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Steps to a Sustainable Mind

Explorations into the Ecology of Mind and Behaviour

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Abstract

This transdisciplinary doctoral thesis presents various theoretical, methodological and empirical approaches that together form an ecological approach to the study of social sciences. The key argument follows: to understand how sustainable behaviours and cultures may emerge, and how their development can be facilitated, we must further learn how behaviours emerge as a function of the person and the material and social environment. Furthermore, in this thesis the sustainability crises are framed as *sustain-ability* crises. We must better equip our cultures with abilities to deal with the complexity and uncertainty of socio-ecological systems, and use these cultural skillsets to survive in and adapt to an increasingly unpredictable world.

This thesis employs a plurality of ecological social sciences and related methodologies—such as ecological psychology, ecological rationality and agent-based modelling—to enlighten the question of how the collective adoption of sustainable behaviours can be leveraged, particularly by changing the affordances in the material environment. What is common to these ecological approaches is the appreciation of 'processes' over 'products': we must understand the various processes through which sustainable forms of behaviour or decision-making emerge to truly locate leverage points in social systems. Finally, this thesis deals extensively with uncertainty in complex systems. It proposes that we can look to local and traditional knowledge in learning how to deal adaptively with uncertainty.

Tiivistelmä

Tässä poikkitieteellisessä väitöskirjassa esitetään lukuisia teoreettisia, metodologisia ja empiirisiä näkökulmia, jotka yhdessä muodostavat ekologisen lähestymistavan sosiaalitieteelliseen tutkimukseen. Tutkielman keskeinen argumentti on: jotta voimme oppia, miten kestävät käyttäytymismallit ja kulttuurit syntyvät ja miten niiden kehitystä voi edesauttaa, meidän täytyy ymmärtää, miten ne syntyvät ihmisen ja (materiaalisen sekä sosiaalisen) ympäristön funktiona. Tässä väitöskirjassa kestävyyskriisiä tulkitaan käyttäytymistieteellisestä ja kulttuurievoluution näkökulmasta. Sopeutuaksemme yhä hankalammin ennustettavaan tulevaisuuteen, kulttuurimme on opittava ja mukauduttava hallitsemaan epävarmuutta sekä tietoisesti ohjaamaan kulttuurievoluutiota kestävään suuntaan.

Tässä väitöskirjassa hyödynnetään lukuisia teoreettisia ja metodologisia tulokulmia, esimerkiksi ekologista psykologiaa, ekologista rationaalisuutta sekä agenttipohjaista mallinnusta. Yhdessä näiden tulokulmien kautta pyritään ymmärtämään, miten voimme paikantaa yhteiskunnista vipupisteitä kestäviin käyttäytymismuutoksiin esimerkiksi materiaalista ympäristöä muokkaamalla. Väitöskirjan tulokulma painottaa erityisesti käyttäytymismuutosten taustalla olevien prosessien tulkintaa: jotta voimme ymmärtää, miten kestävät käyttäytymismallit tai päätöksenteot syntyvät, meidän on ymmärrettävä miten ne syntyvät lukuisten monimutkaisten ja kytkennäisten sosiaalisten prosessien kautta. Tässä väitöskirjassa tutkitaan myös epävarmuutta kompleksisissa järjestelmissä. Väitöskirjassa esitetään, että paikallisesta ja perinteisestä tietämyksestä voi olla paljon opittavaa sopeutuessamme epävarmaan tulevaisuuteen.

Contents

Abstract....5

Tiivistelmä....6

List of Original Publications....8

Acknowledgements....9

1 Introduction....11

1.1 Prologue: *Sustain-ability*....11

1.2 Abstracts of Articles....16

1.3 Synopsis of the Argument....21

2 Ecological Approaches to Social Sciences....25

2.1 Ecological Psychology and Affordance Theory....27

2.2 Cultural Evolution: Niche Construction and Social Learning....31

2.3 Ecological Rationality....35

2.4 Modelling Ecologies of Behaviour....39

3 Steps to a Sustainable Mind....44

3.1 Step 1: Relocating Ourselves in Natural Processes....45

3.2 Step 2: Ecologies of Design....48

3.3 Step 3: Dealing with Uncertainty....65

4 Concluding Remarks....73

References....78

List of Original Publications

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2. Kaaronen, R. O. (2017). Affording Sustainability: Adopting a Theory of Affordances as a Guiding Heuristic for Environmental Policy. Frontiers in Psychology, 8. https://doi.org/10.3389/fpsyg.2017.01974
3. Kaaronen, R. O., & Strelkovskii, N. (2020). Cultural Evolution of Sustainable Behaviors: Pro-environmental Tipping Points in an Agent-Based Model. One Earth, 2(1), 85–97. https://doi.org/10.1016/j.oneear.2020.01.003
4. Kaaronen, R. O. (2020, In print). Mycological Rationality: Heuristics, Perception and Decision-Making in Mushroom Foraging. Judgment and Decision Making, 15(5). https://doi.org/10.31234/osf.io/7g8er

The publications are referred to below by the numbers above (e.g., Article 1).

All articles were written solely by Kaaronen except for Article 3, which was co-authored with Dr. Nikita Strelkovskii at the International Institute for Applied Systems Analysis (IIASA). Kaaronen was the main contributing author for the manuscript, model, and analysis of Article 3. Strelkovksii supervised Article 3 and oversaw the development of its manuscript, model, and analysis.

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For a thesis whose core arguments include the idea that we behave in ways which our environments afford, it is only appropriate to note that the present text would never have become if it were not for the caring and support from my family, friends, and colleagues.

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1 Introduction

1.1 Prologue: *Sustain-ability*

Etymologies

I begin with a digression: I am tremendously partial to etymology, the study of the history and origins of words. Admittedly, some of this affection is by its nature pedantic—I enjoy the trivia of knowing the details of everyday things, and particularly the sharing of such information with others. But I wish to make the argument here that there is a more profound aspect to etymology, one which will reverberate throughout this text. This is the notion that histories of words can afford insightful commentaries on how they are currently used; how they might have lost some of their meaning or gained new ones. Etymologies can reveal political or geographical histories—such as the case of 'rhubarb', which derives from the Greek *Rha barbaron*, or the Scythian name for the river Volga (*Rha*) and the foreigners (*barbaron*) who exported the product to Ancient Greece—or have epistemological or even metaphysical dimensions, such as the etymology of 'person', from the Latin word *persona*, a mask or role in a drama. Whilst I maintain that words are often just words, and at that, quite detached from practice, sometimes, to look to the future, it is necessary to understand how the current state of affairs emerged, and etymologies can be helpful here.

Environment – that which environs, that which surrounds

Given the dismal state of global environmental concerns at the time of writing this text, it is perhaps unremarkable to find that the very word by which we conceptualise our calamitous state of affairs is a misnomer. Environment, or *that which environs (surrounds) us*, is one of the more misplaced nouns in modern English, and unfortunately, has found its way more or less literally translated into several other languages (e.g., my native language, Finnish, *ympäristö*). Here is the gist of my argument, one which shall be elaborated throughout the present text: the system we label the 'environment' is not something that *surrounds us*, it is something we *emerge from* along with other forms of life. To find that much, if not most, of modern sciences that deal with 'environmental' issues regard the environment as something 'out there' is unsurprising. Environmental psychology mainly deals with how we perceive the environment or our attitudes toward it, placing much less emphasis on how we—our patterns of cultures and behaviours—actually emerge from, act upon and act within the natural system. Environmental economics, in turn, seems to have an obsession of its own on with putting a price or utilitarian value on that which 'environs us' (the discourses on 'ecosystem services' and calculations of 'externalities' prove the point), rather than fundamentally serving to safeguard the ecological processes wherefrom we emerge. And so on.

Thus, I argue in the following work, we must foster a move from environmental social sciences to *ecological* social sciences. Fortunately, in doing so, one need not start from scratch, as theoretical frameworks with dealing with ecological human or social sciences, or indeed socio–ecological systems, are plentiful, and have a long history dating to work directly inspired by Charles Darwin (Heft 2001; Wilson 2020). Curiously, Darwin (1859) himself did use the word 'environment' once in the Origin of Species and spoke instead, among other things, of how 'circumstances' shape our individual and collective lives—a much more comprehensive notion which expands to social and cultural forms of life. As we will see below, the challenge with developing ecological social sciences is mainly one of cultivating symbiotic relations between socio–ecological theories that have previously engaged in little exchange of information.

Ecology – the study of our house

The word 'ecology' was first coined by the influential German polymath and artist Ernst Haeckel (also known, regrettably, for his radical eugenicist views) as *Ökologie*, derived from Greek *oikos* (house, dwelling place, habitation) and *logia* (study of). Thus, ecology is the study of our house or home—a much more favourable framing of the system wherefrom we emerge. The matter of fact that ecology has been traditionally accepted as the branch of science that deals with the relationships, networks, or systems between organisms and their environments, provides a more coherent framework to study mutualistic human–nature relations and socio–ecological systems than any 'environmental' science. This is mainly due to the fact that if we do not understand the networks, systems and relations—the 'extraordinary combination of circumstances', to quote Darwin (1859)—by which human societies and cultures emerge, there is, I fear, little hope that we are capable of maintaining these systems within *sustainable* limits.

Sustainability – the ability to sustain

Sustainability is another concept which, curiously, seems to have lost much of its meaning in its overapplication. Thinking about sustainability today, one is quickly reminded of global catastrophes, or perhaps of individual 'green' behaviours, or the flashy icons of the Sustainable Development Goals. Yet sustainability is not, or at least is not synonymous to, any of these. Sustainability (*sustain + -able*) is the *ability* of a system to maintain a sustained state. Sustainability is *sustain-ability*, and in the context of humans, any such ability implies capabilities to perceive, cognise and act in ways which promote our capacity to sustain within defined boundaries, much like any homeostatic system. An ability is nothing other than a set of skills related to, individual or collective, perception, cognition, and action. Thus, sustain-ability is a set of cultural skills, or capabilities, and if we wish to live sustainably it is our utmost duty to make best use of our human capacities to foster the skillsets that keep us within planetary boundaries.

I know—framing sustainability as capabilities reeks of individualism. But this is only true if one regards capabilities as individual features, which is simply not the case. This is another core argument in this thesis. In fact, despite its focus on psychological processes such as action, cognition and perception, the present text is in fact antithetic to individualism. This is because capabilities do not emerge from nowhere: they are products of various cultural, social and ecological processes. Capabilities are, among other things, a function of social and individual skills and learning, cultural niche construction, and available action-opportunities in our socio–material environments. Sustain-abilities should thus involve nothing less than leveraging these factors for collective good, non-human life included. Learning to become sustain-able requires leveraging the potentialities that make us human: (re)designing cultural institutions, social behaviours, norms, and environments to shape or direct our cultural evolution towards a more sustainable state.

Ecology of Mind and Behaviour

The title of this work, of course, pays homage to Gregory Bateson's (2000) great collection of essays, *Steps to an Ecology of Mind*. Considering how influential Bateson's way of thinking has been to the present thesis, it is curious how little Bateson's work appears in its actual content—Bateson's name seems to most often appear in the context of fleeting quotations or aphorisms (at which, I must say, Bateson did excel). But there is something which appealed to me in particular in Bateson's way of parsing together theoretical frameworks from various disciplines, cultivating a genuine systems approach for studying human and cultural sciences, that I always found tremendously inspiring. If we truly wish to understand how sustainable cultures might emerge, it is inevitable that we must look into various theoretical frameworks, and in doing so adopt some kind of pragmatist or pluralist perspective when facing the difficulties of multidisciplinary conversation and theorising.

This thesis includes four research articles, all representing unique theoretical or methodological frameworks. What connects them, retrospectively, is a joint attempt at understanding the *ecology* of the human mind and behaviour, and the implications of this for ongoing sustainability, or *sustain-ability*, crises. Together, these articles ask: How do sustainable ways of collective thinking and doing emerge, as a product of cultural, cognitive or even philosophical processes? In the following summary, I present my attempt at answering this question.

Figure 1. Exploring the ecology of mind entails the blurring of boundaries between human and natural systems, as well as alternating focus between the two when generating explanations for behaviour.

1.2 Abstracts of Articles

Next to the present summary, this thesis consists of four research articles, whose abstracts are presented below. Articles 1–3 have, at the time of writing, been published. Article 4 is currently in print. The research articles discuss several themes related to sustainable dwelling, cognition, and ecological theories of mind and behaviour. In this summary I seek to parse together the key themes of these articles, with particular focus on discussing how they overlap in ways which might not be obvious at first inspection.

For a variety of reasons, not all of my work has been included within the covers of this thesis. These include a research paper on some cognitive mechanisms, particularly cognitive dissonance, which underly most ecological crises (Kaaronen 2018a), an essay on creating resilient systems of scientific inquiry (Kaaronen 2018b), and various more popular scientific chapters and texts on ecological approaches to cognition and behaviour (e.g., Kaaronen 2019c; 2019b). The reader is also pointed to these texts for a more detailed picture of the ecological approach to social sciences built in this summary.

All four articles below are available Open Access. This means that they (or pre-publication versions of them) are free for reading and sharing by anyone. Hyperlinks are provided after each abstract. If the articles, for whatever reason, cannot be accessed, please contact the author at roope.kaaronen@gmail.com or roopekaaronen.com.

Article 1. Reframing Tacit Human–Nature Relations: An Inquiry into Process Philosophy and the Philosophy of Michael Polanyi

Abstract

To combat the ecological crisis, fundamental change is required in how humans perceive nature. This paper proposes that the human–nature bifurcation, a metaphysical mental model that is deeply entrenched and may be environmentally unsound, stems from embodied and tacitly-held substance-biased belief systems. Process philosophy can aid us, among other things, in providing an alternative framework for reinterpreting this bifurcation by drawing an ontological bridge between humans and nature, thus providing a coherent philosophical basis for sustainable dwelling and policy-making. Michael Polanyi's epistemology can further help us understand these environmentally-oriented tacit processes of knowing, and also provide a basis for the political and educational implementation of process-philosophical insights, particularly via the nudging of mental models.

Full citation:

Kaaronen, R.O. (2018). Reframing Tacit Human–Nature Relations: An Inquiry into Process Philosophy and the Philosophy of Michael Polanyi. *Environmental Values*, 27(2), 179-201. DOI: https://doi.org/10.3197/096327118X15162907484466

Open Access (preprint):

http://hdl.handle.net/10138/233395

Article 2. Affording Sustainability: Adopting a Theory of Affordances as a Guiding Heuristic for Environmental Policy

Abstract

Human behavior is an underlying cause for many of the ecological crises faced in the 21st century, and there is no escaping from the fact that widespread behavior change is necessary for socio-ecological systems to take a sustainable turn. Whilst making people and communities behave sustainably is a fundamental objective for environmental policy, behavior change interventions and policies are often implemented from a very limited non-systemic perspective. Environmental policy-makers and psychologists alike often reduce cognition 'to the brain,' focusing only to a minor extent on how everyday environments systemically afford pro-environmental behavior. Symptomatic of this are the widely prevalent attitude–action, value–action or knowledge–action gaps, understood in this paper as the gulfs lying between sustainable thinking and behavior due to lack of affordances. I suggest that by adopting a theory of affordances as a guiding heuristic, environmental policy-makers are better equipped to promote policies that translate sustainable thinking into sustainable behavior, often self-reinforcingly, and have better conceptual tools to nudge our socio–ecological system toward a sustainable turn.

Affordance theory, which studies the relations between abilities to perceive and act and environmental features, is shown to provide a systemic framework for analyzing environmental policies and the ecology of human behavior. This facilitates the location and activation of leverage points for systemic policy interventions, which can help socio–ecological systems to learn to adapt to more sustainable habits. Affordance theory is presented to be applicable and pertinent to technically all nested levels of socio–ecological systems from the studies of sustainable objects and households to sustainable urban environments, making it an immensely versatile conceptual policy tool. Finally, affordance theory is also discussed from a participatory perspective. Increasing the fit between local thinking and external behavior possibilities entails a deep understanding of tacit and explicit attitudes, values, knowledge as well as physical and social environments, best gained via inclusive and polycentric policy approaches.

Full citation (Open Access):

Kaaronen, R. O. (2017). Affording Sustainability: Adopting a Theory of Affordances as a Guiding Heuristic for Environmental Policy. *Frontiers in Psychology*, 8, 1974. DOI: https://doi.org/10.3389/fpsyg.2017.01974

Article 3. Cultural Evolution of Sustainable Behaviours: Pro-environmental Tipping Points in an Agent-Based Model

Abstract

To reach sustainability transitions, we must learn to leverage social systems into tipping points, where societies exhibit positive feedback loops in the adoption of sustainable behavioural and cultural traits. However, much less is known about the most efficient ways to reach such transitions, or how self-reinforcing systemic transformations might be instigated through policy. We employ an agent-based model to study the emergence of social tipping points through various feedback loops which have been previously identified to constitute an ecological approach to human behaviour. Our model suggests that even a linear introduction of pro-environmental affordances (action-opportunities) to a social system can have non-linear positive effects on the emergence of collective pro-environmental behaviour patterns. We validate the model against data on the evolution of cycling and driving behaviours in Copenhagen. Our model gives further evidence and justification for policies that make pro-environmental behaviour psychologically salient, easy, and the path of least resistance.

Full citation (Open Access):

Kaaronen, R.O., and N. Strelkovskii. (2020). Cultural Evolution of Sustainable Behaviors: Pro-Environmental Tipping Points in an Agent-Based Model. *One Earth* 2(1), 85–97. DOI: https://doi.org/10.1016/j.oneear.2020.01.003.

Article 4. Mycological Rationality: Heuristics, Perception and Decision-Making in Mushroom Foraging

Abstract

How do mushroom foragers make safe and efficient decisions under high degrees of uncertainty, or deal with the genuine risks of misidentification and poisoning? This article is an inquiry into ecological rationality, heuristics, perception, and decision-making in mushroom foraging. By surveying 894 Finnish mushroom foragers with a total of 22,304 years of foraging experience, this article illustrates how socially learned rules of thumb and heuristics are used in mushroom foraging.

The results illustrate how traditional foraging cultures have evolved precautionary principles to deal with uncertainties and poisonous species, and how foragers leverage both simple heuristics and complex cognitive strategies in their search for, and identification of, mushrooms. Foragers also develop selective attention through experience. The results invite us to consider whether other human foraging cultures might use heuristics similarly, how and why such traditions have culturally evolved, and whether early hunter-gatherers might have used fast and frugal heuristics to deal with uncertainty.

Full citation (Open Access):

Kaaronen, R.O. (2020; In print). Mycological Rationality: Heuristics, Perception and Decision-Making in Mushroom Foraging. Available on PsyArXiv (to appear in the September 2020 issue of Judgment and Decision Making):
https://doi.org/10.31234/osf.io/7g8er

1.3 Synopsis of the Argument

> 'There is only one world, however diverse, and all animals live in it, although we human animals have altered it to suit ourselves. We have done so wastefully, thoughtlessly, and, if we do not mend our ways, fatally.'
>
> James J. Gibson (1979, 130)

We are in midst of a crisis perhaps unmatched by any other in the history of humankind. The list of ecological catastrophes has been repeated so many times that it has all but become a 21st century banality: we're experiencing global heating of a scale unwitnessed before by humans, biodiversity has plummeted with disastrous consequences to ecological systems and networks, and planetary boundaries have been breached in numerous other domains (not all of which are known to us) (Steffen et al. 2015). This is all the consequence of human societies, and the fundamentally unsustainable development of human cultures.

We, as human collectives, have lost our ability to live within planetary boundaries. We have failed in *sustain-ability*. Yes, some, and particularly a select few industries (and nations), hold much higher responsibility for this calamity than others. Yes, there are culprits who have (at least, for now) benefited from this mess—much brilliant investigative work has gone to illustrate this (Taylor and Watts 2019). Yet the crisis is also a collective one, a cultural one. Human societies have lost or lacked in capacities to reinforce sustainable patterns of behaviour, to reinforce sustainable habits, norms and institutions. Many, if not most, human cultures have forgotten, or detached themselves, from our intuitions for dealing with uncertainty, and have also, for now at least, distanced themselves from direct environmental feedback. Cultural systems, not the least in the affluent parts of the world, have forgotten how to sustain. If we wish to offer future generations and non-human species an opportunity at life within reasonable ecological conditions, we must regain our capabilities to live in ways which respect the processes from which we ultimately emerge.

As the title of this thesis suggests, this work includes inquiries into the ecology of mind and behaviour. By the word ecological here, I wish to imply that I focus mainly on theoretical frameworks which interpret human cognition, behaviour and cultures as emergent properties of organism–environment and organism–organism systems. That is, to explain cognitive or behavioural processes, we must understand cognition and behaviour as products of the person (and its cognitive faculties) and the environment. As Kurt Lewin (1936) once wrote, behaviour is a function of the person and the environment. Only by understanding this process of emergence can we attempt to leverage it towards a sustainable direction.

That I chose 'ecological' theories of mind and behaviour to interpret ecological crises seems like a curious coincidence. However, I doubt this truly is coincidental. After all, if we understand human behaviour as emerging from both personal and environmental processes (and that focusing on only one half of this equation is insufficient to explain the whole), the conclusion is inevitably one where current forms of culture and behaviour cannot sustain if environmental processes continue to degrade. James J. Gibson, an influential ecological psychologist, whom I quoted in the epigraph of this section, seemed to have grasped this connection. Although not, to my best knowledge, a vocal advocate of ecological or sustainability concerns, Gibson too seems to have come to the inevitable conclusion that should we understand human societies and behaviours as emerging from organism–environment systems, little will remain if we continue to disregard the environmental half of the whole.

This thesis aims to interpret ongoing sustainability crises from a variety of ecological social scientific perspectives, all of which have not previously engaged in much discussion. Echoing the work of some of the forebearers of ecological approaches to cognition, such as William James (1977), the position I take is inherently pluralistic: there is not a single lens the sustainability crises should be envisaged through, and multiple theoretical frameworks will be more of a necessity than an option when attempting to understand the numerous ways in which humans think and behave unsustainably. Theories are tools to analyse relations between objects or subjects, and since such relations are practically infinite, it is unlikely that one tool will fit all situations. Much like other cognitive mechanisms studied in this thesis (see Article 4 in particular), theories are tools for collectives of human organisms to adapt to their ecological niche, and the availability of multiple theories for selection may be necessary to guide our way through the uncertain environments we now face.

The main title of this thesis is Steps to a Sustainable Mind. It might have as well been Steps to Sustainable Behaviour, or Baby Steps to either of these. The current title was chosen mainly for cosmetic reasons. Commenting on the latter, a bit of epistemological humility is in place. To argue that a single thesis could provide humans with a collective roadmap towards sustainable behaviour would be nonsensical—in fact, owing to the diversity of human cultures, and the diversity of solutions that ensues, such a blueprint most likely does not exist. However, this thesis provides multiple perspectives on how sustainable modes of thought or behaviour might emerge, and in particular, how ways in which we think and behave are related. As the title suggests, a series of steps is suggested:

Step 1. Relocating ourselves in natural processes. We must re-examine the cognitive models by which we conceptualise our relation to natural processes. Although this began as mainly a philosophical endeavour, it eventually found its way into both practice and methodology. If we wish to think or behave in ways which respect ecological boundaries, we must fundamentally shift our understanding to respect the fact that we ourselves emerge from the processes we call by names such as 'ecology', 'environment' or 'climate'.

Step 2. Ecologies of design. Here, I apply insights from and methods influenced by *Step 1* to locating politically feasible leverage points—or, in Donella Meadows' (2008) famous definition, 'places in the system where a small change could lead to large shift' in the system's behaviour—to induce shifts in the ways in which individuals and societies behave. Thus, the target is to reach social tipping points, or *phase transitions*, rapid shifts from one mode of collective being to another.

Step 3. Dealing with uncertainty. Finally, we must learn to apply both traditional and tacit knowledge to gain insights on how to deal with uncertainty, and foster knowledge of sustainable practices through various processes of cultural evolution.

The research articles that constitute this thesis respond to some specific challenges in each of these steps. It is not my intention in this summary to merely rephrase the findings of these research articles. Instead, here, I seek to connect the dots. Some of the articles were not planned to discuss with each other, yet, retrospectively, interesting connections seem to exist. Article 1, *Reframing tacit human–nature relations* (Kaaronen 2018c), sets the ontological and epistemological ramifications for *Step 1*, and its central ideas reverberate—sometimes explicitly, sometimes tacitly—throughout the rest of the thesis. Article 2, *Affording sustainability* (Kaaronen 2017), sets out to tackle *Step 2*, and in doing so, provides the necessary theoretical background for the formal computational model presented in Article 3, *Cultural evolution of sustainable behaviors* (Kaaronen and Strelkovskii 2020). Article 4, *Mycological rationality* (Kaaronen 2020), applies insights from local and traditional knowledge to inform ways of dealing with uncertainty, and illustrates how cultural know-how is born from ecological interactions between organisms and their environments. These are all elaborated below in section 3.

However, before embarking on this task, a brief overview of the theoretical nomenclature and methodology is in place. The purpose of this is not to give a thorough introduction to each theoretical framework, which would be an exhaustive task (and which is done better by others elsewhere), but rather to give an overview of the ways of thinking which led to the four research articles at hand. Attempts are also made to weave these theoretical frameworks together, although as noted below, some conflicts in theoretical assumptions almost inevitably remain.

2 Ecological Approaches to Social Sciences

> 'In psychology one can begin to describe the whole situation [from which behaviour (B) emerges] by roughly distinguishing the person (P) and his environment (E). Every psychological event depends upon the state of the person and at the same time on the environment, although their relative importance is different in different cases. Thus we can state our formula [...] as B = f(P, E). [...] Every scientific psychology must take into account whole situations, i.e., the state of both person and environment. This implies that it is necessary to find methods of representing person and environment in common terms as parts of one situation.'
>
> Kurt Lewin (1936, 12)

This thesis builds upon several ecological theories of human behaviour and cognition. Therefore, to begin with, it is necessary to define what I mean with ecological theories in this context, and what precisely these theoretical frameworks consist of. Even though ecological theories of mind and behaviour have experienced something of a resurgence in recent years—for instance, in the development of dynamical systems approaches (Chemero 2011; M. J. Richardson and Chemero 2014) and so-called 4E (Embodied, Extended, Enactive and Embedded) approaches to cognitive science (Newen, De Bruin, and Gallagher 2018)—these are by no means new ideas.

Tracing back to the origins of psychological science itself, many of the ideas that constitute an ecological approach to behaviour can be found in the pragmatism and radical empiricism of William James (who, in turn, was greatly influenced by Darwin; see Heft 2001; R. D. Richardson 2007). That is, the central insights from pragmatism that meaning should be associated with both function and context, and that to understand the meaning of a thing or an environment we must understand how it *relates* to the observer, are by no means new (Dewey 1958; James 1975). Yet, perhaps a consequence of the cognitive revolution and the computational metaphors that ensued, ecological theories of cognition have been somewhat hibernating.

An ecological approach to human behaviour should deal with what Kurt Lewin (1936) labelled *whole situations.* To understand how dynamical systems of human behaviour emerge from human–environment interactions, we must account for parameters on both sides of the skin (Chemero 2011): personal factors and environmental structures. In Lewin's now famous equation, behaviour (B) is defined as an emergent function (f) of the person (P) and its environment (E), or

$$B = f(P, E).$$

In Article 3, I go to considerable lengths on elaborating on this equation, complementing it with numerous feedback loops, but this much suffices for now. In James' (1912) words, if we wish to explain the human mind and behaviour, we must learn to be 'subjective and objective both at once.' We must account for the (universal) environmental structures that afford a given behaviour, and the faculties and intentions of the observer that actively guide the subject to interact with its environment selectively and in specific ways.

