiction and mathematics in general and dynamical systems and computational modelling in particular.

As an example of how our discussions would pan out, OP would describe key explanatory principles identified in the literature and as part of the stakeholder interviews and JA would use his experience of standard modelling frameworks and motifs (e.g., a decaying stimulus) and suggest ways in which the explanatory principles could be represented mathematically. As when designing an experiment, many choices must be made in a formal model (e.g., Are decisions made every minute or every hour? Does self-efficacy increase to infinity or is there a maximum value it can reach?). Dynamical systems models often follow some kind of standard framework, tweaked for the purpose in hand. For example, paradigmatic models exist for decision making in terms of utility maximisation, learning, or strategic decisions in the form of game theory. Therefore, one way in which collaboration can be effective between applied mathematicians and health psychologists is to understand standard frameworks that may also apply to the questions at hand. This has been referred to as 'analogical abduction' in the Theory Construction Methodology (Borsboom et al., 2021). We then progressed with OP writing the equations and computer code, simulating the system behaviour for different parameter values and bringing questions back to JA if needed.

To concretise this even more, below is an example of how we formalised exposure to cigarette cues which have, through repetition, become automatically associated with the anticipation of the reward from smoking, and how such exposure contributes to the subjective experience of wanting to smoke (i.e., cravings). We theorised that the reactivity to a given cue lingers for a bit and declines exponentially over time. As such, we formalise cue reactivity (CR) based on a standard motif of a decaying stimulus as:

$$CR(t) = \delta_1 \, CR(t-1) + \delta_2 \, CC(t)$$

where δ_1 is a decay parameter and δ_2 represents the impact of a recent cigarette cue (CC), which could vary between individuals, as we expect

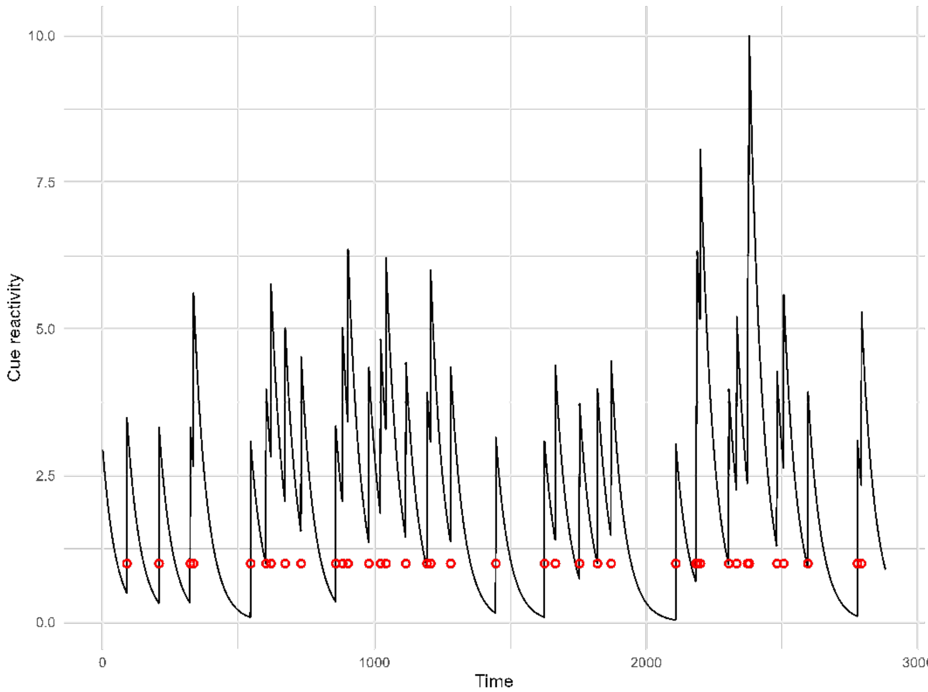

Figure 1. Cue reactivity on the y-axis (0 to 10), with time since the quit attempt started on the x-axis (5-minute intervals). The red dots represent exposure to a cigarette cue.

responses to cues to vary within the population. We then simulated what this may look like for a given individual, assuming that δ_1= 0.98 and δ_2= 3 (see Figure 1).

Tips and tricks for interdisciplinary working to formalise health psychology theories

In our experience, the following might be helpful when collaboratively formalising health psychology theories. First, since there is little guidance for health psychologists interested in formal modelling, it can be difficult to know where to start. Those with modelling expertise rarely document the many choices made during the model development process. However, for those new to modelling, it is difficult to learn without seeing explicit examples of the process. As concluded in our recent scoping review, we encourage researchers interested in using these methods to adopt open science practices to share as much as possible about the development process, including code and other materials (Perski et al., 2023). In addition to making underlying model goals and assumptions transparent, this has the added benefit of allowing novices to draw on available examples to better understand what a formal and computational model looks like and what constitutes ‘good practice’ in regard to the modelling goal.