An ecological approach to studying human behaviour thus assumes at least the seven following propositions:

1. Humans are active organisms that develop varying interests, intentionalities and skills, which dispose them to engage with the world with selective attention. All perception is active and a result of movement and interaction in and with the world.
2. All behaviour and cognition is contextual and should be studied in appropriate context. Behaviours, cognitions, meanings et cetera arise from *relations* between the observer and that observed, and context can therefore not be disregarded.
3. The environment is not passive. The environment itself is in constant flux, and reflects various meanings which we can interpret and interact with. We also actively shape the environments we behave in.

4. Human rationality should be understood in ecological context. Rationality itself—if we choose to understand it in terms of functional success in the world—is a product of both the organism and its environment.
5. The focus on studying behaviour should be on *processes*. If we wish to understand behaviour—and even more so if we wish to affect it by means of interventions—the relevant targets of study are the complex dynamical processes by which behaviours emerge, which include not only intentional, but also environmental and social processes.
6. No behaviour is free from causal mechanisms that extend far to (and beyond) the social and material world they are embedded in. All definitions of systems boundaries should be understood as pragmatic choices, although some make more sense than others.
7. The study of human behaviour should be systemic and focus on nested levels and feedback loops. Collective sets of human behaviours create environments and institutions that, in turn, define the state space of possible human behaviours within that system. In Bateson's (2000) terms, 'the river molds the banks and the banks guide the river'.

In the following sections I discuss briefly the main theoretical frameworks and methods used in the research articles that form this thesis.

2.1 Ecological Psychology and Affordance Theory

Ecological psychology (not to be confused with either *environmental psychology* or *ecopsychology*) is a psychological scientific study of perception-action. Broadly speaking, ecological psychologists—originating mainly with the work of James J. Gibson (1979; 1966)—assert that perception and action should always be studied in tandem. There is no such thing as a passive human observer, and the baseline for studying human behaviour should assume humans to be active agents exploring the material world that they inhabit. Moreover, ecological psychology posits—explaining its curious name, and partly following from William James' radical empiricism

(Heft 2001)—that the world is not meaningless for the active perceiver. Instead, by moving about in the environment, an organism is capable of harvesting and interpreting *ecological information*, the sets of structures and regularities in our environments, such as patterns of light or sound reflected by the physical environment, that allow us to engage and interact with our environments. In other words, the ecological niche we inhabit is permeated with potentialities for interpretation and meaning. By actively moving about in this environment, and interpreting the statistical regularities and information within it, organisms need not create meaning 'inside their heads', but are able to actively encounter the world and experience it directly (Reed 1996). Meanings thus arise from organism–environment relations.

Much debate has gone into discussing how far this direct perception can be taken (Chemero 2011). That is, how much of human cognition can be explained merely through studying our active interaction with the information afforded by the physical environment without resorting to explanations relying on cognitive processing or mental representations? Although this is an interesting and lively (and, at times, heated) debate, I shall not engage in this debate in detail within the scope of the summary of this thesis, since, for one, detailed accounts exist elsewhere (e.g., Chemero 2011; Golonka and Wilson 2019), and second, this discussion is not necessarily directly pertinent to the research questions at hand.

For present purposes, however, I assume a position that is, at the least, heavily influenced by ecological psychology. If we wish to explain the emergence of human behaviour, we must take into central account the structure of the material (and social) environment and the ecological information within our ecological niche. For this purpose, a specific aspect of ecological psychology, *affordance theory*, deserves further focus. Acknowledging that varying definitions of *affordances* exist (and that the definition of affordances is itself subject to vehement debate[1]), affordances are here defined as relations between abilities to perceive and act and features of the environment (Chemero 2003; 2011). More specifically, in a forthcoming article (Satchell, Kaaronen, and Latzman 2020), we define an affordance as a bundle of ecological information sufficiently rich enough to offer behaviours for a perceiver. Affordances are thus the functional meanings of environments for an organism and are specified by the ecological information available in an ecological niche. In its association of meaning with function, affordance theory bears considerable resemblance to the philosophical tradition of pragmatism: the meaning of an environment or object is the function that it affords.

Thus, our environments consist of not merely passive objects to be acted upon, but instead objects and environments actively specify action-opportunities for the observer. The environment is imbued with meaning available for the observer. When humans, a bipedal and mobile species, perceive a chair, for instance, we do not merely observe a passive object, but an opportunity for sitting (Heft 2001). The chair *affords* sitting. Thus, affordance theory is an attempt at overcoming the subject–object dichotomy in psychology by studying the *relations* between the perceiver and that perceived. Note that this does imply that perceivers have (socially and individually learned) skills and bodily capabilities: a bicycle will only afford cycling successfully for those who are able to cycle. Importantly, the concept of the affordance invites focus on the whole dynamical situation from which behaviour emerges, the reciprocity between organism and environment.

Affordances were originally conceived in the field of ecological psychology, where Gibson (1979) and others used the concept to emphasize the functional significance of perception and perceived ecological information. 'The affordances of the environment', writes Gibson (1979, p. 127) in a

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[1] John Dewey (1958, 47) writes, I believe correctly, that philosophical feuds tend to be 'family quarrels', and that the most heated debates are often between those who *almost, but not quite,* agree with each other. Dewey continues: these feuds 'go on within the limits of a too domestic circle' and are best settled 'by venturing out of doors'. Even though I risk omitting some important debates, I choose not to engage here in these terminological debates in order to move 'out of doors' with my core argument.

famous passage, 'are what it offers the animal, what it provides or furnishes, either for good or ill.' The concept of the 'affordance' derives from earlier work in Gestalt, phenomenological and behaviour field psychology, with the neologism explicitly borrowed from Kurt Lewin's '*Aufforderungscharakter*' or 'valence' (Käufer and Chemero 2015, 88–89). Therefore, the similarities between affordances and Lewin's (1936) 'whole situations' are also non-coincidental.

Whilst Gibson (1979) did not exclude 'social affordances' from his original treatment, they received merely a very brief mention and only recently have the notions of social or cultural affordances—the affordances provided by social interactions and culturally designed environments—reached broader popularity (Costall 1995; Ramstead, Veissière, and Kirmayer 2016). More recently, affordance theory has also found interest in broader studies of human–environment relations, including (among other things) design (Norman 2013), architecture (Rietveld and Brouwers 2017), embodied cognitive science (Chemero 2003), child behaviour (Kyttä 2004, Heft, 1988), urban design (Marcus, Giusti, and Barthel 2016) as well as cognitive anthropology (Ramstead, Veissière, and Kirmayer 2016). My research, in turn, has emphasized the role of the intentional design of affordances as a 'leverage point' for sustainable system transitions (Kaaronen 2017; Kaaronen and Strelkovskii 2020; 2019).

Common to these approaches is the underlying assumption that it is insufficient to restrict a study of human behaviour, on the one hand, to environmental *form* (Heft and Kyttä 2006), and on the other, to mental or cognitive representations (Chemero 2011). Instead, behaviour is understood to emerge from a non-decomposable dynamic brain-body-world system (i.e., one which also evolves over time). Environmental form is thereby understood as a part of this ecological behaviour system which solicits, invites or *affords* certain behaviour for an individual organism embedded in the enculturated 'form of life' of a human society (Rietveld and Kiverstein 2014).

Interpreting our everyday environments from this ecological perspective, we are better equipped to study critically the 'psychology of everyday things' (Norman 2013)—the meanings and functions afforded to us, often unconsciously, by our everyday material environments. Moreover, these meanings and functions are not isolate entities, but are together embedded in the societies and institutions that so thoroughly shape our behaviour. In Rietveld and Kiverstein's (2014) terms, we inhabit a 'rich landscape of affordances', where a landscape of affordances refers to the totality of action opportunities in our environment. As skilled and active perceivers, our material and cultural environments afford for us a rich variety of potential behaviours, and if we wish to understand why we behave in ways which we do, these opportunities for behaviour, these affordances, deserve critical inspection. This latter notion, in particular, is a focal point of this thesis.

2.2 Cultural Evolution: Niche Construction and Social Learning

Affordance theory is a very promising basis for studying the emergence of (sustainable) behaviours, but somewhat notoriously has lacked in at least two respects. Firstly, although attempts at defining 'social' or 'cultural' affordances have been numerous and, at times, promising (Ramstead, Veissière, and Kirmayer 2016; Costall 1995), affordance theory and ecological psychology have traditionally lacked in accounting for the social dimension of humans. Yet in explaining behaviour we must also explain the processes through which humans learn their skills for perception and action, forming traditions, norms and institutions through processes of cultural transmission and social learning. Second, although ecological psychologists have documented in detail how physical environments afford behaviours to humans—which, famously, include studies on how we perform everyday activities such as stair climbing (Warren 1984)—they have paid less attention on the processes by which humans culturally *construct* the environments which afford behaviours (although, again, notable exceptions do exist, such as in Reed's (1996) work, which documents how humans create clusters of affordances, forming 'fields of promoted action' in the process). I envisage an ecological theory of social science and psychology where these frameworks could be in fruitful discussion which each other, and have already embarked upon doing so particularly in Article 3, although much work remains to be done.

The scientific field of cultural evolution, broadly, deals with applying Darwinian evolutionary theory to the sociocultural domain. It is therefore an evolutionary theory of social change, and primarily seeks to explain how cultural traits spread in societies vertically (from one or both parents), obliquely (from unrelated elders), and horizontally (within generations) (Mesoudi 2011). Culture, in this context, can be defined as 'information that is acquired from other individuals via social transmission mechanisms' (Mesoudi 2011, 2–3). Ecological information, which we encountered in the previous section, would also often fall under this category, at least in cases when it is reflected by cultural infrastructures or artefacts; affordances of this kind are sometimes referred to as 'cultural affordances' (Ramstead, Veissière, and Kirmayer 2016). The reader is referred to general works on the topic such as Mesoudi (2011) or Laland (2018) for more comprehensive discussion on cultural evolution. For present purposes, I shall discuss merely two presently important drivers of cultural evolution: social learning and (cultural) niche construction.

A feature which sets humans perhaps most apart from other species is our capacity for social learning and cultural development (Laland 2018; Henrich 2015). Therefore, any ecological attempt at explaining human behaviour must also account for the social organism–organism and organism–environment interactions which so thoroughly define our collective emergent behaviour patterns. Social learning refers to processes where learning patterns are 'facilitated by observation of, or interaction with, another individual or its products' (Hoppitt and Laland 2013). The notion that 'products' of human behaviour are included in this definition is important: we do not only learn from each other, but learning (and any consequent behaviour) is also facilitated by engaging with environments and artefacts which other humans have designed.

Although claiming this much would come naturally to most social scientists, the precise definition of the processes and patterns of social learning and cultural transmission are nontrivial endeavours which form much of the basis for studies on cultural evolution (Laland 2018; Hoppitt and Laland

2013). Indeed, much of the variation in behavioural patterns between societies can be explained by processes of cultural transmission (Mesoudi 2011, 15), and a grasp on how social and cultural networks operate is crucial in understanding how societies behave. For the context of the present purposes, it suffices to say that any study of *whole situations* of human behaviour, or any study which seeks to explain how human behaviours emerge ecologically from organism–organism and organism–environment interactions, must first explain how a behavioural trait is influenced by social and cultural circumstances. This is returned to in much detail particularly in Article 3.

As suggested above, humans (and, indeed, other animals) do not only encounter affordances in their ecological niche, but actively construct and *design* the affordances within their niche, thus imposing directional non-random pressures on the selection of any future behaviours. The process by which this occurs is called *cultural niche construction* (Laland 2018), another concept which deserves more specific focus.

Whilst Charles Darwin is most popularly appreciated as the father of the theory of evolution by natural selection, he also had an affinity for studying niche construction, even though he was not wholly able at the time to explicate this conceptually. In his experimental studies on earthworms (Darwin 1892), some of his final work, Darwin noticed that earthworms, 'through their burrowing activities […] change both the structure and chemistry of soils,' which results the alteration of selection pressures within their niche (Odling-Smee, Laland, and Feldman 1996). Although these ideas gained initial popularity, they seemed to escape later mainstream attention, and have only been revived *en masse* since the late 20th century, when several thinkers have made the case for accepting niche construction as a bona fide evolutionary force (Constant Axel et al. 2018; Odling-Smee, Laland, and Feldman 2003; Laland 2018). Hereby niche construction is taken to refer explicitly to the process involving the modification of selective environments by organisms. In other words, according to niche construction theory, organisms are not only objects of natural selection but also active designers of the conditions for natural selection. As a consequent, adaptive fitness is no longer understood as organisms merely adapting to their environment, but rather as a 'two-way process' involving organisms both responding to challenges presented by their environments, as well as creating new opportunities and challenges by altering their environments through niche construction (Laland and O'Brien 2011, 193).

It is perhaps not surprising that ever since niche construction gained mainstream attention, it has been widely studied in various species, particularly those which are most active at modulating their ecological niches, such as ants, wasps, spiders and beavers (Laland and O'Brien 2011). Contrasting with the conventional perspective of natural selection, which takes an asymmetrical approach to organismic adaptation (organisms adapt to the environment), niche construction theory puts symmetrical emphasis on the capacity of organisms to modify environmental states and thus selective pressures (Laland and O'Brien 2011). *Cultural niche construction*, which pertains particularly to cultural and behavioural selection, is a particularly relevant concept here. Broadly speaking, cultural niche construction refers to the process where an organism modifies environmental states in non-random ways (i.e., culturally) and thus imposes systematic biases on the behavioural and cultural selection pressures generated by the environment (Laland 2018). Notably, this effect is also transgenerational. The design of cultural niches defines not only the selective pressures of current generations, but also alters the 'ecological inheritance' of subsequent generations (and thus the ecological information they encounter).

In this regard, it is perhaps even less surprising that the niche constructive behaviour of the ultimate 'ecosystem engineer,' *homo sapiens*, has sparked inquiries in archaeology, biological anthropology and psychology. Humans, after all, live in 'designer niches,' where we construct our ecological niche—our homes[2] and everyday (urban) environments—to afford the perceptions and experiences we cognitively expect and socially strive for (Clark 2015).

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[2] In fact, this idea of niche construction as retrofitting our home has a quite literal connection to the etymology of the word 'niche' itself. Deriving from the Latin nīdus ('nest'), niche construction indeed is the process of reconstructing our nest or home.

In the social sciences, this idea of self-induced feedback can be traced at least to the cyberneticians, who, fronted by the likes of Norbert Wiener and Gregory Bateson, emphasized the ecological dimensions of human existence. Here, cultural development was best described by an analogy: 'the river molds the banks and the banks guide the river' (Bateson 2000, 83). I argue in this thesis, and particularly in Articles 2 and 3, that these biases are transmitted in particular through the conscious and unconscious design of affordances—note that similar arguments have previously been made by Reed (1996) in particular.

In an essay for the independent philosophical journal *The Side View,* I call this process the 'Ecology of Design' (Kaaronen 2019c). By designing and redesigning our everyday environments, we have the potential to tap into curious feedback loops, where 'design breeds affordances, affordances breed behaviours, behaviours breed ideas, and ideas breed design.' As discussed later, in Article 3 I go on to formally define this process and the emergent phenomena that ensue with an agent-based model.

2.3 Ecological Rationality

When analysed from an ecological perspective, that is, as a function of a person and their environment, even our definition of rationality can (and arguably, should) be redefined. In the following section, I discuss in brief the notion of ecological rationality. More comprehensive introductory accounts can be found in, e.g., Todd and Gigerenzer (2012) and Marewski et al. (2010).

Ecological rationality stems from polymath Herbert A. Simon's work, who from the 1950s emphasised that the capacity of human decision-making is necessarily bounded by uncertainty, cognitive limitations and the time and resources available at the moment of decision-making (Simon 1957; Callebaut 2007). Decision-making, and thus rationality, is necessarily *bounded*, and consequently, humans are *satisficers* who, for reasons of efficiency—and surprisingly, sometimes also accuracy—use varieties of cognitive shortcuts to make decisions.

Ecological rationality builds upon Simon's work, and, much like ecological psychology (although the field of ecological psychology rarely deals explicitly with decision-making processes), has an ambition of putting the human subject back into their ecological context. In ecological context, proponents of ecological rationality argue, rational decision-making and behaviour should be understood in terms of cognitive success in the world: the fitness between the mind and the environment (Kozyreva and Hertwig 2019; Gigerenzer and Todd 1999; Todd and Brighton 2016).

However, the study of ecological rationality goes far beyond this descriptive statement, and seeks to explain the processes through which, by leveraging ecologically valid cues in the environment (i.e., reliable statistical regularities), decision-makers are able to circumvent complex optimisation processes and, instead, use simple and efficient 'fast and frugal' heuristics when making decisions. Sometimes, as is discussed in more detail in Article 4, these simple decision-making rules can even systematically outperform more complex cognitive (or statistical) processes. Thus, ecological rationality seeks 'to explicate the mind–world interactions underlying good decision making' (Todd and Gigerenzer 2007, 167).

Heuristics are adaptive cognitive tools, and are particularly sensitive to context. Therefore, it comes as little surprise that local processes of cultural evolution (and cultural selection) can lead to the development of particularly robust heuristics. However, this connection between cultural evolution and heuristics is a less charted one. In Article 4, I contribute to this topic by describing how a traditional foraging society, Finnish mushroom foragers, uses culturally evolved heuristics to adapt to their local uncertain environment. Foragers, Article 4 argues, use socially learned rules of thumb to make robust and safe decisions at the face of uncertainty, and need not bother much with utility calculations (or other optimisation processes) when making efficient decisions. An efficient heuristic is not a general-purpose algorithm, but rather a contextual one, and as illustrated in Article 4, heuristics can be a product of long-term local cultural evolution and traditional knowledge.

Much unlike our risk- and probability-obsessed world, ecological rationality deals primarily with *uncertainty* and uncertain complex systems. Unlike the hypothetical creature *homo economicus*, the real-world human (or homo heuristicus, as per Gigerenzer and Brighton 2009) does not live in a world where decisions can be fully optimised or where probabilities and utility functions can be optimally calculated. As Simon (1957) has noted, three modes of uncertainty in particular impose limits on optimisation. Firstly, due to temporal constraints and limited individual histories, humans can only account for select alternatives when making a decision—it is rarely the case that all options are known to the perceiver. Second, the state space of possible events is unknown. Simply, as is illustrated with the case of mushroom foraging in Article 4, knowledge about the consequences that would follow from each alternative choice are not directly available to the human. These consequences might include unanticipated ones, which in the case of mushroom foraging, include extreme events such as death, which further complicates calculations of costs or benefits. Third, real world environments are unforgivably complex, and even with high degrees of knowledge, the optimal solution may be practically intractable (Kozyreva and Hertwig 2019).

Thus, it follows that 'the laws of logic and probability are neither necessary nor sufficient for rational behavior in the real world' (Gigerenzer 2008). Or, as Egon Brunswik (1955, 1) eloquently writes, 'the crucial point is that while God may not gamble, animals and humans do, and that they cannot help but to gamble in an ecology that is of essence only partly accessible to their foresight'. Uncertainty is therefore an unavoidable feature of a real-world organism–environment system, and thus any real-world—or *ecological*—rationality must find robust methods to deal with this uncertainty.

Such methods, proponents of ecological rationality argue, include heuristics: simple strategies that ignore information as much as they make use of it (Marweski et al., 2010). This 'selective industry of the mind' (James 1890)—or selective attention—has a long history in the study of psychology. In the context of heuristics, selective ignorance can protect us from overfitting our cognitive models, that is, avoid tuning our decision-making models so precisely to past data that our adaptability to an uncertain future is endangered. Sometimes, simplicity might be key to robustness and resilience, and it might be better to be systematically biased than attempting to be optimal. This theme is discussed in detail in Article 4.

Echoing other mutualistic ecological theories of mind and behaviour, such as ecological psychology, Herbert Simon (1990, 7) used his famous scissor analogy: 'Human rational behaviour is shaped by a scissors whose blades are the structure of task environments and the computational capabilities of the actor.' That said, there are clear theoretical tensions here between the anti-computationalism of ecological psychologists and the computational metaphors preferred by proponents of ecological rationality who, e.g., speak of 'algorithms' used for decision-making. Attempts at reconciling these two theoretical frameworks do exist, but are unfortunately uncommon; e.g., Carvalho and Rolla (2019) suggest that perceptual learning and skilled engagement with affordances themselves (as studied by ecological psychologists) are processes for minimising uncertainty, an idea which resonates strongly with research in ecological rationality. At the least, notwithstanding the debate on computationalism, both theories explicitly study successful action in the world as a product of organism–environment mutualism.

The study in Article 4 can be interpreted as a preliminary attempt at reconciling these two theoretical frameworks, with its focus on skilled, selective and active perception (as so often studied by ecological psychologists) and 'fast and frugal' cognitive decision-making processes (as studied traditionally by ecological rationalists). However, the two approaches may be reconciled also by adopting less extreme positions on either end. For instance, the empirical data in Article 4 suggest that heuristic decision-making might rarely be as 'algorithmic' as some ecological rationalists suggest: decision-making processes in messy real-world contexts such as mushroom foraging seem to less commonly resemble clear-cut 'algorithmic' processes, and foragers rather actively inspect multiple sensory cues (ecological information) and use of various forms of expertise, (culturally evolved) traditional knowledge, simple heuristics and intuitions to guide their practice. Reality is often messier than theoretical frameworks, and, once again, a plurality of lenses to view socio-ecological phenomena might be more of a richness than a hindrance.

2.4 Modelling Ecologies of Behaviour

Above, I have advanced the idea that ecological social sciences should deal with the mutualistic relations between organisms and their environments, and that this mutualism should be a starting point in our studies on human behaviour, culture, cognition, and decision-making. Thus, it is quite appropriate to point out methodologies that are explicitly mutualistic, and which focus specifically on modelling complex engagements between agents and their environments. I am speaking, of course, of *agent-based modelling*, the methodological approach taken in Article 3.

Agent-based models, a class of computational models, are used to model agent–agent and agent–environment interactions, usually with a particular focus on the evolution of such systems over time (Railsback and Grimm 2019; Wilensky and Rand 2015). Agent-based models are particularly useful for modelling dynamical systems which include heterogeneous populations and emergent collective behaviour patterns arising from relatively simple interactions (Grimm et al. 2005). Agent-based modelling has become a standard method for studying complex, dynamical and adaptive systems, with a specific focus on studying the evolution of such systems *as a whole*. Whilst many if not most statistical methodologies aim to *reduce* systems to study them (by, e.g., controlling and isolating variables), the aim of agent-based modelling is to understand systems by *growing* them. This is often done by the pattern-oriented approach, modelling patterns at various hierarchical levels, ranging from cognitive, individual to social and ecological dimensions (Grimm et al. 2005). The consequent form of research, generative explanation, is summarised by the following quote accredited to Joshua M. Epstein: 'if you haven't grown it, you haven't explained it'—although I am perhaps less adamant about this, as I discuss below.

At the time when Kurt Lewin (1936) defined his famous equation for studying 'whole situations', B = f(P,E) (recall section 2), it is unlikely that he had even an inkling that a methodology so well-suited for studying his idea would emerge in the future. Whilst Lewin dwelled on the lack of methods suitable for studying 'whole situations', we are now arguably equipped with much better facilities for studying the functions between persons and environments. As user-friendly and accessible software for agent-based modelling, such as NetLogo (Wilensky 2010), have emerged, so has the interest grown in studying complex and emergent patterns of socio-environmental interactions by means of computational modelling.

This should not, of course, come without critical introspection. Firstly, formal definitions of real-world processes—and, to be clear, formal definitions and logical operators are precisely what agent-based models 'eat'—are often either too 'poorly defined or nebulous' (Wilensky and Rand 2015) to be modelled formally, or simply too complex to be defined by algorithms to begin with (Kauffman 2019). It is often distasteful to formally define complex social patterns by simple lines of code, but, again, I wish to emphasise a pragmatic notion here. Studying and gaining data of complex social phenomena in the real-world is a tricky business. Firstly, the numerous feedback loops which define, for instance, the assumptions of Article 3, would be nigh impossible to study with any traditional empirical methodology. Data are, simply, too noisy and complex to interpret, and more than often we lack sufficient means to guard our system of interest from external influences (and indeed, studying the effects of these external influences might itself be interesting—and is possible with agent-based models!). Moreover, studying a complex system in the real-world almost necessary means studying its component parts separately. Yet what makes complex systems so interesting are their emergent properties when their components interact.

Second, when we study real-world complex processes, we only have access to one *unique event* in world history. As Karl Popper noted in *The Poverty of Historicism* (Popper 1957), unique events are not sufficient to make reliable inductive inferences or predictions. Agent-based modelling, on the other hand, gives us the opportunity to play a divine creator and simulate a practical infinitude of alternative scenarios, generating rich amounts of data that would otherwise be impossible to collect (Epstein 2008). At the least, this spares us much of the burden of dealing with small datasets and often unreliable statistical methodology. Another caveat on prediction is in place here: agent-based models deal primarily with complex systems, and as we know from decades of studies with complex systems and social systems in particular, these systems are particularly sensitive to initial conditions[3] and unforeseeable (cultural) evolutionary mechanisms, and are thus inherently unpredictable in the long run (Kauffman 2019; Mitchell 2009). For this reason, I typically assume scenarios represent some possible states of the studied system, but I dare not claim they afford us with predictions.

Finally, relying merely on verbal models, such as those provided in Articles 1 and 2, is insufficient if we really want to put our theory to test. This is where the joy of building comes in. How can we be sure that we haven't omitted any crucial functions or phenomena unless we can see familiar and concrete results emerging from our assumptions? How do we know we have defined a system's crucial components if we have not built it ourselves? How do we know what parameters or initial conditions the model described verbally is particularly sensitive to? Personally, I learned this the hard way. When formalising the processes defined verbally in Article 2, for instance, I noticed numerous factors I had formerly disregarded: one such case is the role of the structure of social networks in the social transmission of sustainable behaviours. However, more on this later (and particularly in the lengthy Supplementary information of Article 3).

I therefore tend to give slack to the incompleteness of formal models; incomplete and sometimes stupid, yes, but certainly not impractical. As Smaldino (2017) writes, 'models are stupid, and we

[3] Sensitivity to initial conditions, a feature of chaotic systems, simply means that an arbitrarily small change in the initial parameters of a phenomenon can lead to fundamentally different future behavior. This, particularly, renders complex and chaotic systems—to which basically all social systems belong—unpredictable.

need more of them'. I personally value agent-based models as extremely useful tools to think with, and view the process of modelling itself as a philosophical conversation with code and model output. In fact, I have come to regard agent-based models as thought experiments on steroids. Thinking out how social or socio-ecological processes might evolve is all fine, but putting these ideas to the test isn't possible without formally defining their assumptions. I noticed that agent-based modelling is not only hard manual work (with all the coding, protocols, sensitivity testing and whatnot), but also an intellectual and theoretical challenge: never before have I had to lay out my theoretical assumptions so thoroughly in public.

Figure 2. Much like photography: a pattern-oriented approach to modelling focuses on describing and discovering patterns on a variety of scales, alternating focus between the macro and the micro. What looks like disorder on one level (above) may give rise to order on another (below).

3 Steps to a Sustainable Mind

> ‘It is often neglected that the words animal and environment make an inseparable pair. Each term implies the other. No animal could exist without an environment surrounding it. Equally although not so obvious, an environment implies an animal (or at least an organism) to be surrounded.’
>
> James J. Gibson (1979, 4)

Bruno Latour, in his work *We Have Never Been Modern* (Latour 2012), contemplates on a conundrum we often face when discussing human–nature relations: if nature is to be understood as constructed by humans, it appears as artificial—plastic, lawless, fabricated, or counterfeit. Yet if it is not, nature appears as remote, foreign and hostile. But what if this distinction itself is a false one? What if, as Latour puts it, ‘we have never been modern’, or never truly lived in an ecosystem where humans should be analytically separated from their natural environment? It is this last conviction the theoretical framework of this dissertation builds upon; a framework where ecological niches are both constructed by humans, and where human activities, collective and individual, emerge from ecological processes. As Gibson writes above, no organism can exist without its environment—but environments are also defined and shaped by organisms, and indeed the word ‘environment’ itself suggests some perceiver, centre for observation, to be environed. This dynamical and mutualistic framework is what I will elaborate below in the form of *ecological constructionism*, the study of how behaviours and cultures are ecologically constructed, as emergent products of organism–environment relations.

I will begin this task in section 3.1 by uncovering the ontological premises of ecological constructionism in the form of a process-relational metaphysics. Here I summarise the key ideas presented in Article 1 and draw connections to my other research where appropriate. In section 3.2 I extend the theoretical framework to ecological psychology and niche construction theory, discussing in more detail how this applies to the emergence of collective sustainable behaviour patterns, drawing particularly from the work in Articles 2 and 3. In section 3.3, in turn, I elaborate on relational theories on decision-making, with a particular focus on survival under uncertainty and Article 4.

3.1 Step 1: Relocating Ourselves in Natural Processes

> 'Nature considered *rationally*—that is to say, submitted to the process of thought—is a unity in diversity of phenomena; a harmony, blending together all created things, however dissimilar in form and attributes; one great whole animated by the breath of life. The most important result of a rational inquiry into nature is therefore to establish the unity and harmony of this stupendous mass of force and matter, [...] and to analyse the individual parts of natural phenomena without succumbing beneath the weight of the whole.' Alexander von Humboldt (1856)

We begin with a metaphysical move—one which is spelled out in detail particularly in Article 1, but which ultimately resonates throughout all articles within this dissertation. This is the assumption of a process-relational, or process philosophical, stance to studying human–nature relations and socio-ecological systems (Rescher 1996; 2000; Whitehead 1957; Mesle 2008). The crux of the argument is this: as long as we categorise, conceptualise or demarcate human systems separately from the natural processes that afford their becoming, we are more or less bound to make decisions and actions which undermine the process of adaptive human emergence from and within natural systems.

As an 'environmental social scientist' (a concept I quite dislike, owing to reasons already discussed above) and as a person who is somewhat vocal in discussing ecological concerns in the public domain, it is quite often that I hear remarks such as that I am 'concerned about the environment', as if this was just one political cause of many to identify with or be worried about. But the position advanced in this thesis, I hope, should clear the air: it is not the 'environment' I am concerned about per se, but the current interplay between complex social, ecological and climatic systems, which will without a doubt lead to wildly unexpected consequences if the deeply disturbing status quo is maintained. And it is not the 'environment', as some external entity, that should be our concern, but the potential collapse of the life support systems that enable the existence of human cultures and non-human life forms to begin with. We desperately need alternative ways to conceptualise our relation to and emergence from natural systems, and Article 1 is an attempt at outlining one potential approach. I acknowledge that I am not the first to suggest such a position. For instance, recently, Jeremy Lent (2017) has developed a convincing argument that the root metaphors that cultures use to construct meaning in their world have longstanding effects on how cultures deal with their natural (and social or political) environments. However, paraphrasing an old adage, repetition—in different forms and contexts—is key to cultural learning.

The core argument is this: to develop collectively sustainable states of mind, we must take a relational stance. This relational stance, or process philosophical position, is defined in detail in Article 1, but is also at the least tacitly present in the relational theories used in Articles 2, 3 and 4 (affordance theory, ecological psychology and ecological rationality), and thoroughly influences the methodological approach in Article 3—agent-based modelling, after all, deals particularly with modelling complex emergent processes arising from agent-environment relations.

Descriptions of process philosophy, primarily a metaphysical approach with particular similarities to (and influences from) the American tradition of pragmatism (Dewey 1958; James 1975), often begin by quoting pre-Socratic philosopher Heraclitus' famous teaching that 'everything changes' or 'everything flows' (*panta rhei*). Whilst many strains of process philosophy exist—some insist on near-literal interpretations of the sometimes esoteric work of Alfred North Whitehead, whilst others, such as Nicholas Rescher (2000; 1996), adopt a more pragmatist approach—the commonality between process philosophical theories is the focus on the ontological or epistemological primacy of *process* over *substance*. My personal taste for process philosophy is mainly influenced by Rescher (1996; 2000), whose pragmatist approach I also find the most practical from the various process philosophies. Here, *things* are what they *do*, and cannot, and arguably should not, be defined otherwise. In this approach, processes, captured by words such as flux, dynamics, change, action, movement, temporality and other 'items better indicated by verbs than by nouns', are taken to be the primary units of interest in both philosophical and scientific inquiry (Rescher 2000, 4).

This involves primarily the study of how 'things' *become*, how they are connected, and how they emerge from (and relative to) larger macroprosesses or smaller microprosesses. At times, this might involve the blurring of the traditionally accepted boundaries of things—as is illustrated in Article 1 with the case of the coastline paradox—and at others, it involves pragmatic choice and agency in defining systems boundaries for some particular practical purpose. Processes, by their fundamental nature, are causally incomplete (Rockwell 2016): unlike traditional 'objects' or 'things', they, or rather their emergence from interconnected systems, can be traced in back in time and out in space, to the point where this can become rather cumbersome. As Humboldt, an early advocate of wholistic science, observed (see quote above), the whole can quickly become too heavy to study rigorously. Therefore, assuming a process-relational philosophy also implies embracing what Amartya Sen (1992) has called 'pragmatic incompleteness': learning to define systems boundaries in ways which are particularly useful for some specific function.

Affordance theory presents us with one such pragmatic boundary. In focusing the target of our study from human 'individuals' or 'societies' to studying the relations between abilities to perceive and act and features of the environment (Chemero 2011), behavioural scientists—and as I argue in Article 2, even policy-makers and designers—are provided with a more wholistic (recall Lewin's *whole situations*) approach to studying how behaviours actively emerge in the process of human–environment interaction. In this framework, the focus is specifically on flux, movement, change and activity: human behaviour is assumed to arise from actively moving about in the world, altering the perceptual environment we behave in, and the unit of interest is the organism–environment relation, the affordance.

That ecological psychology and affordance theory (Gibson 1979; Gibson 1966) go so well hand-in-hand with process-relational metaphysics and epistemologies is no coincidence. As Harry Heft (2001) has masterfully illustrated, the history of ecological psychology can be traced in particular to William James' work, who in turn is often described as a process philosopher (and, of course, pragmatist) and who had a particularly direct influence on the most famous of process philosophers, Alfred North Whitehead (preface in Whitehead 1957; Rescher 1996; 2000).

Although discussion on process philosophy is most often found in speculative metaphysics, somewhat detached from real-world concerns or applications (although welcome exceptions do exist[4]), the process-relational dimension of this thesis is put to practice. For instance, in Article 4, the focus of inquiry is on the processes of how human foragers actively move about and make decisions in uncertain real-world environments, and particularly, how they make *relational* decisions by utilising various environmental cues. In Article 3, the focus is on modelling the multiple processes (five major feedback loops, to be precise) that arguably precede the collective adoption of sustainable behaviour patterns. These are all relational approaches, with a specific focus on studying the *processes* through which human behaviour, and particularly sustainable behaviour patterns, emerge from organism–environment interactions.

3.2 Step 2: Ecologies of Design

Any theory of human behaviour or cognition will come unfortunately short if it cannot account for how humans behave in and design their most common niche today—the City. Today, over half of the world's population live in urban areas or cities, with this number expected to rise to two

[4] See, e.g., the work of Arran Gare (1996).

thirds by 2050. If we truly wish to change human behaviour to become more sustainable, regenerational instead of degenerational, we must understand how humans interact with the city and how they design the functions it affords.

Now, begin with imagining a typical walk in an urban environment—perhaps your home city, or a global metropolis. What does the city invite you to do? What kinds of behaviours does it primarily solicit? What are the functional meanings of its form? What kind of information do you encounter, and what are the action opportunities it specifies? These are all questions pertaining to the perceptual ecology of the city, or the study of how we encounter the urban niches we construct.

Evidently, the answers to the above questions mostly include activities revolving around consumption or transport. Thus, the prime activity a 21st century city solicits, it seems, is consumption of some sort. As cities grow denser and denser, these urban consumption arenas grow in density and in height, until little of the cities historical or organic form remains. Instead, what we encounter is a mechanistic Global Mall tuned for ecological destruction, a fundamentally unsustainable playground for encountering and consuming, next to life's necessities, things we don't need, things which harm us and destroy the ecological systems which, for now, keep the cogs of society turning. We have designed our local ecological niche to suit ourselves, to respond to our culture and to reinforce it—but as James J. Gibson (1979, 130) writes, we have done so wastefully and thoughtlessly, and perhaps fatally. And so, we have lost our sustain-ability, our cultural skill to maintain our local and global ecosystems at a sustained state.

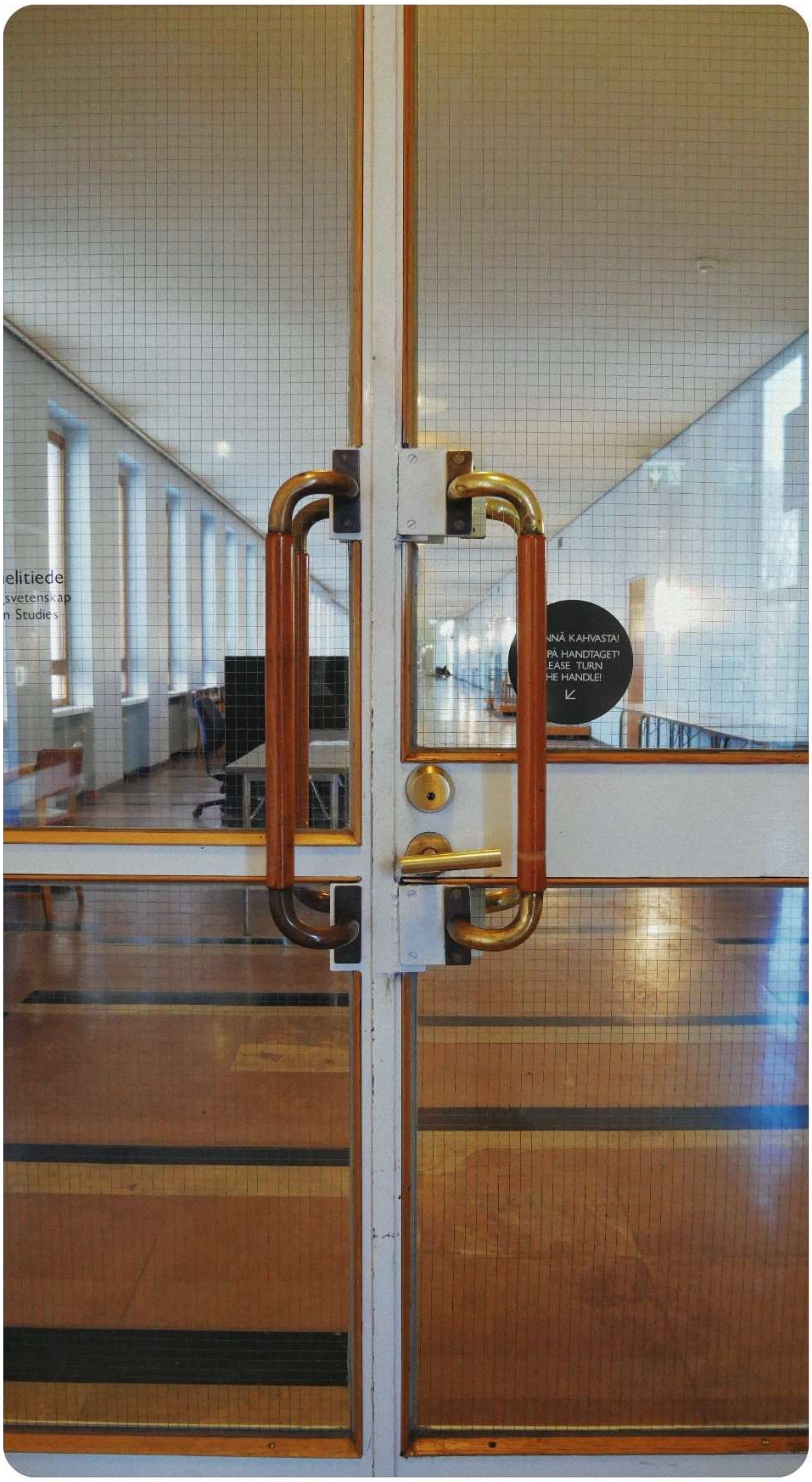
Generally, I like to open my presentations of affordances and urban landscapes with the following analogy (I have previously written about this in both Finnish[5] and English[6]). Close to my university department lies the Metsätalo building, which (ironically, as we will later see) represents the architectural principle of functionalism. One day during the first year of my PhD, I was organising

[5] Kaaronen (2019a): https://wiseproject.fi/kestavyyskriisi-on-myos-suunnittelukriisi/
[6] Kaaronen (2018d): https://www.theconventions.com/articles/society/the-ecology-of-ecological-behavior

an event in the third-floor hallway, sitting at the reception desk by the entrance. To my amusement, many, if not most, of the guests were incapable of entering through the door. First, they tugged the large vertical handle on the door. Then they repeated this in frustration. Finally, after a contagious moment of embarrassment, they slowed down, read the politely imperative instructions by the door handle ('↙ PLEASE TURN THE HANDLE! ', in *three languages* and *capital letters*, just to be clear!), and finally twisted the smaller horizontal handle behind the large vertical one they were instinctively pulling before. The morale of the story? We rarely stop to read instructions if the affordances in the environment, in this case the large vertical door handle, primarily invite us to behave otherwise.

This is a well-known fact in the field of design (Norman 2013)—to the extent that such malfunctional doors are a common joke and even have a colloquial name, 'Norman doors' (99pi 2016)—yet this seems somehow to escape us when discussing large scale societal behaviour change. An obvious analogy to the (non-)emergence of sustainable behaviours is to be made here. Why would we assume, for instance, that humans would stop to read instructions on how to behave pro-environmentally if the affordances in our directly perceivable environment solicit us to behave otherwise? How can we expect humans to behave sustainably, when most, if not all, the new affordances we fit our urban environments with (think: ads, shopping malls, visual displays, audio commercials, etc.) are ones which primarily invite us to behave unsustainably?

Figure 3. A typical ‘Norman door’ in Metsätalo, Helsinki. Imagine encountering this door: Which would you grab first: the wooden vertical handle or the brass horizontal handle? Would you tug the handle before slowing down to read the instructions?



To more thoroughly understand the ecology of perception in a city, we must begin with some premises of perceptual systems. A central concept in the ecological approach to visual perception, as formalized by Gibson (1979), is the *ambient optic array*. The ambient optic array is the structured light in a given environment, with respect to a point of observation. In other words, the ambient optic array is the structure of light which reaches the eye, or the visual information available at the retina. As light reflects on and off the surfaces of an environment, it conveys information about these surfaces, allowing an active organism to harvest, pick up or leverage this information for its use. Furthermore, Gibson posited, this ambient optic array contains in itself enough information and invariant properties so as to specify actions, such as the walk-on-ability of a horizontal plane or the climb-on-ability of a set of stairs.

Consider then the ambient optic array of your typical urban environment and the actions it affords. In this hectic lightshow, the information flow is more than often specified so as to maximize the likelihood of humans engaging with consumptive activities: buy this, fly there, drive that and lust for those. In the urban three-dimensional ambient optic array exist very few points of view which enable us to escape this ecologically unsound information flow. I feel like I risk repeating the obvious here, but it seems clear to me that this is not emphasized nearly enough. Consider the following: private advertisement is generally allowed in urban arenas on the basis that it takes place on private or rented property. Billboards, neon signs, bus stop ads—these are mostly found on rented space or privately-owned property. Relatively few advertisements, for example, are directly placed on areas which we consider truly public (such as roads, the pavement or public lawn), or if they are, they are often considered illegal and removed. However, for the system of visual perception, it is not the placing of the object we are necessarily concerned about, but rather the *information* it conveys in the ambient optic array, and the location where this information reaches the observer.

Thus, an ad might be placed in private space, but the invariant information it conveys and the functions (affordances) this structured information specifies, for good or for ill, thoroughly pervade public space. And it is precisely this information which matters. This is not merely light pollution or visual pollution, but a more specific form of information pollution, which reaches our subjective perceptual realms, and which is practically unavoidable in our everyday encounters with our urban niche. Less and less public space, it seems, is free from consumption solicitations. As malls become the new urban living rooms and public space privatised, it is increasingly arduous to escape the flow of ecologically harmful information. Yet for some peculiar reason, we take this 'pollution of the idea space' (Lovelock 2000) almost for granted, adapt to it, and become perpetuators of this new norm in what seems like a self-reinforcing destructive cycle. Yet, as I will discuss below, it is precisely this self-reinforcing cycle which we can, with appropriate and thoughtful design, leverage to our benefit.

Journalist and activist George Monbiot (2016) once noted the saddening irony in the fact that despite all the calls by global leaders to curb carbon dioxide emissions, very little actual effort is put into keeping carbon in the ground. What exactly are we expecting, Monbiot asks, to happen to all the oil and coal once it is drilled or mined—to magically disappear? The exact same applies to consumption. We must 'Ensure sustainable consumption and production patterns', or so declares the United Nations' Sustainable Development Goal #12, yet most of the growth of urban centres and the information flows they reflect seems to scream at us for more unsustainable consumption and production. We are failing miserably at designing the proper ecology for the behaviour we wish to achieve. No amount of environmental consciousness is sufficient if the ecology of behaviour does not afford sustainable behaviour patterns to begin with. Thus, it seems, we need to radically redesign the urban niches which most of us humans today inhabit. Note that it is not necessarily a 'smart' city I advocate for—a 'dumb' or traditional city might well do the trick if it has less information pollution and less opportunities for ecologically destructive consumption patterns (Fleming 2020; Watson 2019). This need also not mean a return to the proverbial 'stone age'; the reader might entertain themselves by looking at motion pictures from most urban landscapes in as late as the 1960's, and notice how much the information landscape in urban environments has changed since.

The discussion on altering the choice architecture in urban environments has more recently been revived in the form of nudge theory, or more colloquially, 'nudging'. I am somewhat critical of this approach, for reasons stated below. A nudge here is 'any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives' (Thaler and Sunstein 2008, 6). Thaler and Sunstein (ibid.) continue: 'To count as a mere nudge, the intervention must be easy and cheap to avoid. Nudges are not mandates. Putting the fruit at eye level counts as a nudge. Banning junk food does not.'

To begin with, let me be clear: nudge theory has resulted in some interesting behavioural interventions and discussion on the ethics of sustainable design (see, e.g., (Hukkinen 2016)). However, I believe nudge theory is, as a behavioural science, quite misled. This is mainly because it is not an ecological approach to perception or action. Without digressing to a lengthier critique, I wish to point out two things. Firstly, in the real world which human beings inhabit, the structure of the environment *always* affords or constrains some kind of behaviour. Nudge theory focuses on specific, isolated 'nudges', but in the real world of action-perception the ambient optic array and other sensory cues continuously specify new predictable action opportunities and forbids many others. Easy and cheap interventions here and there are of very little use if the rest of our everyday life consists of a bombardment of unsustainable solicitations. Simply, little changes in specific environments are not enough: we need a radical restructuring of our perceptual environment.

Second, nudge associates the forbidding of behavioural options with loss of liberty. This is not the case if we take into account more complex cognitive or temporal dimensions. To begin with, consider the game of chess, where establishing systemic boundaries does not entail the loss of freedom, but rather is the *prerequisite* for both freedom and creativity. A relatively simple set of 91 rules leads to a practically inexhaustible lower bound of 10^{120} possible games (Claude Shannon's estimate—for what it's worth, this is quite a large number: there are an estimated 10^{78} to 10^{82} atoms in the observable universe). Similarly, the establishment of certain boundary conditions (such as regulating outdoor advertisement) does not necessarily entail loss of liberties, and contrarily the altered information landscape might open up new action opportunities, liberties and avenues for alternative or creative self-organising forms of life or patterns of emergent behaviour (Alexander 1979). Nudge theory, it seems, can only account for losses of liberties, whereas a systemic theory of behaviour (such as affordance theory) also accounts for the emergence of liberties. This is not to even mention the intergenerational aspects of liberty (such as: what negative implications do our liberties to consume today have on the liberties of future generations?). Much important work has been done with nudges, but importantly it underemphasizes the crucial notion of the ecological construction of freedoms: establishing boundaries need not reduce freedoms, and contrarily, it can create them. Through thoughtful and even participatory and democratic design procedures we can construct our everyday environments to afford altogether new liberties and forms of life.

In other words, to more comprehensively understand our dynamical relations to our environments, we need more wholistic approaches than mere nudges. But a critique should not be presented without an alternative. Thus, I propose that ecological accounts of human behaviour, such as those promoted by ecological psychologists and niche construction theorists, offer more viable windows into analysing the behaviour of humans in their 21st century econiches. I also argue that this helps us find ways to leverage collective patterns towards a more sustainable trajectory. Together these present a framework which I have called elsewhere (Kaaronen, 2018) the Ecology of Design.

The design of sustainable urban niches is a bidirectional process. If we wish to lead lives which respect ecological boundaries, we need to design niches in which this is the path of least resistance—or rather, the path of maximum affordance. This entails identifying the relational and functional relevance of these areas with respect to their users. In such a relational conception, the environment is not just a uniform box in a flowchart. Yes, the environment affects behaviour—this much has been obvious in the psychological and social sciences since their conception in the

19th century (indeed, it is mere common sense). But how this happens, how it leads to emergent feedback loops between organisms and environments, is a much less charted territory. Instead, we are drawn to ask, as environmental policymakers, urban designers, philosophers or behavioural interventionists, *how* the environment affords prescribed patterns of behaviour. In other words, what are the processes and feedback-loops in cultural and behavioural systems that lead to sustainable behaviours?

One of the most persistent barriers to pro-environmental or sustainable behaviour is the gap that lies between personal states (such as environmental values, knowledge or attitudes) and actualized behaviour (Kollmuss and Agyeman 2002; Jackson 2005). Simply, 'it is easier to be concerned about the environment than it is to act on one's convictions' (Vining and Ebreo 1992, 1604). There are, to my mind, two ways to go on about this so-called attitude–action gap. One is to chastise those who are not acting accordingly with their internal moral drive, and trust in the power of increased information or guilt-tripping to leverage these people into acting as they by all means should. Given the incredibly wide prevalence of the attitude–action gap, I would not bet my money on this working. The other is to adopt a dynamical or ecological stance, or understanding human behaviour as emerging from the feedback loops of continuously evolving human–environment interactions, attempting to actualize the potential for behaviour change by complementing pro-environmental 'personal states' (individual traits) with appropriate environments. It is, of course, the latter for which I argue in this thesis, particularly in Articles 2 and 3. For such a relational task, it is helpful to use a relational concept as a tool for analysis: the affordance (recall section 2.1).

Humans, of course, are by far the most efficient species in altering affordances to suit their needs—in other words, we are arguably the ultimate *niche constructors* (Laland, 2017). We construct the worlds in ways that fit with our mental models (Clark, 2016), and shape natural and urban form to conform with whatever is the current cultural trend. And most of all, whatever affordances we fit our environments with will propagate new behaviours and design efforts in what is evidently a self-reinforcing feedback loop. Thus, quoting from my essay *The Ecology of Design* (Kaaronen 2019c),

> 'Design is the bootstrap by which animals, humans in particular, become capable of lifting themselves up to novel levels of existence. It is how culture ratchets its growth, how social systems encode what they learn, and how people navigate through a near-chaotic world riddled with uncertainties.'

And so, we have the potential to revert the ongoing death spiral by identifying one particularly important leverage point for collective behaviour change: the structure of ecological information in our urban environments and the affordances that they convey. This is the argument put forward in Articles 2 and 3. If we wish to achieve the radical behaviour change the current predicament requires, we must begin by redesigning the affordances within our (urban) environments so that the path of least resistance is sustainable. Arguably (and unlike top-down interventions such as 'nudging'), this is best achieved by polycentric and participatory forms of governance (Ostrom 2010), which are responsive to local demand, capabilities and mentalities. This, I hypothesize in Article 2, could potentially trigger a positive feedback-loop, where the new behaviours afforded by the environment help people 'actualize' their behaviour potential (e.g., growth in pro-environmental attitudes or awareness), leading to pro-environmental habituation, social learning and even further pro-environmental niche construction.

In other words, we must understand the mutualism between organisms and environments to maximise the *fitness* between pro-environmental personal states (attitudes, awareness, intentions, etc.) and environments that afford salient behaviours. Importantly, doing so might result in self-reinforcing feedback loops, as is proposed in Article 2. At the stage of writing Article 2, however, much of this idea was theoretical and hypothetical. The next step was to formalize the mechanisms and study their effects on the emergent socio-ecological system. This is precisely what is done in

Article 3, together with Nikita Strelkovskii at the International Institute of Applied Systems Analysis in Laxenburg, Austria.

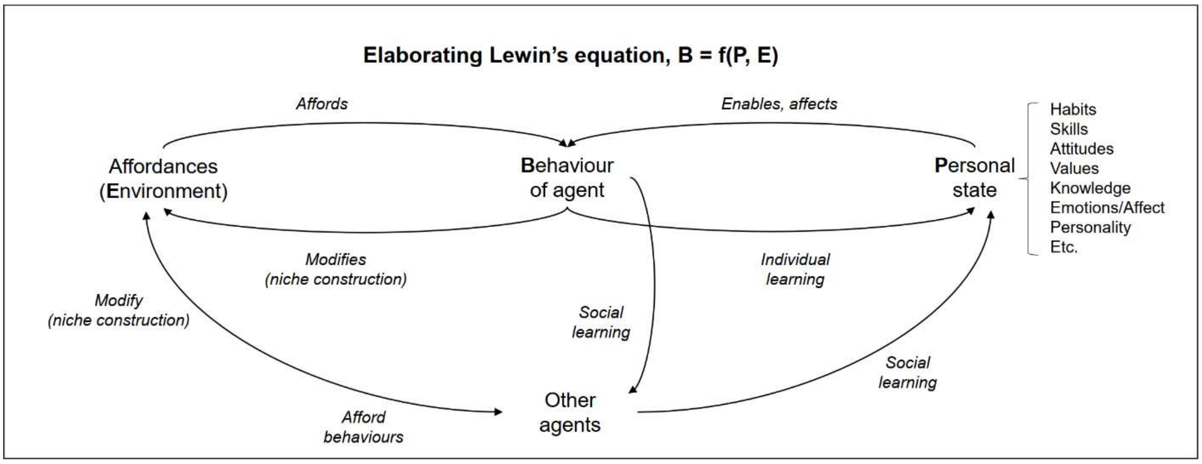
In our agent-based model in Article 3, we define five key processes that underlie an ecological approach to studying human behaviour:

1. The ecological information in the material and social environment specifies affordances for behaviour.
2. The ways in which we behave modulate our personal states (e.g., skills, knowledge, attitudes and whatever traits dispose us to engage with specific affordances) through processes of habituation and individual learning.
3. Personal states direct our individual behaviour patterns.
4. Our collective behaviour alters the environment and its 'landscape of affordances' (Rietveld and Kiverstein 2014) in non-random ways via processes of cultural niche construction.
5. All behaviours occur in social networks and result in social and cultural transmission of information (through, e.g., imitation, teaching or copying).