Second, it is not always easy to know where to meet future collaborators with relevant skills and modelling interests. Not all modellers are interested in the development of explanatory psychological theories and many applied models do not generate enough mathematics or computer science to contribute novel findings to those fields. From JA’s experience, there is often a desire in the mathematical community to collaborate on important empirical topics. However, mathematicians often do not know where to meet researchers with specific subject knowledge and interest in formal modelling. Therefore, it may be useful for those in the modelling community who are already working with health psychologists to begin to make more introductions between colleagues, and for conferences such as the EHPS annual conference to make clear that new methodological approaches are welcome.

Third, a key factor in any of these collaborations is that formal modelling takes time, particularly when initiating a new collaboration. Not only are the languages and assumptions used by health psychologists and modellers very different (e.g., modellers are often quick to abstract away most of a phenomenon in order to easily formalise it, whereas domain experts are often tied to the intricacies of any experience), but formal modelling requires multiple iterations. This can come as a surprise to researchers more familiar with the application of statistical models to empirical data. In addition, for health psychologists without much prior modelling and coding experience, it is important to factor in ample time for skills development.

Conclusion

Here, we introduced the need for the formalisation of health psychology theories to improve their precision and the importance of interdisciplinary working between health psychologists and mathematicians. Tips and tricks for how to work together across disciplines, based on our experience of working together as part of project 'COMPLAPSE' were provided. It remains to be explored whether the increased use of formal and computational modelling within health psychology will accelerate theoretical advancements and practical applications.

References

Borsboom, D., van der Maas, H. L. J., Dalege, J., Kievit, R. A., & Haig, B. D. (2021). Theory Construction Methodology: A Practical Framework for Building Theories in Psychology. *Perspectives on Psychological Science, 16*(4), 756–766. https://doi.org/10.1177/1745691620969647

Carver, C. S., & Scheier, M. F. (1982). Control Theory: A Useful Conceptual Framework for Personality-Social, Clinical, and Health Psychology. *Psychological Bulletin, 92*(1), 111–135. https://psycnet.apa.org/doi/0.1037/0033-2909.92.1.111

Chevance, G., Perski, O., & Hekler, E. B. (2021). Innovative methods for observing and changing complex health behaviors: Four propositions. *Translational Behavioral Medicine, 11*(2), 676–685. https://doi.org/10.1093/tbm/ibaa026

Eronen, M. I., & Bringmann, L. F. (2021). The Theory Crisis in Psychology: How to Move Forward. *Perspectives on Psychological Science, 16*(4), 779–788. https://doi.org/10.1177/1745691620970586

Guest, O., & Martin, A. E. (2021). How Computational Modeling Can Force Theory Building in Psychological Science. *Perspectives on Psychological Science, 16*(4), 789–802. https://doi.org/10.1177/1745691620970585

Hammond, R. A. (2015). Considerations and Best Practices in Agent-Based Modeling to Inform Policy. In Assessing the Use of Agent-Based Models for Tobacco Regulation. *National Academies Press* (US). https://www.ncbi.nlm.nih.gov/books/NBK305917/

Ljung, L., & Glad, T. (1994). *Modeling of Dynamic Systems* (1st edition). Pearson College Div.

Martín, C. A., Rivera, D. E., Hekler, E. B., Riley, W. T., Buman, M. P., Adams, M. A., & Magann, A. B. (2018). Development of a Control-Oriented Model of Social Cognitive Theory for Optimized mHealth Behavioral Interventions. *IEEE Transactions on Control Systems Technology,* *28*(2), 331–346. IEEE Transactions on Control Systems Technology. https://doi.org/10.1109/TCST.2018.2873538

Oberauer, K., & Lewandowsky, S. (2019). Addressing the theory crisis in psychology. *Psychonomic Bulletin & Review, 26*(5), 1596–1618. https://doi.org/10.3758/s13423-019-01645-2

Perski, O., Copeland, A., Allen, J., Pavel, M., Rivera, D. E., Hekler, E., Hankonen, N., & Chevance, G. (2023). The iterative development and refinement of health psychology theories through formal, dynamical systems modelling: A scoping review and initial 'best practice' recommendations. *OSF Preprints*. https://doi.org/10.31219/osf.io/bpcgu

Riley, W. T., Martin, C. A., Rivera, D. E., Hekler, E. B., Adams, M. A., Buman, M. P., Pavel, M., & King, A. C. (2016). Development of a dynamic computational model of social cognitive theory. *Translational Behavioral Medicine, 6*, 483–495. https://doi.org/10.1007/s13142-015-0356-6

Scholz, U. (2019). It's Time to Think about Time in Health Psychology. *Applied Psychology: Health and Well-Being*. https://doi.org/10.1111/aphw.12156

West, R. (2005). Time for a change: Putting the Transtheoretical (Stages of Change) Model to rest. *Addiction,* 1036–1039. https://doi.org/10.1111/j.1360-0443.2005.01139.x

Wilson, R. C., & Collins, A. G. (2019). Ten simple rules for the computational modeling of behavioral data. *eLife, 8*, e49547. https://doi.org/10.7554/eLife.49547

Olga Perski

Faculty of Social Sciences, Tampere University, Finland

Herbert Wertheim School of Public Health and Human Longevity Science, University of California, San Diego, USA

olga.perski@tuni.fi

Jim Allen

MRC/CSO Social and Public Health Sciences Unit, Glasgow University, UK

James.Allen@glasgow.ac.uk