As one can imagine, studying such an amount of feedback loops in the real-world would be tricky, to say the least. Therefore, as described in section 2.4, we chose to analyse this system and its emergent phenomena by means of agent-based modelling. At its core, the system we model can be considered an elaboration and formal definition of Lewin's equation, $B = f(P,E)$, where, recall, behaviour (B) is a function (f) of the person (P) and their environment (E). As we argue in Article 3, however, Lewin's equation is insufficient in its detail to formally model all the processes that underly this function, so instead we looked to various theories of cognition, ecology and behaviour for inspiration.

Our results show, as agent-based models often do, unexpected emergent behaviours. In Article 2 I entertained the idea that changes in the 'landscape of affordances'—changes in the constitution of available pro-environmental affordances in an (urban) environment—might have nonlinear effects on the adoption of sustainable behaviours (Figure 3). According to the results in Article 3, and the associated sensitivity tests (see the Supplementary information of Article 3), changes in the landscape of affordances can have radical effects on collective behaviour patterns, which presents urban designers and policymakers with a particularly strong leverage point. Changing the 'personal states' (e.g., attitudes, intentions…) of agents, on the other hand, proved to be a less reliable leverage point: the case is simply that if sufficient opportunities to behave do not exist, one cannot behave pro-environmentally even if one had the noblest intentions or attitudes.

Figure 4. A nonlinear dynamical system of human behaviour: the conceptual model underlying Article 3.



As the results in Article 3 illustrate, even a linear (or near-linear) introduction of pro-environmental affordances to a social system can have a nonlinear effect on the collective uptake of pro-environmental behaviours, to the extent that this can be characterised as a tipping point or 'phase transition' (the transition of a system to a notably different state). In Article 3, we use the case of bicycling in Copenhagen to empirically validate our model: in Copenhagen, for instance, the introduction of cycling-related affordances (the construction of cycling infrastructure) has likely triggered the accelerating nonlinear adoption of pro-environmental cycling behaviours. However, we maintain that the core argument is a more general one than the case of cycling alone would suggest (the case was chosen mainly due to the convenience of easily available empirical data): where potentialities for sustainable behaviour exist (in forms of 'personal states' such as ecological awareness, pro-environmental attitudes, etc.), they can quite rapidly be actualised by providing the fitting affordances or infrastructures. Moreover, collective behaviour change can be faster in speed than isolated individual behaviour change. More precisely, this phenomenon would fall under the definition of a 'social tipping point', where

> 'a small quantitative change inevitably triggers a non-linear change in the social component of the [socio-ecological system], driven by a self-reinforcing positive feedback mechanisms, that inevitably and often irreversibly lead to a qualitatively different state of the social system.' (Milkoreit et al. 2018.)

The fact that the results of the agent-based model in Article 3 were even more radical than hypothesised in Article 2 illustrates an important lesson: modelling can reveal shortcomings in verbal models. In this case the problem was that Article 2 did not emphasise enough the role of social learning in the adoption of sustainable behaviours. In Article 3, where social networks had to be coded and modelled formally, the effects of social learning on the adoption of pro-environmental behaviours proved to be drastic (and sensitive to modelling choices). However, I maintain that the theoretical framework put forward in Article 2 was essential in helping to formalise the more complex and detailed processes in Article 3.

Before moving on, let us entertain another brief analogy I have previously written about in my essay *The Ecology of Design* (Kaaronen 2019c)—the case of Roman highways. Dalgaard et al. (2018), in their recent study, superimposed maps of Roman roads from 117 CE, the peak of the Roman Empire, onto satellite images of European nightlight density. Their research came to a fascinating conclusion, where Roman road density proved to be a strong causal predictor for contemporary road density and economic activity. In other words, the affordances designed by a distant population two millennia ago have literally paved the way for what now are Pan-European trade networks, giving in the process birth to many of Europe's greatest cities which spawned at the highway intersections. This is despite the fact that the highways were originally constructed not so much for economic trade as for military expansion. Regardless, this process of cultural niche construction—of affordance design—non-randomly altered the ecological inheritance of future populations so that the environment favoured transport on wheels, resulting in increased trading activities, in the process also creating cultural selection pressures for trade-related behaviours and attitudes, the further design of trade-related affordances, and so on (indeed, the process was likely rather similar in kind to the five feedback-loops defined above). This process, although mostly unconscious, resulted in a self-reinforcing ratchet whose (literally) path-dependent effects still reverberate strongly in everyday life today. Now, imagine if a society had the capacity to knowingly tap into a process of feedback loops this strong, designing the Roman highways (*viae publicae*) of today to bring forth a sustainable urban environment tomorrow. Equipped with the right theories, I argue with many others (e.g., Wilson 2020), we might just well be capable of this.

It is worth emphasising, though, that tipping points, like Roman highways, do not generally come for free, and require both considerable effort and maintenance. I do not therefore suggest that reaching a 'social tipping point' is a panacea for sustainability transitions, or that reaching one would altogether be a simple task with clear-cut implementation. For one, even in our model, the tipping point in the adoption of sustainable behaviours is far from free: The shift in collective behaviour patterns only emerges after sufficient affordances are introduced to the social system *cumulatively*, significantly altering the landscape of affordances. In practice, this would require considerable investment into infrastructure, among other factors that might increase the affordances for cycling (e.g., regulations for air quality, speed limits for vehicles, etc.). Indeed, even much-lauded tipping points in cycling cultures in cities such as Copenhagen and Amsterdam have been products of various policy processes, including hard 'command-and-control' measures such as speed limits, considerable investment into infrastructure and economic support for specific transport mode choices, along with softer policy measures such as education and information (Gössling 2013).

This notion—that transitions rarely come for free—is also one that is repeatedly discussed in the context of sustainability transitions. It is easy to imagine a mechanistic clockwork-world where a tipping point could simply be triggered through smart design, but the real world, as is so often the case, is much messier than this. For a social movement to be transformative and to overcome resistance by existing regimes, it needs continued support (in the forms, e.g., of restructured incentives and financial/political facilitation), maintenance (through formal and informal institutions and social activism) and mutual reinforcement or social coordination (Chenoweth, Stephan, and Stephan 2011; Nyborg et al. 2016; Westley et al. 2011). Whilst even small determined minority groups have been shown to be capable of triggering tipping points in social conventions and norms (Centola et al. 2018), adjusting the landscapes of affordances in urban environments will likely require much political and economic determination and citizen activism if we truly wish to overcome the institutional lock-ins and path dependencies our everyday lives are embedded in.

Moreover, much work remains to be done in integrating behavioural theories such as those discussed in section 2 with theoretical frameworks that are more sensitive to institutional, social, political and economic factors and variations. Undoubtedly, this is also a point that remains underexamined in the research articles that compose the present dissertation. Although, as mentioned, attempts at 'socializing' or 'enculturing' concepts such as affordances do exist (Costall 1995; Ramstead, Veissière, and Kirmayer 2016) and applied work is being done in designing affordances for sociability (e.g., Rietveld, Rietveld, and Martens 2017), some central problems remain in over-psychologizing phenomena that ultimately are more efficiently studied through the lens of social and political theory. Most notably, Gibsonian theories of direct perception generally seem to lack focus on the social values, aesthetics, economics, politics and other individual variation that typically mediate our perception of the world (with the notable exception of variation in physical traits, which ecological psychologists have studied). Here, ending this chapter, I propose some promising ways forward.

A notable candidate for studying human–environment interactions or ecological social science from a more institutionally sensitive point of view would be the Capability Approach, as developed by Amartya Sen (1992; 2009) and Martha Nussbaum (2007). Although I only briefly mention Sen's work in Article 1 and Article 2, I should emphasise that this is far from an afterthought: it was Sen's Capability Approach that originally sparked my interest into relational theories of human behaviour (and this was in fact the topic of my first academic thesis, my Bachelor's dissertation). As its name would suggest, the Capability Approach is particularly well-suited for studying sustain-abilities.

The Capability Approach could be summarised as follows. It sets off with a normative axiom: we should begin the development of policy measures from the assumption that, in human societies, the primary moral importance is in the freedom to achieve well-being (Robeyns 2016). Notably, most theoretical frameworks described in section 2 lack such a moral foundation. For instance, research in ecological psychology generally comments very little on how perception, action or niche construction *should* emerge, or indeed *why* specific behaviours should emerge. In this dissertation, much of the moral foundation was rooted in the notion of sustainability and well-being of human and non-human life, however many more normative axioms could be imagined. The point is that whilst ecological psychology as such may strive to be value-free and descriptive, any applied version of it should be honest and self-reflective about its normative assumptions.

The second basic principle of the Capability Approach is that freedoms to achieve well-being should be understood in terms of capabilities (Sen 1992). Freedoms here are to be understood as a product of 'functionings' (the subjects of our behaviour considered in their totality, such as opportunities to behave or exist, not much unlike the 'landscapes of affordances' as discussed in (Rietveld and Kiverstein 2014) and Article 3), resources (e.g., social, cultural and economic capital), and 'capabilities' (the sets of functionings that are feasible for a person to achieve, depending on economic, social and personal resources). The crux of the Capability Approach is that even if the totality of functionings and resources—or the landscapes of affordances—were uniform to people in a society, individuals and local populations differ drastically in their capabilities to act upon these action opportunities due to economic, social and political factors. Therefore, whatever functionings we are able to *achieve* are contingent on our capabilities, which vary person by person. In ecological psychological terms, people are selectively attuned to affordances in their environment based on socioeconomic, political and personal or physical variation. This is not much unlike the distinction Bruineberg and Rietveld (2014, emphasis mine) make between the total 'landscape of affordances' and the 'field of affordances':

> 'LANDSCAPE OF AFFORDANCES: The affordances available in an ecological niche. In our human form of life, these are related to **the whole spectrum of abilities** available in our socio-cultural practices.
>
> FIELD OF AFFORDANCES: The **affordances that stand out as relevant** for a particular individual in a particular situation; i.e., the multiplicity of affordances that solicit the individual.'

Indeed, making and emphasizing such a distinction as Bruineberg and Rietveld (2014) and Sen (Sen 1992) do, between 1. The totality of action opportunities in an environment and 2. Those relevant or feasible for a human to interact with, has several benefits for ecological social science. First and foremost it sensitises researchers to consider that even though the material environment were similar for everyone, not all are 'born equal' in their capabilities of utilising its affordances or functionings (Sen 1992). In other words, there are always dimensions of politics and equality at play when designing affordances. Second, connecting the dots between the various relational theories discussed in this dissertation with the vast literature on the Capability Approach could inspire much research on, for instance, how wealth, social status, scarcity (Mullainathan and Shafir

2013), disability (Toro, Kiverstein, and Rietveld 2020), gender and various socio–political factors mediate perception (of, for example, urban environments or urban affordances). Here, modern methods such as PPGIS (participatory mapping systems) and strategic or experimental design interventions (Rietveld, Rietveld, and Mackic 2014) can help researchers identify the capabilities (and lacks thereof) of local populations for engaging with everyday affordances. This could, in the spirit of the Capability Approach, serve to increase human agency to pursue well-being and various freedoms. These ideas are also guiding my current, yet unpublished, research.

Concluding this section, Articles 2 and 3 in particular illustrate how the functionally relevant aspects of our environment, the affordances within our niche and the ecological information that specifies them, have a profound role in shaping our behaviour. Affordances shape the ways in which we behave, and the ways in which we behave are socially transmitted. If we wish to instigate collective behaviour change on the scale that is required to reach sustainable levels of transport, consumption, et cetera, we need to focus much more on the context and infrastructure we behave in. Pro-environmental opportunities for action should be designed to be on the 'path of least resistance', and we should collectively seek to ensure that our environments are not so thoroughly permeated by information that solicits us to behave unsustainably.

3.3 Step 3: Dealing with Uncertainty

Article 4 discusses how a traditional practice, mushroom foraging, deals with uncertainty by using ecologically rational decision-making. I have previously written on this topic from an autoethnographical perspective (Kaaronen 2019b), and in the spirit of ecological psychology and Jamesian radical empiricism I am quite delighted to report that the research questions here were born from direct personal experience. More specifically, Article 4 deals with how Finnish mushroom foragers make ecologically rational decisions under uncertainty (recall section 2.3) by making use of traditional knowledge, heuristics, and precautionary heuristics. In doing so, its focus is perhaps more restricted than the previous articles'. Article 4 surveys 894 Finnish mushroom foragers with a humbling total of 22,304 years of foraging experience, providing us a representative overview of the art of mushroom foraging. Next to a set of multiple-choice questions and associated statistical analysis, the study included a wealth of qualitative data, providing a comprehensive set of mixed-methods data of decision-making processes in the wild. However, I wish to illustrate in this section that here, too, lie some more universal analogies for skilfully dealing with the sustain-ability crisis.

Article 4 is also a study into tacit, traditional and practical knowledge, a theme previously introduced in the second half of Article 1. Since the definition of tacit knowledge in Article 1 is extensive, it suffices for present purposes to note that Polanyi's (2009; 1974) notion of tacit knowledge assumes that 'we know more than we can tell', and that any formal description of a thing or an event relies on a background of experientially gathered common sense that cannot be explicated at the moment of description. Thus, all knowledge is rooted in tacit knowledge. From Kaaronen (2018c):

> Ultimately, it follows, to know something is to rely on 'common sense' (or a Duhemian *bon sens*) in the face of fundamental incompleteness. Explicit knowing, then, whilst being a 'superb instrument', ultimately 'requires a background of common sense', or tacit knowledge, for its operational basis (Whitehead 1947, 74). Whilst tacit knowledge can be possessed or embodied in itself, explicit knowledge must rely on being tacitly understood: all knowledge is '*either tacit* or *rooted in tacit knowledge*' and a '*wholly* explicit knowledge is unthinkable' (Polanyi 1969, 144).

Dealing with uncertainty, it seems in the case of Finnish mushroom foragers, requires a considerable amount of tacit knowledge. As the results of Article 4 illustrate, foragers often make their decisions regarding where and what to forage based on intuitions and hunches, and their decision-making is characterised by utilising sets of 'fast and frugal' heuristics—sometimes even without the foragers themselves knowing why they do so.

In Article 4, decision-making is studied as an active practice, where perceivers make use of the environmental cues they encounter to guide even difficult decisions. Article 4 illustrates how mushroom foragers use simple heuristics, such as the rule 'avoid white mushrooms', as precautionary principles to prevent unwanted surprises (such as encounters with the deadly white *Amanita virosa*). Thus, it is a study of how safe decisions can be made under high uncertainty. The uncertainties of mushroom foraging not only include poisonous lookalike species, but also the fact that mushrooms themselves are highly variant in their form and colour. It is common knowledge in Finland that, when mushrooming, it is better to be safe than sorry. Safety, in turn, can be achieved by applying a relatively simple 'adaptive toolbox' (Gigerenzer and Selten 2002) of foraging rules.

Recall that a central feature of ecologically rational decision-making is the use of heuristics, or simple and satisficing 'rules of thumb'. These can include stopping rules for searching through sequences of available alternative behaviours, or task-specific heuristics to aid 'fast and frugal' decision-making, often relying on coarse one-reason judgments (Gigerenzer and Todd 1999). When operating in the context where these heuristics are designed, such rules have repeatedly been shown to deal particularly well with uncertainties, and are capable of outperforming more complex computations and judgments in both effort and accuracy (Kozyreva and Hertwig 2019; Todd and Gigerenzer 2012). Article 4 illustrates several cases where Finnish mushroom foragers use one-reason judgments to make decisions, and curiously, even the most experienced foragers often resort to simple rules to guide their search for mushrooms. For instance, foragers seem to avoid specific subclasses of mushrooms, such as white mushrooms or unrecognised ones, and at other times use simple but reliable perceptual cues (such as the 'white milk' secreted by edible milk-caps) to make safe decisions (see Figure 5 below).

Figure 5. Finnish foragers often tend to altogether avoid white mushrooms, due to possible confusions with the deadly *Amanita virosa*, pictured below. Particularly a young *A. virosa* (bottom left and right) can look similar to many edible white mushrooms, including the champignon and its wild relatives. See Kaaronen *(2020)* on how foragers employ heuristics analogous to the precautionary principle in foraging strategies.

The reason why simple judgments or rules of thumb might outperform more complex cognitive algorithms in uncertain environments has its roots in the bias–variance dilemma (see Kozyreva and Hertwig, 2019). Simply put, in uncertain environments—or environments with large and unpredictable variance—an organism might have higher cognitive fitness when it is biased than when it is not. This owes to the fact that, in terms of survival, it might be more adaptive to be systematically biased (and avoid fatal large events) than to suspect oneself to high variance (such as unrecognised mushrooms). In such cases, persistent biases (propagated by, e.g., social norms or traditions, or other forms of intuitive or tacit knowledge) can protect communities from uncertainties, unwished events and risk of ruin. Mushroom foraging, it turned out, was a fascinating case for studying such biases. Foragers use systematically biased rules to avoid deadly encounters with poisonous mushrooms, and also bias their search for edible mushrooms by associating specific mushrooms with particular terrains or environments.

The findings of Article 4 suggest that mushroom foragers, equipped with strong intuitions, tacit knowledge and cultural traditions, are not 'probability calculators' or 'optimisers' as much as they are 'satisficers' and 'uncertainty avoiders'. Probability theory only provides the best answers when the rules of the game are certain (Gigerenzer 2015), and this is rarely the case in mushroom foraging. Thus, good intuitions to deal with uncertainty are required, and traditional rules of thumb are necessary to succeed in the practice. For instance, foragers seem to generally prefer a conservative rule similar to the 'minimax' rule (ibid.): 'Choose the alternative that avoids the worst outcome'.

Recall also from section 2.3 that ecological rationality suggests that rational decision-making should always be understood in context: whatever counts as rational or adaptive behaviour is a product of both the organism and its environment. Accordingly, foraging heuristics and rules are *local*: they only work in the context they are embedded in, and the foragers surveyed in Article 4 seem well aware of this. These practices have likely culturally evolved over decades or centuries, and have in the process developed simple rules of thumb to deal with local uncertainties. In Article 4 I also briefly discuss where such local heuristics fail: for instance, populations moving to new countries (e.g., refugees) have faced fatal accidents when using their respective traditional rules in unfamiliar environments.

Given how far studies in ecological rationality emphasise 'context', it is curious how few studies in the paradigm actually study behaviour in natural settings. Most research in ecological rationality seems to be focussed on uncovering 'fast and frugal heuristics' in abstract settings or in the domain of immobile cognising. Therefore, studying how people actually use heuristics in the wild, as Article 4 does, proved to be a fruitful and rewarding endeavour, one which I hope increases our understanding of how humans make decisions in natural environments. Often these decision-making processes were less 'algorithmic' or clear-cut as many studies in ecological rationality might suggest, and the decision-making processes rather involved active movement and use of multiple sensory cues (from olfaction to haptic to gustatory). In my essay *The Art of Mushroom Foraging* (Kaaronen 2019b) I describe these processes from an autoethnographic perspective. With this and the mixed methodology (qualitative and quantitative) used in Article 4, I aimed to broaden the scope of studies into decision-making to include more of what Herbert Simon (2000) called the 'processes of choice' (as opposed to mere 'products' of choice). Indeed, in some of his final work, Simon (2000, 35–36) emphasised in particular the need for a plurality of methods when studying decision-making:

> 'The traditional empirical tool of economics, collection of aggregated data and their analysis by statistical regression, can only provide one weapon in the armory, and that not the most important. One key requirement for forward movement is broadening the training of economists in methods of gathering data. Especially, they need to understand how to carry out field studies on decision making (and field experiments) [using] methods of observing and interviewing, of taking and analysing verbal think-aloud protocols, of extracting information about decision processes from written records, and of drawing conclusions reliably from multiple studies of these kinds. [...] It is especially important that they learn how to use non-numerical data (e.g., verbal and written information expressed in natural language). '

By analysing natural language, reports of experiences from the field, verbal descriptions of decision-making protocols along with numerical data, Article 4 (along with its autoethnographic sibling essay) responds to this call for broadening the scope of methodology in decision-making research.

Article 4 is a specific study of ecological rationality in a specific niche, and the results are presented in Article 4 in enough detail that further discussion on the specifics would be redundant. Instead, I would like to use this space on discussing the generalisability of Article 4 and its potential societal relevance. Article 4 presents a clear case where humans, sometimes intuitively, use precautionary and risk averse heuristics to make decisions when they have 'skin in the game' (Taleb and Sandis 2013)—i.e., when they would experience direct personal consequences from adverse extreme events (in this case, mushroom poisoning and the associated pain, malaise, organ failure, or even death). Mushroom foragers make conservative decisions and seem to generally avoid taking calculated risks. After all, cost-benefit calculations in this domain make little sense if potential costs are infinite (death by poisoning). I am led to wonder whether there might be a valuable lesson to be learned here regarding risks and uncertainties.

It is curious that this tendency to avoid uncertainty, which comes so tacitly and intuitively to us as foragers or practitioners of a traditional culture, should so quickly disappear on the modern large-scale societal level. Risk and uncertainty management seems to differ drastically in situations where there is personal skin in the game (such as mushroom foraging) vis-à-vis situations where institutions, industries and markets have distanced decision-makers from direct environmental feedback. Perhaps there is, therefore, something we can learn from traditional risk management—such as the ample use of precautionary principles—when preparing risk management for the Anthropocene. In fact, I am writing the present summary in midst of a pandemic that might well have been mitigated or avoided with strict precautionary measures. It almost seems like our tacit intuitions for dealing with uncertainty quickly disappear when the challenges get more abstract and collective, and are interpreted through the lens of institutions and not people. Whilst the precautionary principle is instinctively applied when individuals' personal lives are at direct danger, it is far less often applied when harm is external, time-lagged or an effect of second-order consequences. Part of this undoubtably has to do with the free-rider problem and similar institutional mechanisms—political concerns which are far beyond the scope of this thesis—but I hope Article 4 is read with an eye for applying its insights to the societal scale.

The mismatch between traditional and modern modes of dealing with uncertainty is certainly one that seems to call for further inquiry. Although it should be noted that evidence for truly sustainable traditional socio–ecological management practices is scarce (Smith and Wishnie 2000), and that unsustainable human transformations of the environment can be traced far into the late-Pleistocene (Stephens et al. 2019), perhaps our risk-, profit- and probability-obsessed cultures should seek to learn select lessons from traditional knowledge for dealing with uncertainty in socio–ecological systems. Applying intuitive and conservative rules of thumb, similar to the precautionary measures used by foragers, might just lead us out of harm's way.

4 Concluding Remarks

> '[I]n the industrialized world all of us are largely reduced to consumers. [...] Even in our lives in nature we are reduced to consumers, and our few remaining wild places, to commodities. But the value of these parks is life itself and our participation in it. [...] We of the industrialized world forget that our current value system is only one of a range of choices. We desperately need a global ethic that is richer than our mere concern about ourselves as consumers.' Stuart A. Kauffman (2008, 9.)

This thesis deals with various *sustain-abilities*, examining how we as individuals, societies and cultures can better equip ourselves with skillsets to deal with the many dimensions of the ecological crisis. These skillsets range from learning to conceptualise our natural world in ways which respect systemic interconnectedness, leveraging our capacity to design environments which support sustainable behaviours, and dealing adaptively with uncertainty. Although these perspectives afford merely some windows for viewing the sustainability crisis, they present a uniform attempt at developing an ecological social scientific framework for studying the emergence of sustainable states of mind and behaviour. Similar perspectives are also available in my other work not included within the covers of this thesis (Kaaronen 2018a; 2019c; 2018b). I hope these perspectives afford a more wholistic picture of how human cognition and behaviour is shaped by not only what is inside our heads, but the environmental regularities we find ourselves in.

We are not mere consumers roaming on an unbounded ecological system, although much modern discussion has appropriated the word 'consumer' as a near-synonym for being human. We cannot go on with the process of separating natural systems into compartments more suitable for human consumption.[7] Instead, we must collectively learn to regenerate the synthesis of these parts, and as

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[7] Interestingly, the word consumption itself can be traced from Latin, *con-* 'altogether' and *sumere* 'take up', originally meaning 'to destroy by separating into parts which cannot be reunited'. How very appropriate.

Article 1 discusses, to reconceptualise ourselves as an inseparable emergent property of natural systems—or else, I quote Bateson (2000, 501), 'The creature that wins against its environment destroys itself'. Bateson (2000, 509) continues:

> 'I regard the grooves of destiny into which our civilization has entered as a special case of evolutionary cul-de-sac. Courses which offered short-term advantage have been adopted, have been rigidly programmed, and have begun to prove disastrous over longer time. This is the paradigm for extinction by way of loss of flexibility.'

The steps in this thesis illustrate some ways of regaining this flexibility through cultural skillsets to deal with long-term sustainability. For one, we humans are the ultimate niche constructors, and we have the option to use this capacity for good: by designing environments where sustainable modes of behaviour are the path of least resistance—or path of maximum affordance—we would at the least be on the right tracks. We need to design *whole situations* which support and direct the evolution of sustainable cultures. As Articles 2 and 3 illustrate, this has the potential to lead to surprisingly rapid tipping points in collective behaviour patterns. Second, in the process of dealing with unsustainable modes of culture, we can look back at how some traditional societies have dealt adaptively with uncertainties, and learn valuable lessons on how to deal with systems where potential losses are extreme and gains limited. Article 4 sheds some light here, and provides us an analogy on how we should behave when our lives are in direct danger: by applying precautionary principles and other adaptive heuristics.

Retrospectively, much of the process of writing this dissertation has altered how I perceive social and ecological systems. Whilst Article 1 was an attempt at formulating some ideas I had been entertaining for a longer while, the rest of this thesis emerged in the process of writing and tinkering. Modelling, in particular, seems to have left a mark on how I perceive the world. Let us entertain a thought-experiment here. If I were to model the evolution of culture, I should naturally place us on a timeline of emergent processes. In this timeline, we—the agents of our model—should always find ourselves at nodes at the far edge of this process, poised between an interconnected history and an unforeseeable future. All agents in this model are connected, either by social networks or their common environment, and the future states of affairs are determined by how they emerge *together*. 'We are agents who alter the unfolding of the universe', writes Stuart Kauffman (2008, 113).What a great responsibility it sets on us, to find ourselves at this novel point at the edge of a chaotic system, with the agency and potential for shifting it into a more sustainable phase. My hope is this thesis, and the work that follows it, will provide at least some tools to help us achieve this transition.

I set on the process of writing this doctoral dissertation with the following question in mind: how can we use ecological theories of mind and behaviour to guide a transition towards more sustainable cultures and societies? By focusing on organism–environment systems as the main unit of my study, I employed insights from ecological psychology to understand how cultural systems might be leveraged to learn into more sustainable habits (Articles 2 and 3). In Article 1, I uncovered what I believe are some fundamentally unsustainable mental models, and presented an alternative in process philosophy to reframe how we conceptualise nature in both everyday life and scientific inquiry. In Article 4, finally, I studied a society with considerable traditional knowledge, analysing in detail how they survive in uncertain environments by utilising precautionary measures—a topic I have described above as particularly relevant for our era of uncertain ecological disruption.

Together, these inquiries have contributed to sustainability science and socio–ecological systems research in general, as well as to the more focussed fields of research in which each research article is respectively situated (e.g., ecological psychology, ecological rationality, process philosophy). Articles 2 and 3 make direct contributions to the more politically relevant aspects of ecological psychology, shifting the field's typically descriptive studies to a more normatively oriented approach. Article 3 is also, to my best knowledge, the first ecological psychological agent-based model, and hopefully will inspire others to study affordances with similar computational methodology. Article 4 presents an attempt to take studies in ecological rationality—which so often deals merely with 'algorithmic' or otherwise sterile laboratory-environment decision-making processes—'into the wild', studying ecological rationality in (appropriately, I would like to think) ecological context. Article 4 also contributes to our understanding of the cultural evolution of foraging strategies. Article 1 is an attempt at bringing process philosophy back to the forefront of philosophical inquiry by applying it to some of our most urgent ecological concerns, and hopefully this will also inspire others to discuss socio–ecological systems in process-philosophical terms.

This thesis therefore also presents multiple new avenues for future scientific inquiry. Article 3 offers a new way into studying ecological psychological phenomena computationally, and I can imagine plenty of work to be done here elaborating the studied mechanisms with interdisciplinary collaboration. Much work can be done in defining the model parameters and processes more precisely, as well as making the model more realistic. Article 3 also presents a novel way to study the phenomenon of social tipping points, which has gained increasing interest in recent years (Milkoreit et al. 2018). Article 4 invites us particularly to study whether other traditional foraging societies exhibit similar decision-making rules (particularly, precautionary heuristics), and also proposes mushroom foraging as a particularly suitable avenue for studying human perception-action. The themes of Article 4 also could be extended to more comprehensive inquiries into the cultural evolution of foraging practices and precautionary heuristics, research topics which I have recently embarked upon.

Article 2 develops a framework for studying policymaking and particularly urban behaviour in terms of affordances, and these ideas could be developed much further by collaborating with, for instance, urban designers and landscape architects. As discussed in section 3.3, there is also much potential in complementing affordance theory with more politically and institutionally sensitive theories, such as the Capability Approach. Process-philosophical approaches for studying socio–ecological systems, such as that presented in Article 1, have recently garnered some momentum (Hertz, Garcia, and Schlüter 2020; Mancilla Garcia, Hertz, and Schlüter 2019; Walsh, Böhme, and

Wamsler 2020), and it remains to be seen whether sustainability science will catch up with the process philosophical mode of thinking which I believe would suit it so well.

Much work remains to be done with creating a synthesis between the various ecological social scientific approaches presented in this thesis. Some obvious theoretical conflicts remain in particular. However, this might not be as much a fault as is it a necessity: we are contextual and complex beings, and capturing the whole of humanity within a single theoretical framework might be akin to forcing a mobile, complex, lively and evolving organism into a rigid and cold mould. Something always dies in the process of forcing the real-world into a model, and perhaps adopting a pragmatic pluralistic perspective would do social science a larger favour than we can currently imagine.

Here, we have embarked on steps to a sustainable mind. My hope is that by engaging with future collaborative efforts, we can pave our way with a higher variety and number of stepping stones, and ultimately develop a pluralistic research program dedicated to the study of sustainable modes of cognition and behaviour, helping us cross and navigate through the treacherous and uncertain rapids of the ecological crises.

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Reframing Tacit Human–Nature Relations: An Inquiry into Process Philosophy and the Philosophy of Michael Polanyi

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ABSTRACT

To combat the ecological crisis, fundamental change is required in how humans perceive nature. This paper proposes that the human–nature bifurcation, a metaphysical mental model that is deeply entrenched and may be environmentally unsound, stems from embodied and tacitly-held substance-biased belief systems. Process philosophy can aid us, among other things, in providing an alternative framework for reinterpreting this bifurcation by drawing an ontological bridge between humans and nature, thus providing a coherent philosophical basis for sustainable dwelling and policy-making. Michael Polanyi's epistemology can further help us understand these environmentally-oriented tacit processes of knowing, and also provide a basis for the political and educational implementation of process-philosophical insights, particularly via the nudging of mental models.

KEYWORDS

Process metaphysics, tacit knowledge, sustainability, environmental policy, nudging.

1. INTRODUCTION

In recent years, there have been several calls for a better understanding of the interconnections between human, societal and natural systems. In particular, several writers have proposed that some sort of cognitive 'reframing' is

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required, if we are to come to appreciate the fundamental relations between humans and the ecosystems to which they belong (Honig et al., 2015: 677; Hukkinen, 2012; Richardson et al., 2015). While this 'art of the cognitive war to save the planet' is undoubtedly a political task, involving both systemic and behavioural change, it can also be interpreted to represent a philosophical – even metaphysical – endeavour of reframing the ontological and epistemological relationship between humans and their environment (Antal and Hukkinen, 2010; Hukkinen, 2012). Accordingly, there have been calls for a revised comprehension of the relationship between individual actors and socio-ecological systems (SESs), to transcend dichotomous frameworks such as human–nature, human–environment, realism–constructionism and individual–SES (Antal and Hukkinen, 2010; Hukkinen, 2012). I suggest in this article that environmental philosophers and policy-makers might find two particularly interesting philosophical allies in (1) process philosophy and (2) Michael Polanyi for drawing the bridges between the aforementioned dichotomies, and strengthening the philosophical ties between society and the environment.

The philosophical proposition I develop is a twofold argument, built on the insights of process philosophy and Michael Polanyi's epistemology. Firstly, in Section 2, I show that the dichotomies mentioned above, among others, arise from a predominantly substance-biased metaphysical framework, and that the best alternative to reframe these 'bifurcations of nature' is through a philosophy which emphasises the ontological primacy of process over substance (Whitehead, 1978). I suggest, providing illustrative examples such as the 'coastline paradox', that a process-biased worldview might have the potential for inducing a sustainable '*Gestalt* switch' (Kuhn, 2012) in how both experts and the public relate to and think about nature and the environment; it might also facilitate the development of the policy tools needed to accomplish this.

Following the insights of process philosophy, in Section 3 I introduce some central ideas of polymath Michael Polanyi. What I propose is that mental and bodily modes of knowing are fundamentally interconnected; as a result, reframing some of our most fundamental (often tacit or implicit) substance-biased philosophical presumptions with process-philosophical alternatives might open doors for novel modes of sustainable behaviour and a revived appreciation of nature. Finally, in Section 4 the insights of process philosophy and Michael Polanyi are discussed in relation to their potential for setting a philosophical framework for environmental policy development. In particular, I suggest that the nudging of our unsustainable mental models might result in an effective political and educational instrument.

Yet there remains an important secondary motive for writing this article. The theoretical frameworks of both process philosophy and Michael Polanyi are often sidelined in mainstream philosophy and policy, despite their obvious relevance to acute socio-environmental concerns. Consequently, I argue that to reconsider process philosophy and Michael Polanyi's work – two strains of thought which have received generous praise from prominent thinkers Bruno Latour (foreword in Stengers, 2011) and Amartya Sen (foreword in Polanyi, 2009), respectively – under the *aegis* of environmental policy and philosophy holds great potential for novel development towards a sustainable future.

2. PERSPECTIVES ON PROCESS PHILOSOPHY

2.1. Process and processists

Process philosophy, generally considered an endeavour in speculative metaphysics, represents a long strain of thought which can be dated (in Western Europe) at least to the pre-Socratic philosopher Heraclitus, and his famous teaching that 'everything changes'.[1] Since Heraclitus, processists have had the commonality of stressing the ontological (or at the very least, epistemological) primacy of process – i.e. change, movement, dynamism, flux, temporality, activity or other 'items better indicated by verbs than by nouns' (see Table 1) – over substance (i.e. static 'things') (Rescher, 2000: 4).[2]

Table 1. Ontological or epistemological primacy (Based on Rescher 1996; 2000)

Substance Philosophy		**Process Philosophy**
staticity		dynamicity
discrete individuality		interactive and reciprocal relatedness
separateness		wholeness (totality)
humans, society	nature, environment	socio-environmental process
classificatory stability, completeness		classificatory stability, incompleteness
passivity (things acted upon)		activity (agency)
product (thing)		process
persistence		change, novelty
being		becoming
digital discreteness		analogical continuity

Due to its broad underpinnings, it comes perhaps as little surprise that process philosophy has historically found a large variety of interdisciplinary – or 'hybrid' (Hård and Jamison, 2005) – applications, with notable advocates ranging from American pragmatists John Dewey, C.S. Peirce, G.H. Mead and William James, and chemist-philosophers Ilya Prigogine and Isabelle Stengers to, most

1. Often referred to as *panta rhei* ('everything flows').
2. 'Processists' is a neologism developed by Nicholas Rescher (1996; 2000), along with the related concepts 'substantialist', 'processual', 'processism' (and so on), in order to cope with the insufficient lexical resources in English for dealing with process-related issues.

famously, mathematician-turned-philosopher Alfred North Whitehead (see Rescher, 1996). More recently, prominent process-philosophy scholars include Nicholas Rescher – on whose interpretation of process philosophy this text is most heavily based[3] – and Arran Gare, while process philosophy is also known to have influenced Bruno Latour. Interdisciplinary biologists such as Francisco Varela, Humberto Maturana and Stuart Kauffman might also be read to support process-philosophical endeavours in their theories of autopoietic or emergent systems. Finally, I suggest in this article that Michael Polanyi (1969: 132) – a polymath whose intellectual career spanned physical chemistry, economics, social sciences and philosophy – might be considered amongst the processists, particularly due to his advocacy of the view that 'knowledge is an activity which would be better described as a process of knowing' and that science is a dynamic inquiry 'ever on the move'. Before getting into further detail, however, a disclaimer should be placed here: process philosophy cannot be considered a unified doctrine or ideology, and it naturally follows that not every claim I make for process philosophy will apply to all those labelled 'process philosophers'.

2.2. Process and substance

Western[4] (European) philosophy, broadly speaking, has predominantly been biased towards substance as the basic ontological unit of reality (Rescher, 1996: 29 and 51; 2000: 3–4). Rescher notes that, as is often the case with philosophy, process philosophy is perhaps best understood in terms of what it opposes: the ontological supremacy of substance over process. By reversing the ontological order of priority (that is, by prioritising process over substance) process philosophy can be understood to provide a philosophical framework for reinterpreting the paradigmatic bifurcations – most prominently the human–nature dichotomy – which have left a significant mark on human dwelling and its environmentally pathological manifestations. Instead of viewing substances (or things) as discrete entities, process philosophy reconceptualises substances as manifolds of process: substances are reduced from their status as ontologically separate entities to relatively static modes of dynamic process, always subject to pragmatic limitation in definition. As Rescher (1996: 28) writes, 'substantial things emerge in and from the world's course of changes', and thus 'processes have priority over things'. For process philosophy, there is no

3. I regard this as the most coherent and accessible compilation of the general theses of process philosophy.
4. I duly acknowledge the problematic nature of the term 'Western' here, for two reasons. Firstly, 'Eastern' and 'Western' philosophies are often exaggeratedly contrasted, and falsely stereotyped as 'holistic' and 'dualistic', respectively. Second, to reduce the question of cognitive bifurcation to merely being a 'Western' issue would not make for a coherent account of our biological and evolutionary tendency for dualism and bifurcation. See Slingerland (2008) for related discussion.

fundamental ontological distinction between subject and object, nor subject and predicate; an actor is not ontologically isolated from its environment, nor is it ontologically separate from its dispositions (i.e. what it does). Rather, the world is best described a 'unified macroprocess', consisting of 'a myriad of duly coordinated subordinate microprocesses' (Rescher, 1996: 84).

One primary argument against substance-biased philosophy is its neglect (or downplay) of action. Indeed, if a substance does nothing, it lacks property and is thus meaningless – we can only know about 'things' as they relate to and interact with other 'things' (including the knower) (Rescher, 1996: 47). An entirely static world would have no qualities (Dewey, 1958: 90). Hence substance simply cannot do without process – yet the same does not apply when the parts are reversed (Rescher, 1996: 57, 62–3). Processes, such as climate change, can exist and be very real without having a static identifiable substantial form or spatiotemporal borders. It thus follows naturally for processists to ask: why insist on the separateness of static entities if they only appear as real when interacting? Is the world not more coherently portrayed as the interaction and interrelation of things, and if so, is process not ontologically precedent to the substance form that interactive processes temporarily take? Accordingly, processists emphasise the pragmatic maxim that 'things' are better described as what they 'do' rather than what they 'are' (Rescher, 1996: 47; Whitehead, 1967: 157).

Process philosophy is thus best described as a one-tier ontology, where the bifurcations of thing–activity (and similarly, the primary/secondary-quality distinction) and of subject–object are replaced with a 'monism of activities of different and differently organised sorts' (Rescher, 1996: 49). The subject and object, generally separated in a substance metaphysics, are united as not different 'kinds' of substance but rather as pragmatically distinguishable 'degrees' of process. The difference between subject and object is hence not in kind but in degree. If process is taken to be the basic ontological unit (that is, all things are fundamentally processual), the matter of clearly distinguishing one thing from another is always suspect to fundamental limitations, and is necessarily a pragmatic action.

An explicated definition of a thing, therefore, is analogous to taking a set of filmstrip-like photographs of a flying arrow: the photographs provide us interesting detail, but fail to exhibit the 'structure of spatiotemporal continuity' and thus the totality of the process (Rescher, 1996: 39). No fixed categories can completely capture the contingency of reality, although they are undeniably of extraordinary instrumental use. Yet still, for processists, 'once reality falls apart into disjointed discreteness, not all the king's horses and all the king's men can get it together again' – discreteness always induces loss of reality at the price of pragmatic value (Rescher, 1996: 40). Hence it follows that a process philosophy always adheres to a degree of incompleteness in definition. I shall make use of Sen's (1995) concepts here to shed light on the question at hand: for process philosophy, the explicated knowledge of reality always remains 'fundamentally incomplete' (reality is always in process and static descriptions cannot fully capture this dynamic) – yet there remains all reason to be 'pragmatically incomplete' (i.e. make tangible sense of the process) by means of pragmatic limitation.

Here, it could be argued, is also the key for bridging the bifurcation of constructionism–realism through a framework of process philosophy: process philosophy is simultaneously realistic about process and idealistic about substance (yet the ontological priority is on the former). Process is basic 'and things derivative, since it takes a mental process (of separation) to extract "things" from the [Jamesian] blooming buzzing confusion of the world's physical processes' (Rescher, 2000: 7). Thus substance is always a category imposed on process, yet process remains real even without substance. The caveat is, though, that the act of categorisation or separation is not arbitrary, since the structures of processes afford certain types of categories. As Rescher (1996: 71) puts it, 'abstraction [social construction] does not *create* structure but presupposes it [realism]' (brackets added for emphasis; see also Heft, 2001). Constructionism and realism are thus reframed as long-lost relatives. Thus Dewey's (1958: 47) idea that philosophical feuds tend to be 'family quarrels' seems appropriate: these conflicts 'go on within the limits of a too domestic circle' and are best settled 'by venturing out of doors'. The realist–constructionist and idealist–realist debates mostly occur within a substance-metaphysical framework – perhaps they too are best settled through the 'outdoor' prospect of process philosophy.

But what about the individual–system relation? This is certainly an imperative question for the ecological sciences. Process philosophy approaches this issue by adhering to the notion that reality is processual 'all the way down': processual entities themselves consist of clusters of processes (Rescher, 1996: 54–55). Processes are parts of wider structures and themselves contain inner structures, constituting what is essentially a nested *holon* (Koestler, 1967; Ostrom, 2005) or 'Chinese box' of processes within processes. Central to this organismic analogy is also its inherent notion of hierarchical emergence: lower processes form structures, from which novel higher forms of processes emerge. Nature, it follows, is an integrated whole of emergent processes;[5] it is humans who 'for our own convenience, separate them into physical chemical, biological and psychological aspects' (Rescher, 1996: 55). Since a process is always Janus-faced (it looks both inwards and outwards), causality and feedback are interpreted as two-directional: socio-ecological systems emerge from the interaction of constituents (e.g. the dynamic relations between actors and natural resources), but the SES also has influence on how its dispositional particulars act within the system. As is generally the case with process philosophy, the difference between human actors and the SES is not in 'kind' but rather in

5. Thinkers such as Gare (1996), Polanyi (1974) and Kauffman (1995) have highlighted the necessity for humans to locate themselves in this process of natural emergence.

'degree'. A system is thus not some 'magical' entity hovering above the individual, but both emerges from individuals and affects how individuals operate (Hukkinen, 2012; Slingerland, 2008).

This is a particularly important notion, since all too often cognitive and socio-ecological systems are treated as ontologically separate entities. While the focus of this article is on the former, I wish to re-emphasise that in order to achieve sustainability, we require change in both macro systems and cognitive (micro) systems, and most importantly we need to acknowledge the reciprocal relationship between the two. This entails designing policies, societies, economies and environments which 'afford' (i.e. enable: Heft, 2001) the realisation of sustainable mental models. Since process philosophy, at its heart, acknowledges and emphasises these reciprocal interconnections between micro- and macro-level systems, it is a particularly fitting ontology for comprehensive sustainability transitions.

The strength of process philosophy also lies in its intrinsic dynamism: it can be advocated in either its ontological (strong) form or its epistemic (weak) form. While ontological forms of process philosophy are by no means toothless – against even the harshest critique[6] – process philosophy represents, at the very least, a pragmatic epistemic instrument for reconceptualising the basic premises that lie under an unsustainable culture. Thus, at the very least, process philosophy represents a pragmatic 'thought instrument' for organising both everyday and scientific knowledge (Rescher, 1996: 25, 34, 165; 2000: 3–4). It is also worth emphasising that process philosophy does not stand against materialism, but rather reconceptualises physically stable things as static 'stability waves' in a dynamic 'sea of process' (Rescher, 1996: 53). Process philosophy, in other words, does not do away with substance, but imposes an alternative way of looking at things by reducing the ontologically fundamental status of substance to what is best described as 'pragmatic' or instrumental.[7] It is also worth noting that process philosophy does not necessitate changes in explicit language: it does not imply that we explicitly call 'this pen' by the convoluted phrase 'this instance of a pen process' (Rescher, 1996: 33). Indeed, Rescher (ibid.) goes on to note how 'Copernicans have not desisted from speaking of sunrises'. What process philosophy does imply, however, is a tacit Gestalt shift in how we relate to the world. I return to these themes in more detail in Section 3.

2.3. Reframing environmental bifurcations

Below I discuss at least five potentially unsound features of substance-biased mental models which might be pro-environmentally altered through the 'conceptual blend' of 'substance' reframed as 'process' (Fauconnier and Turner,

6. See, for example, Rescher's (1996) responses to P.F. Strawson's critique.
7. Yet, importantly, the pejorative phrase 'merely pragmatic' would be ill-placed here.

2002; see Table 2). Moreover, since it is also particularly important to consider how changes in policy, behaviour settings and education can help bring about these changes, some empirical examples of how a processual mode of thought or behaviour can be brought about through policies and education are also provided.

Table 2. Processual reframing of environmentally pathological substance-bias

1. Human and environment are unified under a comprehensive processual framework.
2. Things are what they do and how they become: process has priority over product.
3. The ontological status of change (e.g. climate change) is strengthened.
4. Potential alternative for the realist–constructionist debate and the science wars.
5. Individual actors are merged with their systemic counterparts and vice versa.

(1) First is the ontological separation of things from their surroundings. This is best portrayed in the prominent mental framework between humans and their environment: nature is substantialised and commodified unsustainably, viewed as an ontologically separate order on which human subjects impose their sovereign will and control. Technological and economic progress is portrayed as a victory against nature, while in reality, seemingly independent individual actors are merely strengthening the processual feedback-relations between them and their socio-ecological environment through excessive and unsustainable material consumption (Latour, 1991; Antal and Hukkinen, 2010).

It seems, therefore, that a sustainable society has to further emphasise the interrelations between humans and their natural environment. Indeed, perceptions which emphasise ecological interconnectedness – as advocated by process philosophy – are often associated with pro-environmental behaviour (see e.g. Davis et al., 2009). In fact, Davis et al. (2009: 179) even go so far as to suggest that positive ‘focus on dependence and interconnectedness with the environment may yield longer lasting or more pervasive transformation of motivation’ than negative ‘approaches that highlight prevention or threat’ (e.g. risk communication). Even if we duly acknowledge the existence of a significant ‘value–action gap’ between reported value-sets and actual behaviour (Kollmuss and Agyeman, 2002), the importance of mental models in promoting sustained pro-environmental behaviour patterns should not be overlooked, and reinforcing these sustainable mental models is an important task for any society wishing to strive towards sustainability.

(2) Second is the ontological separation between products and processes. Products are displayed and branded as hard-edged substance, while production processes are (often deliberately) hidden and untraceable. Carefully branded products are not portrayed as process (e.g. how they became, how they were manufactured, how they will manifest as waste) but rather as discrete modes

of substance separate from their environment. The action of inanimate things is downplayed, and feedback is often left unnoticed.

While acknowledging the processual interconnectedness between things, production processes and their ecological consequences might itself lead to altered behaviour in consumption patterns, policymakers can also seek to take steps towards what could be called 'process-biased environmental policy'. This can happen, for instance, by directly strengthening feedback between 'subjects' (human consumers) and 'objects' (products), which is greatly facilitated by technological advances. For example, continuous electronic feedback has been noted to be an effective tool for inducing pro-environmental behaviour changes (e.g. energy conservation), potentially also resulting in heightened awareness of environmental impacts (Abrahamse et al., 2007). Developing similar processual policies which strengthen the interconnections between products and consumers can thus contribute to significant positive changes in sustainable behaviour patterns.

(3) Third is the subjugated ontological status of change. Within a substance metaphysics framework, as has been noted above, change is often perceived to be less real than stability. This is a direct concern for an era in which understanding change is of primary importance for the survival of civilisation. Environmental concerns, often dealing with slow, ambiguous and fuzzy modes of change (e.g. anthropogenic climate change), are commonly subjugated to more hard-edged and tangible ideas (e.g. material consumption and natural resource extraction). Alarmingly, the case with climate change in particular is that once its consequences become tangible, the changes might be irreversible. Thus we need to further understand how climate and environmental change, albeit slow and less tangible than our typical substances, are both real and highly consequential. Therefore, by reifying the ontological status of change, perhaps a processual approach to education could provide a framework for the reinterpretation of complex and slow events such as climate change.

This could happen, for example, by promoting the use of experiential education (first-hand vivid involvement with environmental processes, dealing directly with environmental change) next to the more traditional substance-biased learning methods (such as learning about 'things' from static entities such as textbooks). Indeed, Epstein (1994: 711) notes that 'experientially derived knowledge is often more compelling and more likely to influence behaviour than is abstract knowledge'. Similarly, Leiserowitz (2006: 63) suggests that 'experiential processes', or personally derived vivid and affect-laden knowledge gained from direct first-hand involvement (referred to later in this text as 'tacit' knowledge), most likely have a heavy impact on risk perceptions concerning global warming.

(4) Fourth is the academic and intellectual division between constructionists and realists, which has effectively separated the 'hard' and 'soft' sciences and

resulted in what are commonly referred to as the 'science wars' (Gould, 2000). If humans do not construct nature, nature appears as remote, foreign and hostile; if humans do construct nature, nature appears as artificial (Latour, 1991: 30–31). The effort to overcome this dilemma is apparent in much, if not most, of the social sciences in particular. As has been noted, a processual framework does not allow such a sharp distinction between constructionism and realism, and effectively unifies the two when claiming that while processes are real in themselves, any strict categorical imposition on them is fundamentally incomplete and thus potentially value-laden.

Moreover, process philosophy emphasises the fundamental interconnection between the natural sciences, humanities and social sciences – an increasingly topical issue due to the 'hybrid' and multifaceted nature of most global problems (e.g. climate change) (Latour, 1991). Therefore, by emphasising the interconnected and gradient borders between scientific fields – recall Rescher's (1996: 55) emphasis on how 'physical chemical, biological and psychological aspects' emerge from the same nested reality – process philosophy can also contribute to the development of inter- and transdisciplinary perspectives on sustainability, and thus help overcome the disciplinary discordances most radically symbolised by the 'science wars'.

(5) Fifth and last is the disjunction between systems and individuals: 'micro' and 'macro' are reframed as not bifurcated ontological entities but rather as mutually and reciprocally constituent (Latour, 1991; Heft, 2001). Individuals and systems are merged seamlessly within one philosophical framework, without downplaying the influence of the actor or the system. In a processual framework, therefore, individuals cannot merely 'blame the system' (since they themselves are, as cognitive actors, a part of the emergence of a system), although a marked change in the SES's institutional basis will (of course) have great effects on the processes and events that occur within it. This process-philosophical emphasis on the reciprocity between cognitive and macro systems (be they termed 'socio-economic', 'socio-political' or 'socio-ecological') should particularly guide policymakers in designing policies which not only develop pro-environmental knowledge or values (i.e. mental models) but also environments and societies which create 'affordances' (or action possibilities: Heft, 2001) for the realisation of these models.

In conclusion, the primary question for process philosophy is not how the human acts environmentally, but rather how the human-embedded-in-nature manifests itself within a reciprocal socio-ecological process.[8] The human, for process philosophy, is not a separate entity with fixed borders, but rather part and parcel a manifestation of the 'megaprocess' we call nature (Rescher, 1996, 2000). These simple tenets emphasise the notion that no human action happens

8. This fundamental emphasis on non-bifurcated perceiver–environment interaction is also, interestingly, a central idea in 'ecological psychology' (see e.g. Heft, 2001).

without environmental consequences, and that feedback is always expected. Yet, even more, process philosophy raises a fundamental question about our ontological identity with the natural process that we both constitute and are constituted by. To locate the human in the process of nature should, of course, come naturally for anyone remotely acquainted with evolutionary theory (indeed, many of the early processists and pragmatists were influenced by Charles Darwin), yet the fundamental bifurcation of human–nature still seems to remain strong in our cultural *mythos*, pathologically reinforcing phenomena such as ecocide, climate change, mass extinction and even evolution denialism (see e.g. Dawkins, 1993).

2.4. The coastline paradox: An illustrative example

A paradigmatic example of the central arguments related to process philosophy can be made with reference to the coastline paradox. While the paradox is by nature mathematical (and, indeed, inspired Benoit Mandelbrot to develop fractal geometry), my reference to it will be allegorical at best. Essentially, the paradox states that a coastline cannot have a completely defined length, since the result of the measurement is inherently dependent on the method used to measure it. In other words, when measuring the coastline of, for example, an island, the length of the measured coastline is dependent on the length of the ruler used. If one were to measure the coastline with a standard 30 centimetre ruler, the coastline would appear to be considerably longer than when measuring it with a yardstick, since the use of a shorter tool would entail more bumps and curves to measure around. The paradox gets particularly interesting when the hypothetical ruler gets shorter and shorter: as the length of the ruler nears zero, the coastlines theoretical length approaches 'infinity', or at the very least, 'undefinability'(Mandelbrot, 1967). It follows, then, that there is no completely definable length for a coastline, since the process of measurement necessarily affects its result.

Here we can note similarities to several process-philosophical themes addressed above: firstly, the coastline is fundamentally incomplete, since it escapes precise definition and can (theoretically) expand to huge lengths and even infinity. Second, the coastline is pragmatically incomplete in that, regardless, it is possible to agree on a certain length by pragmatic methods or political reasoning.[9] Indeed, evoking the words of polymath Henri Poincaré (1958: 129), the island might be measured 'very nearly' (and enough for pragmatic application), even if the exact description remains 'necessarily incomplete'. Moreover, the island is processual 'all the way down', since the information we acquire at any scale is dependent on the process of measurement. As

9. It is not far-fetched to draw an analogy here to the political nature of science. Intriguingly, the coastline paradox has in fact resulted in several actual political feuds related to border lengths and territorial ownership.

Rescher notes (2000: 81–82), physical nature 'can exhibit a very different aspect when viewed from the vantage point of different levels of sophistication in the technology of the nature-investigator interaction', and is thus cognitively inexhaustible. Thus an analogy to overcome the constructionist–realist debate follows: the coastline's structure undoubtedly is there, insofar as it affords measurement and experience (realism), but any acquired information is inherently dependent on the selective act of measurement (constructionism).[10]

Yet even all this is assuming the island and its coastline to be an ideal-type static entity, which simply does not apply to real life. Indeed, stepping back on the hypothetical island, we shall notice that the island itself is in dynamic process. Thus not only is the island's coastline not precisely measurable in a static ideal-type situation (due to the processual nature of measurement), it is also embedded in the dynamic process of constant contingencies affecting the measurement. Tides (caused by the gravitational effects of the Moon and the Sun, as well as the Earth's rotation), erosion (due to water flow and wind), human and other organic impacts (including the very act of measurement), climate change (sea level rise) and plate tectonics are all among the indefinite factors constantly shaping and reshaping the island. That is not, of course, even considering the question of how to measure around, for example, deltas, estuaries and tidal flats. It follows then that even the island itself is, ontologically speaking, better defined in processual than substantial terms. Islands come and go, emerge and perish;[11] during any attempt to measure a precise account of a coastline, the coastline would have changed. To ontologically describe the island as a substance with fixed properties and borders would be in Whitehead's (1978) terminology a 'fallacy of misplaced concreteness'. The static substance-island can only ever be a pragmatic categorisation of the island-in-process. Thus, paraphrasing Heraclitus, 'we do not step twice on the same island', although it is undeniably pragmatic to assert that we do.

The real insight here is that there is no fundamental reason why the analogy of the coastline paradox shouldn't apply to every form of substance. This 'fuzzying of borders', of course, has often been applied to discussions related to plastic or gradient 'things', such as race, gender and sex (Haraway, 1991), equality (Sen, 1995), ethnicity and identity (Barth, 1969) and even species (Dawkins, 1993). But analytical process-philosophical applications in these domains remain scarce, and I sincerely believe that process philosophy would provide a pragmatic framework for interpreting these (and so many other) issues as well.

10. This should not be, however, read as an offensive towards the scientific enterprise: it is simply the reverse side of science's 'strength as an endlessly versatile intellectual instrument capable of accommodating itself to ever-changing cognitive circumstances' (Rescher, 1984: 4). The perceptive limitation of processual structure when forming conceptual entities is at the heart of all cognitive efforts (see Heft, 2001).

11. A substance metaphysics would also run into trouble in defining when precisely a substance-island would begin or cease to exist (see Rescher, 1996).

In the context of this article, however, applying these insights to the human–nature bifurcation is of the highest importance: there are no fundamentally fixed borders between humans and their environment. Thus, the coastline paradox also provides a metaphorical basis for an ecological reinterpretation of individualism. Although we can pragmatically speak of an individual as a separate entity, it is, like the island, fundamentally embedded in the worldwide web of interrelated processes from which it emerges. Thus even describing an individual in the metaphorical language of 'an island' (e.g. an independent and rational decision-maker) should lead to the interpretation that, fundamentally speaking, the individual has no fixed borders, and inevitably exists in and under the influence of a world of dynamic socio-environmental process. As Whitehead (1967: 225) remarks, 'we cannot tell with what molecules the body ends and the external world begins', and hence 'human experience is an act of self-origination including the whole of nature'. This insight, I believe, is fundamental for developing sustainable modes of thought where individual actors simply cannot fundamentally dissociate themselves from their environment, even if they at times are pragmatically required to do so. Hence, 'no person is an island', or alternatively, people are islands, but 'islands aren't what they appear to be' (Mesle, 2008: 9).

3. THE PROCESS OF TACIT KNOWING

I hope to have established by now a comprehensive (albeit brief) reasoning for reframing some of the basic tenets of what might be called 'substantialist' metaphysics, in order to draw a process-philosophical bridge between some of its potentially environmentally pathological features. Yet the question of how humans – both experts and the public included – carry these metaphysical convictions requires further illustration. The move is now from ontology-oriented analysis to specific epistemology. I shall approach this issue through Michael Polanyi's philosophy of 'personal' (1974) or 'tacit' (2009) knowledge. An afterthought to his accomplished career in physical chemistry, Polanyi sought to develop a philosophical system bridging the knower and the known, the subject and the object, as well as facts and values. I argue here that Polanyi presents us with a through-and-through embodied account of knowledge, carrying with it further implications on how even the most intellectual endeavours are embedded in tacit knowledge arising from socio-ecological processes. Polanyi's epistemology can thus be particularly insightful regarding the feedback between mental models and human–environment relations. If much of our environmentally oriented decision-making and behaviour arises from embodied, or 'indwelled', tacit knowledge, might we seek to alter environmental behaviour by consciously reframing tacit-knowledge frameworks?

I begin with Polanyi's (2009: 4) simple and heuristic notion that 'we can know more than we can tell'. As Polanyi (1974) himself has acknowledged, for some this statement might seem too obvious to merit high emphasis, whilst for others it might seem to bear almost mystical features. I argue that neither of these claims are true, since Polanyi's account of epistemology has profound implications while being in no sense logically untenable. The conception that we can know more than we can tell takes its most intuitive (yet impoverished, as shall be explained later) form in acts of physical motion. Polanyi (1974: 49) notes that 'the aim of a skilful performance is achieved by the observance of a set of rules which are not known as such to the person following them'. Indeed, few people familiar with the skilful performance of swimming are consciously aware of the delicate manner in which they keep themselves afloat via regulation of respiration (i.e. maintaining an increased level of buoyancy by refraining from emptying their lungs when breathing out and by inflating them more than usual when breathing in). Similarly, the casual cyclist is likely to be completely unaware of how balance is maintained through intricate manoeuvres making use of centrifugal forces. These examples are, of course, commonsensical – this is wholly intentional, since much of Polanyi's (1974: 94) work is focused on drawing a bridge between 'sound common sense' and sophistication. Consequently, the notion of tacit knowing becomes increasingly more intriguing when taking the step from the practical domain to the intellectual.

Although tacit knowledge is often (mistakenly) referred to merely in the context of practical know-how, Polanyi (2009: 7) – who was the first to coin the concept of tacit knowledge – had no intent to separate the practical realm of knowledge from the intellectual. Hence, it cannot be stressed enough that for Polanyi (1969: 133; 1974: 257 and 312; 2009 *passim*), the unformalised tacit coefficient permeates all knowledge, practical and theoretical, and there are no reasonable grounds to accept a fundamental distinction between the two kinds. The tacit coefficient of knowledge is no 'mere imperfection' but in fact a necessary component of all knowing. Polanyi's stance, therefore, represents a radical distaste for the 'Cartesian doctrine of "clear and distinct ideas"', and extends the embodied knowledge hypothesis to include the most rational and explicit forms of knowing (1974: 87 and 257).[12]

To support the idea that all knowledge is rooted in tacit knowledge, Polanyi (1974: 88) quotes Whitehead (1948: 73) to demonstrate the incomplete nature

12. An analogy here lies to discussions about the dual mode of cognition, or the idea that humans are characterised by distinguishable type 1 (fast, automatic and unconscious) and type 2 (slow, deliberative and conscious) cognitive processes (see e.g. Hukkinen, 2012, 2016). Polanyi's philosophy supports claims that type 1 ('tacit') and type 2 ('explicit') cognitive processes are deeply intertwined, and that tacit intuitive cognitive processes are fundamental constituents in even the most rational forms of knowing.

of any explicit formalised statement:[13] 'There is not a sentence which adequately states its own meaning. There is always a background of presupposition which defies analysis by reason of its infinitude'. Hence, strictly speaking, nothing we say can be said precisely: every act of explicit statement bears with it a reference to some thing or experience, which at the moment of utterance, remains tacit and fundamentally incomplete. While we can explicate some of the particulars to which we are tacitly referring, this explication only brings forward new tacit presuppositions which would themselves require explanation, *ad infinitum*.[14]

Ultimately, it follows, to know something is to rely on pragmatic 'common sense' (or a Duhemian *bon sens*) in the face of fundamental incompleteness. Explicit knowing, then, while being a 'superb instrument', ultimately 'requires a background of common sense', or tacit knowledge, for its operational basis (Whitehead, 1948: 74). While tacit knowledge can be possessed or embodied in itself, explicit knowledge must rely on being tacitly understood: all knowledge is '*either tacit* or *rooted in tacit knowledge*' and a '*wholly* explicit knowledge is unthinkable' (Polanyi, 1969: 144). It follows, contra the caricaturised 'early Wittgenstein', that we should not stay 'quiet about what we cannot speak of', as this would very fundamentally contradict the nature of human knowledge. Formalising all knowledge to the exclusion of any tacit knowledge is evidently self-defeating (Polanyi, 1969: 133; 1974: 87 and 91; 2009: 20).

Formalisation can and does immensely expand the powers of the mind, but only when explicit rules sink into the tacit matrix (Polanyi, 1969: 156). Rules or maxims do not determine the practice of the art when alienated, and maxims are only successful guides when embodied and integrated into practice (Polanyi, 1974: 49 and 162). Furthermore, when explicit maxims are 'interiorised' (embodied) into the tacit domain, they become faster and more intuitive (Polanyi, 1969: 144). This is akin to what Dreyfus and Dreyfus (in Flyvbjerg, 2001: 9–24) and Collins and Evans (2007) call 'expertise': fast, holistic, non-rule-based, intuitive and embodied decision-making. It is also what Rochlin (1997) simply calls 'having the bubble'.

Polanyi argues (1969; 1974; 2009) that the relation between tacit and explicit modes of knowledge is based on the distinction between 'subsidiary' (proximal) and 'focal' (distal) awareness, and what Polanyi calls the 'from–to' structure of knowing. In essence, the argument follows: knowledge is formed in integrating embodied tacit particulars into an explicit whole (Gestalt), to which we attribute meaning. A physiologist who has completely mapped all that takes place in the eyes and brain of a human being does not see what the

13. It is perhaps noteworthy that much of Polanyi's (1974) philosophy is influenced by Gödel's incompleteness theorems.

14. A clear analogy here could be drawn to the Duhem thesis: no scientific hypothesis can be tested in isolation, since any empirical test is dependent on interconnected auxiliary hypotheses.

human being subject to the mapping sees, because the physiologist is merely looking 'at' these happenings and not attending 'from' them 'to' something – this is, of course, not to deny that the physiologist might learn something useful from the mapping process (Polanyi, 1969: 147).

This is particularly what Polanyi (1974; 2009) refers to when claiming that we cannot learn an art – or science – by simply learning its maxims, but we learn through experience and its bodily internalisation. Only when we subsidiarily interiorise or embody an art or scientific theory can we focally interpret things in its light. We attend from tacit subsidiary awareness to focal explicit awareness. Therefore, to rely on a theory for understanding nature is to interiorise it, or to 'dwell' in it (Polanyi, 2009: 17). This is, for Polanyi, the bodily root of all knowledge, and this is also why I consider Polanyi akin to processists. Polanyi (2009: 15) argues that our bodies are the ultimate instruments of all our external knowledge, whether intellectual or practical. Since our body is involved in the process of perceiving external objects, it participates in the process of knowing external things by 'dwelling' in them – it follows that the subject and object are necessarily merged in the act (or process) of knowing (Polanyi, 2009: 29). Indwelling applies to all forms of knowledge, both practical and intellectual: just as we dwell in the hammer to drive in a nail, we dwell in a scientific theory to make sense of empirical observations (Polanyi, 1974: 60). Both are acts of skill and connoisseurship, and both involve a degree of personal commitment, which is hence involved in all acts of intelligence (Polanyi, 1974: 61). In both acts, consequently, we also rely on embodied tacit knowledge.

Herein, I believe, lies the fundamental insight of Polanyi's philosophy for environmental policy and philosophy. Let us first assume, like Polanyi does, that intellectual and practical knowledge are both bodily functions fundamentally embedded in the tacit domain. It follows, therefore, that any feat of environmental behaviour is not fundamentally rooted in rational explicit knowledge of nature, but rather in our tacit belief frameworks and embodied experience in relation to nature. Consequently, our focal awareness of the environment – that is, the way we experience our environment and attach meaning to it – is embedded in a subsidiary framework which we have tacitly interiorised, embodied, and been 'habituated' to (Dewey, 1958: 14). Polanyi (2009: 17) calls this the 'tacit framework for our moral acts and judgments', the framework 'from' which we attend 'to' things seen in its light. In other words, we have a tendency to project our conceptual worldview (which at the moment of observation remains tacit) onto how we focally experience, or dwell in, the world.[15]

15. Note that this personal co-efficient of knowledge is not, in a fundamental sense, subjective (nor a pure 'social construct'), as it is reciprocally shaped by our dynamic interaction with the socio-ecological environment. It would be a dire misrepresentation to portray Polanyi as a subjectivist, despite his obvious distaste for impersonal objectivism.

It follows, then, that similarly to how the layperson is unaware of the tacit knowledge underlying an act as simple as riding a bike, the layperson – or even the expert – is unaware of the primary tacit metaphysical frameworks from which meaning is attached to the socio-ecological environment. This implies that our environmental action and its precedent moral judgments are tacitly grounded in the (relatively static) metaphysical framework we have embodied [16] – through culture, tradition, conviviality, authority, and (not least) ecological and evolutionary processes[17]– and ultimately result in the focal experience by which we *prima facie* confront the world and attach meaning to it (Polanyi, 1974: 207). We 'believe many things not because they are so', but because we have been habituated through 'unconscious effects' to do so (Dewey, 1958: 14). We dwell, subsidiarily, in tacit embodied metaphysical convictions, which manifest in our focal awareness of the world: we attend from our tacit belief systems to our explicit manner of attaching meaning to the world.

I have already established above that the dominant metaphysical conviction in which we dwell is one where substance is asymmetrically biased over process. Since knowledge is an activity better described as an embodied 'process of knowing', modifying this 'tacit framework' changes how we dwell in the world (Polanyi, 1969: 134). In other words, tacit belief frameworks manifest themselves in how we act towards nature and the environment. As Dewey emphasised, 'the *ways* in which we believe and expect have a tremendous effect upon *what* we believe and expect' (1958: 14). That such metaphysical convictions, for most, are tacit does not make them any less real, since all knowledge is fundamentally rooted in its tacit predecessor.

While it then follows that this tacit framework will escape any complete explicit formalisation, it is reasonable and justifiable to apply pragmatically incomplete measures to attempt to explicate an environmentally unsound tenet of metaphysical thought in which much of our civilisation dwells. I suggested above that we live in a framework of substance metaphysics, where the human has separated itself from nature and has justified its abuse of its environment at the price of both its own and the environment's well-being. As Honig et al. (2015) note, altering environmental behaviour requires a novel understanding of how society and earth systems are connected, yet to achieve this it is simply not enough to attempt to modify human–environment interaction through building on explicit or rational knowledge. A more thorough Gestalt shift in how we attend to the world is required, and I suggest that process philosophy can serve as the metaphysical basis for this thorough reinterpretation of

16. An analogy can be drawn here to Bijker's 'technological frames' (2007: 122). Just as technological frames induce stability in 'ways of thinking' and 'fixed patterns of interaction', people dwelling in particular metaphysical tacit frameworks 'will find it difficult to imagine other ways of dealing with the world'.

17. Indeed, to omit biological factors from this list would be folly, although further addressing the question of 'innate cognitive dualism' is outside the scope of this article (for an overview, see e.g. Slingerland, 2008).

human–environment interaction. To dwell in a tacit framework of process, due to the five tenets mentioned in Section 2.3, arguably has the potential to be more sustainable and environmentally sound than a substance-biased framework. It is the implementation of this framework, which Gare (1996) has dubbed a 'metaphysics of sustainability', that is left for environmental policy-makers to consider.

4. CONCLUSION AND DISCUSSION

So far I have suggested that some of the most environmentally pathological 'bifurcations of nature' arise from substance-biased metaphysics, and we therefore might have sufficient reason to look at alternative frameworks for interpreting, and thus dwelling in, reality. As has been noted, a process metaphysical approach might be able to play the role of such an alternative, due to its emphasis on the reality of 'change' in nature and the fundamental interconnectedness it ascribes to artificially-bifurcated entities such as 'human' and the 'environment', or 'products' and 'processes'. Using Polanyi's theory of knowledge, we can draw a fundamental line of interconnection between the mental and physical processes of knowing, which suggests that the ways in which we tacitly apply meaning to the world have fundamental effects on how we dwell in our environment. Yet while these insights are valuable in themselves, they can also be regarded as pragmatic instruments for facilitating the development of a sustainable culture. Therefore the evident question remains of how to go about changing the most unsustainable mental models, in which human and nature are bifurcated.

Education, of course, would be the most obvious means. This comes as no surprise, since two major figures quoted in this article, Whitehead and Dewey (and to a slightly lesser extent, Polanyi) deeply emphasised the role of education in social progress. Common to these thinkers was a 'process' approach to education; that is, learning should happen through participatory, experiential, transdisciplinary and pragmatic means. Environmental education should not be substance-biased (i.e. merely learning 'about' things), but rather learning through process (i.e. participation and direct experience, thus building on tacit knowledge and expertise). These ideas are in line with claims that strictly rational or explicit learning methods are not sufficient to induce sustainable behavioural patterns (see e.g. Kollmuss and Agyeman, 2002). Indeed, other behaviour-affecting parameters suggested in sustainability research, such as values, attitudes, socio-economic processes, awareness, affect, interconnection and involvement could all be interpreted to be at the heart of the process-philosophical inquiry (Kollmuss and Agyeman, 2002; Honig et al., 2015; Richardson et al., 2015).

Yet due to the urgency of the issue at hand – the direct pro-environmental effects of educational reforms, for instance, might take a generation to fully kick in, far too slow to tackle immediate ecological crises – it is the responsibility of environmental policymakers to consider supplements to educational methods and more traditional policy means, in order to swiftly move civilisation towards sustainable dwelling. Recent discussions in environmental policy (Hukkinen, 2012, 2016), drawing insights from theories of embodied cognition (e.g. Lakoff and Johnson, 1999), have addressed the 'nudging' of mental or cognitive models in order to induce sustainable behaviour patterns. Nudging in this context is to be interpreted as the political means of designing 'cognitively attractive and empirically sound mental models that have the capacity to alter people's behaviour toward socio-ecologically sustainable transitions' (Hukkinen, 2012: 2).[18]

Since I have already addressed the fact that tacit substance-biased mental models might be at the very heart of unsustainable thinking, I propose that policy-makers could find particular interest in process philosophy when designing sustainable cognitive models. Nudging towards process-biased thought could happen, for example, by perpetual and repetitive use of process-relational metaphors (see e.g. Table 1) in textual or visual contexts in environmental communication, since the 'process' of process thought itself starts with the simple substitution of the fundamental metaphor 'things are static' (substance) with 'things are dynamic' (process). While the concrete development of sustainable process-biased cognitive models is beyond the scope of this article, what should be briefly discussed is what exactly might be expected to result from them.[19]

The intended result is the evocation of what is perhaps best described as 'double-loop' thinking. Instead of thinking of things 'as substance' (single-loop), the trick to process-relational thought is to think of 'substance through process' (double-loop).[20] In Polanyi's (2009) terminology, the process-loop would represent the 'tacit dimension' of thought, whereas the substance-loop would represent the business-as-usual 'explicit' dimension. What results is, essentially, 'thinking about thinking', with the caveat that 'thinking' here should largely happen in the tacit dimension for it to be truly habitual and consistent – this is, essentially, 'tacit metacognition' (Swartz and Perkins, 1990).

18. I agree with Hukkinen (2016) that while nudging is not ethically unproblematic, the 'fate of human beings as socially and materially circumscribed organisms is to constantly nudge and be nudged'. Nudging can be criticised on democratic grounds – although I would not regard it as 'eco-authoritarian' (Shahar, 2015) – but a truly undemocratic society would prevail in a post-ecocide future, and it is the responsibility of political actors to prevent this future from occurring.
19. See the 'roller-coaster blend' in Hukkinen (2012) for what I regard a sustainable process-relational cognitive model.
20. Recall Rescher's metaphor of substance arising from a 'sea of process'.

If successfully implemented, it is not a long stretch to see this resulting in more sustainable behaviour. Complementing substance-bias (e.g. 'I need this thing [substance]…') with process-bias (e.g. '…but this thing emerged from [$process_1$] and will result in [$process_2$]') could result in more sustainable consumption patterns, as well as heightened environmental consciousness. To imagine this scenario in, for example, a mundane grocery-store setting is even less far-fetched. The single-loop mental scenario 'go to a store [store-substance] and buy familiar food [grocery-substance]' should be replaced by a double-loop mental model of 'think of how to get to the store [process of transport] and how products have become [process of production] and shall become [process of disposal]'. Think of how, for example, the coastline paradox was used above to reframe how we think of an island (from 'island as substance' to 'island as environmentally embedded process'), and how similar mental models could be used to reframe a variety of human–environment relations. Moreover, as was noted in Section 2.3, this tacit substance-bias can also be tackled by other policy means, for example by increasing the frequency of direct feedback in consumption processes (Abrahamse et al., 2007), yet these are only a few of the many potential process-biased tools that policymakers can consider and experiment with.

Again, however, as important as mental models are for sustainability transitions, all this comes with the significant caveat that developing sustainable mental models should never happen inseparably from broader systemic change, whether it be social, political or economic. The focus should instead be on overcoming this dichotomy between mental models and macro systems, by promoting the design of sustainable 'affordances' (Heft, 2001), or behavioural settings which build the necessary pro-environmental capability sets (Sen, 1995) to facilitate the behavioural realisation of sustainable mental models. While further processual investigations and applications are, for now, left to the imagination of the reader, I believe applied process philosophy could prove to be a fruitful framework for environmental policy developments, and therefore play a particularly innovative part in the transition towards a sustainable future.

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II

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Affording Sustainability: Adopting a Theory of Affordances as a Guiding Heuristic for Environmental Policy

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Human behavior is an underlying cause for many of the ecological crises faced in the 21st century, and there is no escaping from the fact that widespread behavior change is necessary for socio-ecological systems to take a sustainable turn. Whilst making people and communities behave sustainably is a fundamental objective for environmental policy, behavior change interventions and policies are often implemented from a very limited non-systemic perspective. Environmental policy-makers and psychologists alike often reduce cognition 'to the brain,' focusing only to a minor extent on how everyday environments systemically afford pro-environmental behavior. Symptomatic of this are the widely prevalent attitude–action, value–action or knowledge–action gaps, understood in this paper as the gulfs lying between sustainable thinking and behavior due to lack of affordances. I suggest that by adopting a theory of affordances as a guiding heuristic, environmental policy-makers are better equipped to promote policies that translate sustainable thinking into sustainable behavior, often self-reinforcingly, and have better conceptual tools to nudge our socio–ecological system toward a sustainable turn. Affordance theory, which studies the relations between abilities to perceive and act and environmental features, is shown to provide a systemic framework for analyzing environmental policies and the ecology of human behavior. This facilitates the location and activation of leverage points for systemic policy interventions, which can help socio–ecological systems to learn to adapt to more sustainable habits. Affordance theory is presented to be applicable and pertinent to technically all nested levels of socio–ecological systems from the studies of sustainable objects and households to sustainable urban environments, making it an immensely versatile conceptual policy tool. Finally, affordance theory is also discussed from a participatory perspective. Increasing the fit between local thinking and external behavior possibilities entails a deep understanding of tacit and explicit attitudes, values, knowledge as well as physical and social environments, best gained via inclusive and polycentric policy approaches.

Keywords: ecological psychology, affordance theory, pro-environmental behavior, attitude–action gap, environmental policy, socio–ecological systems, nudging, radical embodied cognitive science

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INTRODUCTION

Human behavior is a common determinant underlying most of the major ecological crises of the 21st century, and there is simply no escaping from the fact that behavior needs to be changed for socio-ecological systems to take a sustainable turn (Steg and Vlek, 2009; Antal and Hukkinen, 2010). Yet whilst making people and communities behave pro-environmentally is one of the fundamental targets of environmental policy, this foundation is surprisingly often left unspoken, or at least understood from a very limited, non-systemic, perspective. The aim of the present article is to elaborate pro-environmental behavior change policy and intervention analysis by introducing a theory of affordances to the environmental policy community. Affordance theory, which interprets environmental behavior from a dynamical and coupled *systems* or *ecological* approach (Gibson, 1979), is shown to be a promising heuristic for systemic behavior analysis. Particularly, it can help policy-makers locate and make use of 'leverage points,' or places where small changes can lead to large shifts in a system's behavior, for systemic behavior change interventions (Meadows, 1997, 2008; Lockton, 2012). This can help not only individuals, but whole socio–ecological systems to learn to adapt to more sustainable habits.

Affordances are defined in this paper as the 'relations between abilities to perceive and act and features of the environment' (Chemero, 2009, p. 150). As Guagnano et al. (1995) and Jackson (2005) note, such integrative approaches, which take into account the dynamical relations between 'internal' and 'external'[1] behavior antecedents, have traditionally been lacking. I argue therefore that a theory of affordances has a particularly valuable niche to occupy within the multidisciplinary field of environmental policy, since it effectively crosses the artificial divide between internal and external behavior antecedents and studies the dynamical and coupled systems relations between human actors and their (physical and socio-cultural) environment. Moreover, affordance theory invites us to study how this behavior system, as a whole, 'unfolds over time' (Chemero, 2013, p. 149). This, in turn, accounts for a more complete picture of environmental behavior and helps us understand why pro-environmental knowledge, values or attitudes are not alone sufficient to induce behavior change (the attitude–action gap), or why everyday environments fail to make the full use of our internal behavior potential. This is particularly relevant since the overwhelming consensus is that despite many or even most of us having pro-environmental attitudes, we are not behaving sustainably (Blake, 1999; Kollmuss and Agyeman, 2002; Abrahamse et al., 2005; Kennedy et al., 2009; Steg and Vlek, 2009).

In the present text, these mismatches between internal and external behavior antecedents are analyzed in terms of affordances, and it is suggested that by increasing pro-environmental affordances we can facilitate systemic and even self-reinforcing pro-environmental behavior change. Moreover, it is also argued below that an affordance-based approach to behavior change intervention can make the best use of the pre-existing latent pro-environmental behavior potential of both humans (capabilities to act, including attitudes, values, knowledge etc.) and everyday environments. This seems to call for a thorough understanding of latent behavior potentials of local populations, suggesting that affordance-based governance should be polycentric (or decentralized), inclusive and participatory, reducing local helplessness and increasing social acceptability.

The crux of this article is therefore to make a case for adopting a theory of affordances as a guiding heuristic for environmental policy. With a heuristic, I mean a fast instrumental and conceptual tool which facilitates 'exploring and conceptualizing' pro-environmental behavior, also helping us to 'identify points of policy intervention' (Jackson, 2005, vi). A successful heuristic facilitates quick decision-making and helps avoid costly errors. By adopting a theory of affordances as a guiding heuristic, I argue that policy-makers and scholars are better equipped to systemically analyze the ecology of pro-environmental behavior, understand the dynamics between its internal and external antecedents, as well as design appropriate policy interventions.

Adopting the definition from Steg and Vlek (2009, p. 309), environmental behavior is defined in this paper as 'all types of behavior that change the availability of materials or energy from the environment or alter the structure and dynamics of ecosystems or the biosphere.' Pro-environmental behavior (abbreviated hereafter as PEB), correspondingly, 'refers to behavior that harms the environment as little as possible, or even benefits the environment' (ibid.). The question of what exactly counts as pro-environmental and what does not is not problematized further within the scope of this paper. However, it is worth emphasizing that harming the environment as 'little as possible' is not necessarily *pro*-environmental and that pro-environmental behavior in one domain or context might emerge as unsustainable in another.

The body of this article is divided into three main sections. Firstly, in section "The Attitude–Action Gap, or Why We Don't 'Walk the Talk"' the attitude–action gap and its relevance to environmental policy is briefly discussed. Particularly, I suggest that, all too often, pro-environmental behavior research has limited its focal variables to either internal (e.g., values, attitudes, personal norms, habits, and knowledge) or external (e.g., physical infrastructure, economic factors, and institutions) ones (see Jackson, 2005 for an overview). I argue that to overcome the barriers between pro-environmental motivations and behavior, we must understand how our everyday environments provide or constrain the actualization of our pro-environmental internal factors. This requires the simultaneous and dynamical inspection of both internal and external behavior antecedents, as well as particular focus on how these dynamics evolve over time (Chemero, 2013). In section "A Theory of Affordances," drawing particularly on ecological psychology (e.g., Gibson, 1979) and recent advances in radical embodied cognitive science (e.g., Chemero, 2009), I argue that a theory of affordances provides an effective heuristic framework for studying these coupled and dynamical human–environment behavior systems. In section "Affording Sustainability" I discuss the policy-relevance and potential applications of affordance theory, where affordances can be utilized as leverage points to induce systemic behavior change. In section "Affording Sustainability" I also include a brief meta-empirical survey of how affordance-like ideas have

[1]I acknowledge here, at the very beginning of this text, that the use of the terms 'internal' and 'external' imply a dichotomy that, ontologically speaking, simply does not exist (it is a 'false dichotomy'; Gibson, 1979). Indeed, this paper is devoted to show that they are not dichotomous, and are instead mutually implicative and systemically relative (there is no internal without external). However, due to linguistic insufficiencies I maintain that a cautious upholding of this dichotomy is necessary for pragmatic purposes.

been implemented in environmental policy and psychology, and discuss how intentional adoption of a theory of affordances can hasten the arrival at well-functioning policies at various nested systemic levels. Section "Conclusion" concludes the article.

THE ATTITUDE–ACTION GAP, OR WHY WE DON'T 'WALK THE TALK'

It is widely accepted amongst those studying pro-environmental behavior (PEB) that a significant gap lies between possessed values, knowledge and attitudes and behavior (Blake, 1999; Kollmuss and Agyeman, 2002; Abrahamse et al., 2005; Jackson, 2005; Kennedy et al., 2009; Steg and Vlek, 2009). In other words, an attitude–action gap, a knowledge–action gap or a value–action gap exists between internal human factors and behavior patterns. For practical purposes, I from here on refer to this discrepancy between internal factors (such as attitudes, values, knowledge, personal norms, intentions and emotions) and behavior simply as the attitude–action gap, humbly acknowledging that this does a disservice to the great body of research focused on studying the relationships between these individual internal factors and pro-environmental behavior (see Kollmuss and Agyeman, 2002; Abrahamse et al., 2005; Steg and Vlek, 2009 for an overview on the topic).

The attitude–action gap does not imply that internal factors do not have *any* effect on pro-environmental behavior, but rather that a great amount of PEB cannot be explained with internal factors alone. Generally, it seems that internal factors are more likely to lead to change in low-cost (low in time and effort) actions than in high-cost behavior (Kollmuss and Agyeman, 2002; Abrahamse et al., 2005; Steg and Vlek, 2009), although not all research fully supports this (e.g., Hunecke et al., 2001). Moreover, the case seems to be that internal factors seem to correlate more strongly with behavior when they are specific to a certain domain. This is, perhaps, common sense: positive recycling attitudes strongly predict recycling behavior (and not, for example, travel behavior), whilst more generic pro-environmental values do so only to a much lesser extent (Vining and Ebreo, 1992).

The attitude–action gap is, at the root of it, rather intuitive. Many people with pro-environmental intentions will have experienced the uncomfortable feeling of cognitive dissonance when they have taken part in environmentally harmful yet seemingly banal activities such as air travel. Simply, as Vining and Ebreo (1992, p.1604) observe, 'it is easier to be concerned about the environment than it is to act on one's convictions.' This mundane and banal phenomenon, however, takes on direct policy relevance when combined with an urgent need for humans to change their behavior patterns and habits to tackle ongoing ecological crises. We talk the talk, but systemically fail at 'walking the talk' (Kennedy et al., 2009). Since significant portions of national populations are pro-environmentally motivated, translating these latent pro-environmental behavior potentials into action becomes an imperative task for environmental policy. For one example, Kennedy et al. (2009) found that Canadians adhere much more strongly to the 'New Ecological Paradigm' world-view (which states, inter alia, that 'humans and other species are intricately connected') than to the so-called 'Dominant Social Paradigm' ('mankind was created to reign over the earth').

A comprehensive literature review on the attitude–action gap is beyond the scope of this article. Fortunately, such work has already been done, notably by Kollmuss and Agyeman (2002), Abrahamse et al. (2005), Jackson (2005), and Steg and Vlek (2009). Briefly, however, it should be noted that studies on the relations between mental models and behavior have progressed significantly from the oldest and simplest models known as 'rational,' 'linear,' or 'information-deficit' models, which established a direct linear relation between knowledge, values and behavior. More complex and nuanced models have taken into account how attitudes, norms, beliefs, intentions, emotions, affect, altruism, locus of control, self-identity and a large variety of other variables influence pro-environmental behavior, also including sociological factors, situational variables and, to a somewhat limited extent, the structural and physical environment (Steg and Vlek, 2009, p. 314).

I argue, however, that many of these accounts on pro-environmental behavior – important as they are for understanding the complexities of human practices – suffer from a very fundamental a priori assumption, which limit cognition 'to the brain' (Rockwell, 2005). In this paradigm, often implicit in environmental psychology, contextual factors, if considered at all, have usually been 'introduced in the form of subjectively perceived environment,' and not as systemic ecological situations (Hunecke et al., 2001). Moreover, when the effects of external (such as economic) factors on behavior have been studied, it has often been done so with the cost of excluding internal human factors. Integrative approaches, which take to account the dynamical coupling between internal and external behavior variables, have traditionally been scarce (however, see Guagnano et al., 1995; Stern, 2000; Hunecke et al., 2001; Jackson, 2005).

This is, of course, traceable to a long tradition of Cartesian materialistic thinking, often implicit in the psychological and cognitive sciences (Heft, 2001; Rockwell, 2005; Chemero, 2013; Ch. 7 in Reed, 1996). That is, the notion that behavior and cognition are *ecological*, construed dynamically in an ecological system, is most often downplayed in favor of more limited approaches which reduce cognition and behavior to the internal domain (e.g., mental representations). Whilst this might be a pragmatic and even useful limitation at times, treating human cognition as a 'static' entity, ontologically separable from outside variables, can also be wildly misleading (Kurz, 2002, p. 269). What is suggested below is that rather than focusing on single static variables underlying behavior we should take a dynamical stance, such as that provided by a theory of affordances.

Affordance theory originates from the field of empirical and theoretical research known as *ecological psychology*. Ecological psychology draws mainly from perceptual psychologist James J. Gibson's work (most influentially Gibson, 1979), which emphasizes the dynamical and systemic coupled relations between animals and their physical environment. As used in this text, ecological psychology should not be confused with environmental psychology or other strains of research going by the name of ecological psychology (such as Roger Barker's), although many similarities between these fields exist (see Heft, 2001 for a useful overview). I argue that ecological psychology and its more recent descendants in radical embodied cognition theories (e.g., Chemero, 2003, 2009, 2013 as well as Rockwell, 2005) should be revisited in order to understand more comprehensively the role our everyday and urban environments play in shaping our environmental behavior. This is elaborated in detail in sections "A Theory of Affordances" and "Affording Sustainability" in the form of a theory of affordances.

A few caveats are in place before moving onward. I am not proposing a silver bullet to solve the problem of the attitude–action gap altogether. As Kollmuss and Agyeman (2002, p. 248) rightly note, the gap is 'such a complex one that it cannot be visualized in one single framework or diagram.' This is wholly unsurprising from a systems theoretical point of view, where it is generally understood that no static conceptualization or model can capture the whole complexity of a contingent system (Meadows, 2008). Indeed, to map the complete causality underlying a behavior system is practically impossible, since it would take an astronomical scale (Rockwell, 2005). Accordingly, 'there will always be something of a tension between simplicity and complexity' in modeling behavior, and a 'good conceptual model requires a balance between parsimony and explanatory completeness' (Jackson, 2005, p. 23, vi). Therefore, what is merely suggested below is that a theory of affordances provides us with a pragmatic (see Rockwell, 2005) and adaptable heuristic for understanding and intervening with behavior from a systems perspective. Such a heuristic not only facilitates and hastens the arrival at working policy solutions, but also importantly helps us avoid unintended consequences and making costly mistakes. For now, in section "A Theory of Affordances," however, it is in place to provide a more detailed description of what exactly we mean when talking about a theory of affordances.

A THEORY OF AFFORDANCES

An affordance, in its simplest – yet most philosophically impoverished – definition, refers to the action possibilities provided by objects or environments. Whilst, as is elaborated below, the concept is in fact significantly more nuanced than this, the aforementioned definition of affordances has been widely adapted by, for instance, the design community: 'when used in this sense, the term *affordance* refers to the perceived and actual properties of the thing, primarily those fundamental properties that determine just how the thing could be possibly used' (Norman, 2002, p. 9). It follows then, that a chair provides support and thus *affords*[2] humans with (or 'is for') sitting. Apples afford, among a huge variety of behavior, throwing, eating, baking and cutting. Bananas afford – explaining their huge urban popularity – easy, fast and locally clean eating as well as exportability, since they ripen after picking.

However, a more nuanced treatment of affordances does not consider affordances as *properties* of objects or environments, but rather in terms of ecological situations. As Chemero (2003, 2009) remarks, affordances are functionally meaningful features of whole situations. These whole situations are better defined as fluctuating behavioral fields emerging from brain–body–world interaction (Rockwell, 2005, 2010). Here, the similarity to Lewin's (1951) field theory, a theory positing human behavior as "a function of a dynamical 'field' of internal and external influences," is obvious (Jackson, 2005, p. 26; see also Heft, 2001). Affordances from this more refined perspective are not – contra the popular understanding (see e.g., Kurz, 2002; Norman, 2002) – dispositional properties of things or environments, but rather functionally meaningful 'relations between abilities to perceive and act and features of the environment' (Chemero, 2009, p. 150; c.f. Turvey, 1992). The environment here is to be understood to refer to the whole of the material world, physical, cultural and social environments included. This is the definition of affordances used in the remainder of this text.

Affordances are therefore dynamical and coupled organism–environment relations, hence through and through systemic and ecological (Chemero, 2009). A chair, given the right conditions, affords sitting for an erect bipedal species such as ours, whilst its affordances are wholly different for other species not adapted to walk and sit. Affordances are therefore not 'psychologies of things' (contra Norman, 2002), but rather psychologies of organism–environment relations. Affordance theory posits that active cognitive agents perceive and experience the world in terms of affordances, or functionally meaningful relations with the environment. We do not perceive the world passively as having pre-given objective and action-neutral properties, but rather as active opportunities for action (Ramstead et al., 2016). Our everyday lives are ridden with affordances, and they are continuous, dynamic, reciprocal and evolutionary processes: affordance-sets constantly affect organisms and populations, whilst organisms continuously adapt to and modulate the niches (or sets of affordances) they inhabit (Heft, 2001, xxix; Chemero, 2003, p. 190; Reed, 1996, p. 26).

The ontology of affordances is therefore one which attempts to effectively cross the artificial subject–object divide (Chemero, 2009).[3] This is perhaps best captured by the following oft-cited, yet slightly cryptic, quote by Gibson (1979, p. 129):

[2]The transitive verb *to afford*, in the whole of this text, should be read to imply the meaning 'to make available, give forth, or provide naturally or inevitably' (as defined by the Merriam-Webster dictionary). This should not be confused with the more common definition 'to be able to bear the cost of' something. The noun *affordance* is a neologism coined by ecological psychologist James J. Gibson (see e.g., Gibson, 1979) and, of course, refers merely to the former definition of the verb 'to afford.' To cite Gibson (1979, p. 127) himself, 'The verb *to afford* is found in the dictionary, but the noun *affordance* is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment.'

[3]I suggest that affordances are best interpreted via an anti-Cartesian ontology, which does not separate subjects from objects. Good candidates for such an ontology can be found in early American pragmatism, for instance the works of John Dewey (e.g., Dewey, 1958) and William James (see Heft, 2001). This is no coincidence, since Harry Heft's (Heft, 2001) brilliant exposition on ecological psychology reveals James' radical empiricism's direct influence on James J. Gibson's ecological psychology. Common to these perspectives is the ontological priority of *processes* over *substances*, sometimes labeled 'process metaphysics' or 'process philosophy' (Rescher, 1996, 2000). For an introduction to process philosophy see the work of Nicholas Rescher (Rescher, 1996, 2000), and for an interpretation of process philosophy in the context of environmental policy, see Kaaronen (in press).

> 'an affordance is neither an objective property nor a subjective property; or both if you like. An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points bothways, to the environment and to the observer.'

Whilst this might seem unnecessarily muddling and counterintuitive to some – or even violative toward the law of non-contradiction (*viz.* 'neither an objective property nor a subjective property' or 'both if you like') – Gibson's definition contains a valuable insight: when understood ecologically, behavior is not constrained to the perceiver nor to the perceived, but is rather a dynamical and coupled systems relation between the perceiving organism and the environment it inhabits. From this perspective, it is distasteful to reduce cognitive systems to the brain (or even body), but cognition and behavior rather emerge over time from a 'dynamical brain–body–world nexus' (Rockwell, 2005; Anderson et al., 2012; Hutto and Myin, 2012). Hence affordances imply a degree of extended cognition: the perceived world is not construed by the brain or mind, but rather emerges from the interaction between a nervous system, a body capable of perceiving and an environment which affords perception (via, for example, latent information in the form of structured ambient light in the environment) (Gibson, 1979; Reed, 1996; Chemero, 2003, 2009; Rockwell, 2005, 2010; Anderson et al., 2012). Affordance theory implies that meaning is not construed by the brain alone (by any means of 'mental gymnastics'), nor is it merely a social construct, but rather is latent in the environment and (directly) perceivable in organism–environment interactions (see the 'radical embodied cognitive science' of Chemero, 2003, 2009). In contrast to inferential theories of perception, where 'meanings arise inside animals, based on their interactions with the physical environment,' affordance theory suggests that 'the animal simply gathers information from a meaning-laden environment' to actualize some function (Chemero, 2003, p. 181; see also Gibson, 1979, p. 238–263). Meaning, cognition, perception, and thus also behavior, are thoroughly ecological. Hence, of course, *ecological* psychology.

Importantly, as Gibson's quote above implies, affordances are not idealistic (in the ontological sense), and despite their hardly tangible nature, affordances are indeed real, perceivable and empirically observable (Chemero, 2003, 2009; Heft, 2003; c.f. Kurz, 2002 who, among others, claims affordances are mere subjective perceptions). Chemero (2003, p. 187) suggests that for us to understand affordances we should consider the 'taller-than' in the statement 'Shaquille is taller than Tony.' The taller-than is neither a property of Shaquille or Tony, yet it is still an empirically observable and real relation in the whole situation. Affordances are equally real. To further elaborate, Chemero (2009, p. 150), drawing on Dennett (1998), likens affordances to the state of being 'lovely': a hippopotamus can continue to have the potential for being lovely even when it is not, at that moment, observed by another organism. In other words, the hippopotamus' physical structure has latent *potential* to be lovely for a *potential* observer, even if the affordance of 'being lovely' is only actualized when complemented by another organism which has the abilities to perceive and experience its latent loveliness, given that the right conditions are met. Affordances are, as Chemero (2003, p. 193) notes with dry wit, 'lovely.'

Our everyday lives make use of innumerable affordances even when we are not conscious of them (I would argue that we mostly are not), and affordances do not require us to be able to consciously locate them. Take for instance Polanyi's (1958/1974, 1966/2009) well-known example that we can, without effort, recognize familiar faces without being able to explicate how we achieve this (i.e., familiar faces afford recognition).[4] A similar tacit use of affordances is illustrated by the so-called 'gaze heuristic,' by which humans (and, it seems, dogs) can catch flying objects unconsciously (and without any mental gymnastics such as trajectory calculation) by simply fixing their gaze on the object, starting to run, and adjusting running speed so that the angle of the gaze remains constant (see the 'ecological rationalism' of Todd and Gigerenzer, 2012). The 'catchability' affordance of an object is, therefore, specifically an active organism–environment relation. Moreover, to tacitly recognize affordances is no trick unique to humans; all organisms are evolutionarily adapted to their ecological niche and can make sense of the affordances within it. Charles Darwin, who made less famous advances in animal perception, noted how earthworms very delicately adapt to the affordances within their ecological niche (see Reed, 1996, p. 20–28; Darwin did not, of course, use the term 'affordance'). We do not need to consciously recognize affordances to make use of them – certainly earthworms do not, at least not to our human standards of consciousness. However, we *can* knowingly identify and recognize affordances sufficiently for us to modulate them, as will be discussed in section "Affording Sustainability."

In this section I have asserted that organism–environment relations are coupled and dynamical systems. For our purposes, this means that human cognition and behavior are, on an ontological level, formed simultaneously, continuously and dynamically from both internal (organismic) and external (environmental) behavior potential. Moreover, affordance theory implies that we not only study the way external and internal factors cause changes in behavior, but rather 'the way the system as a whole unfolds over time' (Chemero, 2013, p. 149). **Figure 1** illustrates this as a coupled and dynamical feedback system. The rationale for modeling environmentally significant behavior in such a non-linear fashion, with potential for positive feedback (this is returned to in the following section), stems from affordance theory's recent resurgence in radical embodied cognitive science, which attempts to describe psychology by combining 'non-linear dynamical modeling with ideas about the nature of the mind' (Chemero, 2013, p. 145; see also Rockwell,

[4] Interestingly, Polanyi's philosophy of tacit knowing seems to have, to some extent, influenced Gibson (1979, 22, 260–261). Drawing on Polanyi, Gibson notes that knowledge can be said to be both *tacit* and *explicit*, but that there has to be a tacit 'awareness of the world' before it can be explicated ('put into words'); 'perceiving precedes predicating'. Gibson continues: 'However, skilled an explicator one may become one will always, I believe, see more than one can say'. See also Kaaronen (in press) for discussion on sustainability, M. Polanyi and affordances.

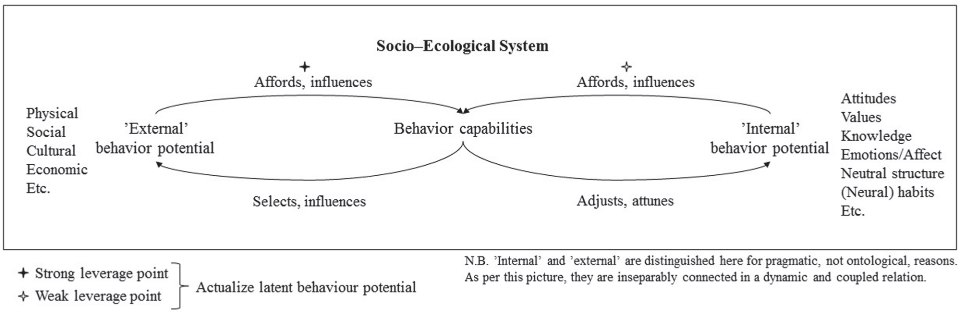

FIGURE 1 | The dynamical and ecological behavior system.

2005 and Chemero, 2009). This is necessary since, as Chemero (2013, p. 148) continues, it 'is only for convenience (and from habit) that we think of the organism and environment as separate; in fact, they are best thought of as forming just one non-decomposable system.'

Here we can identify a processual scheme dynamically interconnecting 'internal factors,' 'behavior capabilities' (e.g., socio–physical abilities to act) and 'external factors.' Importantly, this behavioral process is not linear, but all events (arrows) of the process are interconnected and active simultaneously and constantly. To paraphrase Gibson (1979, p. 240), behavior is a flux and not a sequence – a continuous evolutionary act which is ceaseless and unbroken. Behavioral systems are 'processual' and not discrete (in terms of process philosopher Rescher, 1996, 2000) or 'loopy,' and not 'linear' (as per enactivists Hutto and Myin, 2012: 6 or Varela et al., 1991). The ecological behavior system is dynamical (it evolves continuously) and coupled (its constitutive parts are interconnected, and a change in one variable results in changes in the others). This situation model in **Figure 1** represents, essentially, a self-organizing coupled dynamical system where 'the river molds the banks and the banks guide the river' (Bateson, 2000, p. 83). Whilst **Figure 1** presents internal and external factors as collections of variables, we could also choose this model to analyze dynamics between specific internal and external variables. Note also that whilst affordances are generally taken to refer to merely the arrow connecting external factors to abilities, I have also chosen to use the verb 'afford' to connect internal behavior potential with abilities. After all, the latent structure of internal factors affords individuals with behavioral abilities, even if not always to the same force as the structure of external factors. This figure is returned to with practical examples in the following sections.

I argue below that the notion that our everyday worlds are infused, often unknowingly to us, with innumerable affordances, takes on a very political nature. Whilst affordance theory is generally considered a realistic or naturalistic description of organism–environment relations, it can, and arguably should, also be politicized. What kinds of affordances do we reinforce, foster and inhibit, and how is this reflected in everyday behavior patterns? More precisely, how (if at all) do the most prevalent features in our socio–ecological system afford pro-environmental behavior, and are available affordances equal for different populations? Affordance theory presents us a framework for studying the ecology of human behavior, and particularly for focusing on how our everyday and urban environments systemically nudge individuals and local populations to behave in environmentally significant patterns and habits. A better understanding of local behavior potentials (internal and external) and their dynamics over time can facilitate the design of urban and everyday environments which help to actualize these potentials, resulting at best in self-reinforcing systemic learning patterns. This would suggest for local, decentralized (or polycentric) and even participatory governance, where policy-designers are more specifically attuned to local behavior potentials and capabilities. An imperative question arises here for those involved with environmental policy. How do we, as a society and culture, as individuals, as local communities, as policy-makers, *afford* sustainability? These issues are elaborated in the following sections.

AFFORDING SUSTAINABILITY

Having outlined the conceptual aspects of a theory of affordances, it is now time to consider its policy-relevance. I have suggested above that environmental policy-makers should adopt affordance theory as a guiding heuristic for policy development, particularly to understand the attitude–action gap in environmental behavior and target policy interventions to induce systemic behavior change. An efficient and coherent heuristic is more than a semantic advantage; a good heuristic model can shape the way in which we intuitively perceive the world and therefore promptly aid policy- and decision-makers in identifying points for policy intervention, hastening the arrival at working-as-intended policies and helping to avoid costly (in time, effort and money) mistakes (Jackson, 2005).

Since affordance theory provides us with a through-and-through systemic understanding of environmentally significant behavior, focusing on the dynamics between internal and external behavior antecedents, it helps us locate systemic leverage points (Meadows, 1997, 2008; Lockton, 2012) for policy intervention. Leverage points are here to be understood as 'places in the system where a small change could lead to large shift' in the system's behavior (Meadows, 2008, p. 146). Since environmental behavior is a coupled and dynamical system which evolves over time (see **Figure 1**), by making use of leverage points policy-makers have the capacity to help this system learn to behave more sustainably. This is in Bateson's (2000) terms *deutero-learning* (learning to learn), in other words inducing second-order change to the system to complement the usual first-order trial and error (environmental behavior as usual). By understanding and leveraging these feedback loops, we can, again quoting Bateson (2000, p. 274), 'not only solve particular problems but also form *habits* which we apply to the solution of *classes* of problems.' A central task for environmental policy-makers and scholars is therefore to help our socio–ecological system – not just its individual constituents – to learn to behave more sustainably. What follows is an attempt to describe such systemic learning.

To understand the attitude–action gap in terms of a theory of affordances, we should begin with asking why our everyday niches *do not* afford sustainable behavior. Here Norman's (2002) insights from cognitive science and design are of direct relevance for environmental policy. Norman (2002, p. 51) suggests that two 'Gulfs' separate internal mental states from being complemented by external physical ones, namely the Gulf of Execution and the Gulf of Evaluation.

The first of these gulfs is the Gulf of Execution, which exists when the actions provided by a system do not match those intended by a person, or when a system does not allow a person to execute the intended actions directly and without significant effort (Norman, 2002). In the case of the attitude–action gap then, this would equal to a person with high pro-environmental intentions (let us signify this here with INT+, for internal factors) yet with low action possibilities provided by their ecological niche (EXT−, for external factors).

The second gulf Norman (2002, p. 51) specifies is the Gulf of Evaluation. The Gulf of Evaluation exists when a system does not provide physical representations that can be directly perceived and interpreted in terms of intentions and expectations of a perceiver. In other words, the Gulf of Evaluation exists during lack of functionally meaningful feedback. For this Gulf to be crossed, the amount of effort that a person must exert to 'interpret the physical state of the system' must be low and the person must be able to determine how well their expectations and intentions are met. Systems should provide information that is easy to acquire and interpret, and match the way in which the person perceives the system. Because 'people generally do not know which and whose behaviors significantly affect resource use,' or at least such knowledge is bound to be vague and filled with misunderstandings, feedback is important from an educational point of view, giving instructions for future behavior (Steg and Vlek, 2009, p. 310). A system intended to overcome the attitude–action gap must therefore not only provide simple and comparative feedback, but also provide functionally meaningful 'feedforward' ('how to act from here on') (Lockton, 2012).

Consider now, drawing back on **Figure 1**, the attitude–action gap in terms of dynamical and coupled human–environment relations, or affordances. If a population's pro-environmental internal set (values, knowledge, attitudes etc.) is high (INT+) and we are witnessing a lack of behavior, the heuristic answer per a theory of affordances would be that the niche does not provide sufficient affordances for the actualization of the internal sustainability potential (thus EXT−). Most likely, this is due to insufficient action possibilities (Gulf of Execution) and feedback (Gulf of Evaluation).

Now, consider that by policy means we cross the Gulfs of Execution (make the system afford physical actions) and Evaluation (make the system provide feedback/feedforward). In other words, we alter our niche to have better capacities for actualizing our latent pro-environmental potential, thus increasing sustainable affordances. This would particularly entail intervening with the strong leverage point in **Figure 1** ('External' behavior potential → Behavior capabilities, or altering the material aspects of the environment). Now we have a coupled feedback loop of INT+ and EXT+. With the increase of affordances in our niche (via EXT+), the latent potential of INT+ can be actualized. That is not to say that intervening with the weak leverage point (see **Figure 1**) is unnecessary here, since abilities to utilize any external factors also have to be taught and learned – the case is merely that without the strong leverage point being activated (e.g., recycling being physically possible) no amount of weak leveraging will suffice.

A case example demonstrating such a positive sustainable feedback loop between internal and external factors would be a couple, call them Alfa and Beta, both possessing high pro-environmental attitudes and knowledge (INT+), and thus high latent potential for recycling, living in a suburban environment without easily accessible recycling systems (EXT− due to a Gulf of Execution; e.g., inconvenient drop-off recycling locations). Note also that their waste disposal system provides no feedback or feedforward as to how they are acting or how they should act (EXT−). To remind Alfa and Beta (say, via information campaigning) about their unsustainable action is unlikely to substantially change behavior, and it might at worst result in Alfa and Beta experiencing cognitive dissonance and thus blocking the dissonant information or delegating responsibility elsewhere (by means of self-justification).[5] Now, imagine a local environmental policy-maker, after surveying the local populations' environmental perceptions and identifying latent pro-recycling attitudes, deploys each household in the suburb with easily accessible curbside recycling systems (crossing the Gulf of Execution).

Alfa and Beta now have affordance for recycling (EXT+ and INT+). Moreover, since it is now convenient for them to recycle, the very act of recycling is likely to strengthen their pro-environmental identities and attitudes. One explanatory theory for this is the theory of cognitive dissonance, which suggests that humans have a tendency of adjusting attitudes to conform to behavior patterns (Cooper, 2007). This increase in internal behavior potential makes it possible now for Alfa and Beta to further adjust their ecological niche and fit their everyday environments with less wasteful affordances (e.g., by altering

[5]In fairness, it should be acknowledged that cognitive dissonance could, at best, result in Alfa and Beta going through excess measures to recycle (i.e., adjust behavior to match values), although it is arguably more likely that they take the 'path of least resistance'. As Cooper (2007, 8) notes, 'the relative ease of changing one's attitudes rather than one's behavior has made dissonance more relevant to attitudes than to any other concept.'

the prevalence of certain products and appliances). This again reinforces their pro-environmental identities, and so on. Whilst the recycling example is a mundane one (and arguably a minor factor in the global ecological crisis), it is one of the more researched fields of PEB and therefore serves the purpose here to illustrate such cyclic systemic learning patterns. Steg and Vlek (2009, p. 312) note, accordingly with the logic of **Figure 1**, that the 'introduction of recycling facilities may result in more positive attitudes toward recycling (e.g., because it is more convenient), and positive attitudes may in turn result in higher recycling levels.'[6] Vining and Ebreo (1992, p.1604) research on recycling similarly concludes (inter alia) that increased recycling opportunities (implementation of curbside recycling) not only significantly increased recycling behavior but also led to an increase in positive 'global environmental' and 'specific recycling' attitudes, thus 'strengthening already positive environmental attitudes.' Guagnano et al.'s (1995) study also concluded that having a curbside bin increased pro-environmental recycling behavior (by reducing barriers between latent pro-recycling attitudes and action) and, importantly, awareness of the social and environmental consequences of recycling. Moreover, a similar feedback loop (or 'positive interactive cycle') has also been found by Kyttä (2003, p. 98, Kyttä, 2004) in studies on child-environment relationships: a child-friendly environment 'allows a positive interactive cycle to develop between a child and the environment' where 'actualized affordances for their part motivate the child to move around more in the environment, which creates more possibilities for new affordances to become actualized.'

Basically, we have here the potential for systemic leveraging, where by actualizing a sufficient number of pro-environmental affordances (by intervening with the strong and weak leverage points of **Figure 1**) we can reinforce the pro-environmental identities and motivations of populations, which again further spurs PEB and potentially even further spontaneous pro-environmental modulation of everyday environments. In such a case we can imagine the behavior system in **Figure 1** running smoothly, and to an extent self-reinforcingly, evolving over time toward more sustainable habits. For Reed (1996), the whole notion of culture arises from this kind of bootstrapping, where the agglomeration and proliferation of certain types of affordances forms a 'field of promoted action,' which spurs new practices, ideas/inventions and socio-cultural interactions. This is also known as the 'ratchet-effect,' or the notion that human socio-technological culture accumulates (often irreversible) modifications over time (Tomasello, 1999; Tennie et al., 2009). This 'cultural ratchet' of cumulative learning, of course, also involves the social dimensions of teaching, social imitation and norm conforming (Tennie et al., 2009). We are no longer dealing here with individual organism–environment relations, but rather a 'rich landscape of affordances' (Rietveld and Kiverstein, 2014) which promotes certain social practices (see Shove et al., 2012) and reinforces what Ramstead et al. (2016) have recently called 'shared expectations' or 'local ontologies' of a population (behaving in ways which others expect one to behave). These shared expectations and local ontologies are embodied at various levels from brain networks, cultural artifacts and constructed environments, which further reinforce enculturated practices (ibid.).

For instance, when enough people are incentivized to recycle and the built environment supports this behavior (i.e., recycling is systemically afforded), it becomes a normalized social and cultural practice, or a cultural affordance, where we expect others to expect us to recycle (see section "Object-Level Affordances" for a case example). A cultural affordance in this context refers to the possibilities for action which depend on the skillful leveraging of 'explicit or implicit expectations, norms, conventions, and cooperative social practices' (see Ramstead et al., 2016, 3; although more specifically, Ramstead et al. call this a 'conventional' cultural affordance). The principal lesson here for those involved with environmental policies is therefore that by actualizing, or locating and activating in large enough numbers what I have called systemic leverage points, the recycling case being only one of innumerable possibilities, we not only promote individual sustainable behaviors but also reinforce the emergence of sustainable pro-environmental sociocultural practices and hasten the transition toward a more sustainable culture. This implies that we are essentially helping our socio–ecological system to learn more sustainable habits. A central task for those involved with environmental policies therefore emerges as the need to redesign our ecological 'niche,' or 'designer environment' (Ramstead et al., 2016), so that its rich landscape of affordances systematically promotes pro-environmental behavior. In such an ecological niche, pro-environmental behavior would emerge in many respects as the path of least resistance and the default form of life.

That is not to say that these positively reinforcing feedback loops would go on forever, since they would eventually settle down to, or oscillate around, some relatively steady state, depending on the availability of affordances, or be disrupted by external forces. Moreover, a single feedback loop might not spill over to other PEB domains (e.g., from recycling to increased bicycling), or at least current research is very dubious as to whether or not this is the case: spillover effects have been reported to be both positive (PEB in one domain leads to a PEB in another) and negative, where, quite concerningly, PEB in one domain rebounds as a lack of PEB in another (Truelove et al., 2014). The case seems to be, though, according to Truelove et al.'s (2014, p. 132) meta-empirical review, that "those who engage in a PEB because their environmental identity has been activated will be likely to exhibit positive spillover because the participants' role will get reinforced and strengthened as the result of the initial decision." Contrarily, external coercing of PEB might have a converse effect. This suggests that we should particularly make our everyday environments afford sustainable actions that reinforce *pre-existing* latent pro-environmental internal factors,

[6]This is similar to the concept 'virtuous circle' (or 'foot-in-the-door') in social psychology. For example, children who perceive themselves as being generous because of a previous act of (even haphazard) generosity are more likely to continue to behave generously (Tavris and Aronson, 2015). This is predicted by the theory of cognitive dissonance: when someone behaves in a certain manner, they are likely to afterward self-justify the previous behavior in order to maintain consonance (Festinger, 1957). Sustainable behavior can lead to sustainable thinking (and vice versa) in a 'virtuous circle' or sustainable feedback loop.

making us perceive that we are (knowingly and willingly) acting in consonance with our pro-environmental identities and not enforced or coerced by external authorities to do so.[7] This is a relevant observation for environmental policies, where behavior interventions should particularly be implemented in domains where significant latent pro-environmental behavior potential (e.g., attitudes or knowledge) exist. Here, the provision of material environments which afford PEB has higher potential to lead to spillover effects and positive feedback loops in PEB. Moreover, since pro-environmental internal factors are, in many respects, pre-existing unutilized resources (as exemplified by the attitude–action gap), their actualization is also a cost-effective way of inducing pro-environmental behavior and habits.

Making the best use of affordances as leverage points is a fascinating opportunity for those involved in environmental policy and behavior interventions, although any applications must be preceded by a thorough understanding of system dynamics. Simplistic ‘if-you-build-it-they-will-come’ or ‘one size fits all’ policy approaches are insufficient for identifying leverage points (see Ostrom, 2010 for criticism on such top-down approaches), since affordances are transactional. To make the full use of these self-reinforcing feedback loops and sociocultural ratcheting processes, we need to understand *which* external structures complement a *certain* population’s set of internal factors. This calls for local, decentralized and perhaps even participatory policy approaches, where local behavior potentials (internal and external) are thoroughly charted before the implementation of behavior change strategies. This also a political reasoning for not defining affordances as uniform ‘properties’ of things or environments, since physical environments can afford environmentally significant behavior patterns very unequally. Affordance theory takes on a very political nature here, and must be particularly sensitive toward socioeconomic factors and behavior capabilities. Firstly, individuals might have variety in their ability to utilize affordances and transform resources into valuable activities. Second, the distribution of environmentally significant affordances might be fundamentally unequal between local populations and socio-economic groups (see the ‘capability approach’ of, e.g., Sen, 1995 for similar arguments). For instance, targeting costly information campaigns or ‘blaming strategies’ at non-recycling low-income families might be unfairly patronizing if recycling affordances are scarce to begin with (Jackson, 2005, p. 54). Moreover, ‘fetishizing’ actions such as recycling – to which less fortunate populations might have less affordances – at the expense of letting ‘political minefields’ such as air travel off the hook is certainly questionable on moral and political grounds (see Capstick et al., 2015).

Therefore, affordance theory seems to quite naturally call for polycentric (Ostrom, 2010), local and inclusive governance which understands the behavior potentials (internal and external) of local populations and encourages, facilitates and guides local populations to act accordingly with their latent pro-environmental attitudes. Indeed, participatory problem solving of this kind has also been claimed to reduce helplessness (since it helps people understand and explore problems) and thus induce sustained and long-term pro-environmental behavior (Kaplan, 2000; see Jackson, 2005).

Applied Affordances

I have stated above that socio–ecological systems, everyday environments included, are thoroughly infused with affordances. To comprehend the full potential of affordances in environmentally significant decision-making, it is worth explicating how diverse the analysis and leveraging of affordances can be. Here, scalability and adaptability are what truly make a theory of affordances stand out from other theoretical models.[8] Since affordances are systemic relations, an affordance is a scalable heuristic applicable to whatever system we are interested in observing. We can therefore choose to analyze affordances from a nested order of systems (Gibson, 1979, see also Ostrom, 2005). This systemic nature of affordance theory makes it an incredibly versatile analytical tool, basically applicable to any area of interest of environmental policy. Consider, for example, how we could choose to study affordances related to (1) objects and everyday items, (2) households (3) urban environments or (4) socioeconomic systems, and how this can inform us about potential leverage points for environmental policy intervention. These adaptations of affordances are briefly discussed below with affordance-relative case studies.

Object-Level Affordances

Physical objects are perhaps the most intuitive of affordance-relatable entities. As was the case in this article, introductions to affordance theory usually begin with imagining what functions objects afford for humans. It comes then as no surprise that affordances of objects have been studied with quite some detail, particularly by the design community. For instance, in recent years several authors have published under the umbrella-term of ‘design for sustainable behavior,’ which (often drawing on the work of Norman) study how objects afford pro-environmental behavior and how variables such as understandability, ease of use and functional meaningfulness affect sustainable product use (see e.g., Lockton et al., 2008; Bhamra et al., 2011; Lockton, 2012; Selvefors, 2017). Often, though, affordances are in this context generally defined merely as properties of objects, a conception against which I have argued in this text (in favor of affordances as systemic animal–environment relations, see section “A Theory of Affordances”).

[7]A complicating factor here is that it seems that high-cost PEB is more likely to promote positive spillover PEB than low-cost behavior (Truelove et al., 2014). This makes sense from a cognitive dissonance perspective: when a person is highly invested in one practice, they are likely to self-justify other similar behavior (Cooper, 2007; Tavris and Aronson, 2015). The question for policy-makers remains: how can people be supported to act in consonance with action they perceive as high-cost?

[8]From other theoretical frameworks possibly relatable to affordance theory, I can think of at least Giddens (1984) structuration theory, Lewin’s (1951) field theory, Sen’s (1995) capability approach, practice theory (e.g., Bourdieu, 1990 and Shove et al., 2012), Paul Stern and colleague’s (Guagnano et al., 1995; Stern, 2000) attitude–behavior–context model, nudge theory from behavioral economics (Thaler and Sunstein, 2008) as well as the whole discourse on ecosystem services (see e.g., Danley and Widmark, 2016).

A great example of objects affording sustainability can be found in the Finnish bottle deposit-refund system, where each bottle or can sold is placed with a deposit ranging from 10 to 40 cents added to the beverage's retail price (PALPA, 2017). The system gives consumers monetary incentive to recycle, since the deposit is refunded when bottles and cans are returned to stores and kiosks. The bottles afford a visual prompt for recycling (overcoming the Gulf of Evaluation), and recycling points are abundant (crossing the Gulf of Execution, since each store that sells deposit-items is required to also receive them).

Technically speaking, it is not the bottles and cans alone which afford recycling here, but rather both the objects and the whole recycling system they are embedded in. However, it is clear that 'recycling' has become a prominent affordance (functional meaning) which consumers perceive when encountering a bottle or can in the Finnish culture. The deposit system has been hugely successful, with the recycling rate of bottles and cans ranging from 89 to 98%. Arguably, a point has also been reached where the recycling system reinforces shared expectations and social practices (in other terms, recycling has become a social or cultural affordance), whereby deviations from this norm are considered unacceptable (circa 90% of the population sample self-reportedly always/often recycle bottles and cans; Blom et al., 2010). However, I suspect the pro-environmental affordance-potential is not used to its full capacity in this case, since feedback from recycling mainly concerns monetary benefits, and to a much lesser extent environmental welfare.

Household Affordances

Abrahamse et al. (2007) acknowledge in their study on energy consumption behavior, households are responsible for a highly significant portion of greenhouse gas emissions, and domestic environments should therefore be considered an important target group for behavior change interventions. The authors (Abrahamse et al., 2007, p. 266) note that whilst knowledge itself predicts pro-environmental behavior rather poorly, tailored information and feedback as well as feedforward (in the form of goal setting) can be effective strategies for encouraging energy conservation. This is particularly the case with continuous electronic feedback, made possible by digitalized energy systems. In Abrahamse et al.'s (2007) study, experimental groups were given access to an online website with information on energy consumption and related ecological problems, along with a list of tailored energy-saving measures and an online tool which could calculate relevant and practical energy-saving means. Basically, the tool gave simple and comparative feedback and feedforward on how to reach the intended goal of 5% energy consumption reduction. The 5-month long intervention resulted (among a variety of other interesting findings) in the experimental groups lowering their direct (gas, electricity and fuel) energy consumption by 8.3% as opposed to the control group, whose direct energy consumption increased by 0.4% (although indirect energy consumption was not affected nearly as strongly as direct energy use).

This would suggest, although the authors do not discuss the results in terms of affordances, that when household energy systems are designed to afford sustainable behavior (in this case, by crossing the Gulf of Evaluation), they have the potential to significantly strengthen pro-environmental behavior patterns. Importantly, as opposed to a control group, the intervention also resulted in heightened energy conservation knowledge within the experimental groups, signaling potential for a sustainable feedback loop, where not only heightened explicit knowledge but also tacitly acquired practical 'know-how' would further increase the ability to adopt more sustainable consumption habits (see Darby, 2006). Affordance theory also implies that the intervention would have likely been even more effective had the Gulf of Execution and Evaluation been crossed more efficiently: instead of using a website (which must be accessed with significant intent) the information could be ready-to-hand[9] at a constantly visible location within the household (e.g., an interactive LCD-screen). With the dawn of smart energy systems in digitalized domestic environments, such high pro-environmental affordance systems could become mainstream in the near future. This is potentially a big step forward from current electric billing, which affords sustainable energy consumption behavior particularly poorly due to technical and rare (e.g., quarter-yearly) feedback and lack of prompts regarding how to change behavior.

Urban Affordances

Marcus et al. (2016) explicitly discuss affordances in the context of urban design. The authors note that 'most approaches to sustainable urbanism still share the conception of the humans–environment relations that characterized modernism' and therefore do not emphasize the dynamical systemic properties of urban environments. Instead, affordances could form the core of a 'new epistemological framework of the human–environment relation in sustainable urbanism' (Marcus et al., 2016, Abstract, 440). Against the backdrop of the Cartesian human–environment dualism implicit in much of urban design, we should rather advocate a dynamical and interactive two-way understanding of the relations between humans and the urban environment. Marcus et al. (2016, p. 445), in fact, go as far as recognizing that 'cities, as the physical objects we generally envision them to be, are also cognitive objects, that is, they are not something only out there but also a type of extensions of the human mind.' As noted above, such 'extended cognition' follows naturally from a dynamical systems understanding of affordances (Chemero, 2003, 2009; Rockwell, 2005; Anderson et al., 2012).

The transactional nature of affordances suggests that, when designing urban environments, local attitudes and interests should also be charted in an inclusive and even participatory

[9]The Heideggerian notion of ready-to-handedness (see Heidegger, 1927/1978) is often implicit in ecological psychology (see e.g., Chemero, 2013). Being 'ready-to-hand,' very briefly, implies that an object 'is for' (or affords) the achieving of some function without the need for theorizing or other analytical activities. For those familiar with behavioral economics, particularly nudge theory (Thaler and Sunstein, 2008) and Kahneman's (2011) dual system approach, there is something inherently System 1 (fast, automatic behavioral processes) in ready-to-handedness.

process. In other words, affordances "cannot be imposed by expertise themselves but need to consider the 'meanings' of the local community" and "cannot be implemented as abstract 'demands' but have to cognitively engage and motivate people, even if on a low key" (Marcus et al., 2016, p. 443). Kurz (2002, p. 273) supports this idea by noting that financial rebates on public transport systems are not sufficient if, for example, people are more attuned to the social status their private vehicles afford them with. Interestingly, Kurz's notions on public transport are supported by a study by Hunecke et al. (2001), which suggests that an additive 'economy-plus-moral' (subway fare plus normative ecological orientation, i.e., external plus internal) formula best determines public transport travel choice in urban environments. As discussed extensively above, environments do not afford pro-environmental behavior alone, but always in relation to human abilities and motivations.

Marcus et al. (2016, p. 446) also cite their previous work (Giusti et al., 2014) to highlight the importance of green urban affordances. The provision of green affordances (accessibility to urban nature in Stockholm) for preschool children was shown to lead to increased ecological knowledge and impact awareness, as well as strengthened emotional connection with nature. These internal factors, again, could be termed as further latent potential for pro-environmental behavior. In this respect, urban environments can ratchet cognitive processes: by redesigning urban environments to reinforce sustainable affordances (e.g., accessibility to nature), we can promote a wealth of pro-environmental identities and habits, which may over time reinforce the transition toward a culture of sustainability.

In fact, the notion of the affordance could be extended to include a whole socioeconomic system. This goes far beyond the scope of this article, but (e.g., Sen's, 1995) capability approach has elaborated a very similar idea, where abstractions such as 'equality' and 'freedom' are assessed as the actual capabilities (which relate to both individual physical abilities, or 'functionings', and the system's distribution of action opportunities) of human-beings. In other words, even concepts such as freedom, justice, equality can be assessed in terms of functionally meaningful human–environment relations (where the environment, of course, includes social, cultural and economic determinants).

CONCLUSION

> 'There is only one world, however, diverse, and all animals live in it, although we human animals have altered it to suit ourselves. We have done so wastefully, thoughtlessly, and, if we do not mend our ways, fatally' (Gibson, 1979, p. 130).

Affordance theory, as presented in this paper, studies the dynamics of organism–environment systems and their evolution over time. In this context, internal and external behavior antecedents should not only be studied as interdependent entities, but as a single, non-decomposable, evolutionary system (**Figure 1**). In this respect, affordance theory particularly helps us understand the ecology of environmentally significant behavior. It has been proposed in this paper that those involved with environmental policies adopt affordance theory as a guiding heuristic for the design and implementation of pro-environmental behavior change interventions. Several reasons exist to as why this should be the case:

(1) Affordances can be understood to represent leverage points for systemic behavior change interventions, since their actualization can lead to large and self-reinforcing shifts in environmentally significant behavior. Affordance theory, as a dynamical systems approach, can therefore guide us to conceptualize and identify leverage points which can help individuals and socio–ecological systems to learn more persistent sustainable habits. This second-order change (helping the system learn) not only solves particular individual problems, but also forms habits which apply to the solution of classes of problems (Bateson, 2000, p. 274).
(2) By identifying and activating pro-environmentally significant affordances in large enough numbers, we can induce positive feedback loops (**Figure 1**), where, for instance, changes in the material environment reinforce pro-environmental identities and promote pro-environmental sociocultural practices (which again can lead to further modulation of the socio-material environment, and so on). The reinforcement of these feedback loops can further serve to normalize pro-environmental habits as socio-culturally and materially embodied practices.
(3) Affordance theory, as an ecological approach to behavior analysis, helps us conceptualize and understand the lack of fit between internal and external behavior antecedents. Focus in policy interventions should be particularly directed to domains where mismatches between internal and external factors exist. One exemplary case is the widely prevalent attitude–action gap, where latent pro-environmental internal factors pre-exist but are not yet actualized due to lack of affordances. The actualization of pre-existing pro-environmental internal factors is also more likely to lead to positive spillover effects than other interventions (Truelove et al., 2014), making it a particularly important leverage point.
(4) Affordance theory is a particularly useful and versatile conceptual framework for policy interventions, since it is, due to its systemic and nested nature, applicable to practically any environmentally relevant policy-arena from the sustainable design of objects and households to urban environments.

This, I believe, presents us with a conceptual framework for a systemic *mending of our ways* (in reference to Gibson above) toward a sustainable future, where pro-environmental behavior would emerge as a default path of least resistance and form of life. Moreover, affordance theory has the potential to be a participatory approach at that. A thorough understanding of latent local behavior potential seems to call for participatory and decentralized policy-making, with heightened understanding of locally embedded meanings and local environments. This also has the potential to increase the social and political acceptability of behavior change interventions (which 'nudge' interventions, in particular, have struggled with, see e.g., Hukkinen, 2016) and reduce helplessness in local populations. Whilst this mending of our ways is by no means an easy task (and much is left to be studied in how pro-environmental feedback loops can be practically implemented) and not perhaps the radical systemic change some commenters seem to call for (see e.g., Capstick et al., 2015), there are reasons to be optimistic that little strokes fell great oaks. After all, any organism–environment system is necessarily infused with affordances, and by mending affordances toward a self-reinforcing, less wasteful and thoughtless, direction there is hope that our socio–ecological system will ultimately take a sustainable turn.

AUTHOR CONTRIBUTIONS

RK made sole contribution to the conception and design of the work. RK drafted the work and revised it critically for important intellectual content. RK agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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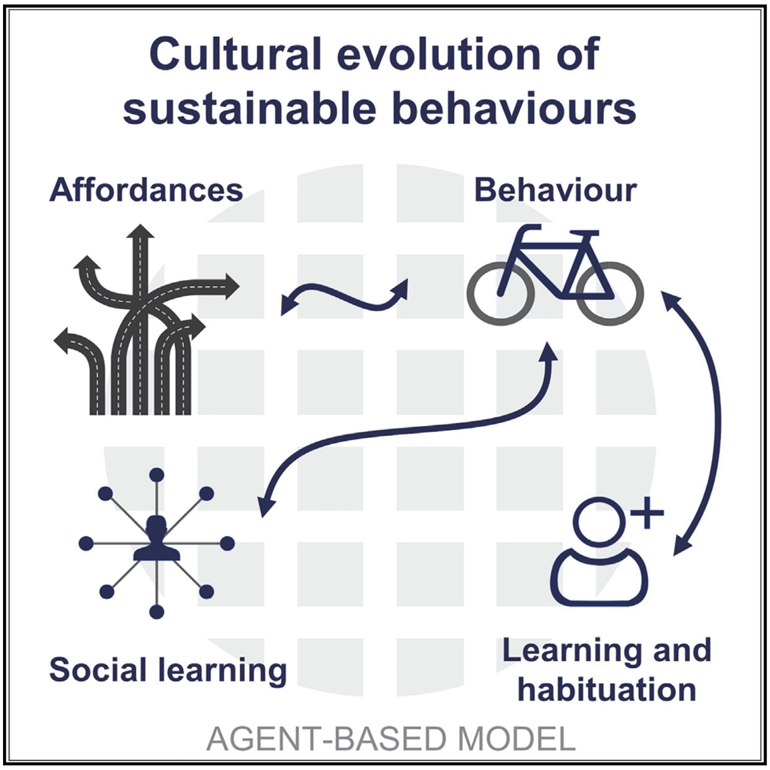
III

One Earth

Article

Cultural Evolution of Sustainable Behaviors: Pro-environmental Tipping Points in an Agent-Based Model

Graphical Abstract



Highlights

- An ABM is used to study the cultural evolution of sustainable behaviors
- Behaviors emerge as a function of affordances, social learning, and habits
- The affordances in an environment have a major effect on behavior adoption
- The ABM is validated against cycling behaviors in Copenhagen

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In Brief

Kaaronen and Strelkovskii have designed an agent-based model to study the cultural evolution of sustainable behaviors. Behaviors emerge as a product of personal, environmental, and social factors. Particularly the structure of the environment has an effect on the adoption of pro-environmental behaviors. Even linear changes in pro-environmental affordances (action opportunities) can trigger non-linear collective behavior change. The model is validated against cycling behaviors in Copenhagen. This model gives further justification for policies and urban design that make pro-environmental behavior psychologically salient, accessible, and easy.

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One Earth
Article

Cultural Evolution of Sustainable Behaviors: Pro-environmental Tipping Points in an Agent-Based Model

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SCIENCE FOR SOCIETY To mitigate climate change and safeguard ecosystems, we now more than ever require drastic change in behavior patterns. An urgent challenge is for humans to collectively adopt pro-environmental habits, including sustainable consumption and transport behaviors. However, there is only so much that individuals can do if sufficient opportunities for behaving sustainably do not exist. Therefore, we must understand how pro-environmental behaviors emerge systemically as a product of infrastructural, social, and individual factors. Using an agent-based model—a computational method for simulating interactions between individuals and environments—we illustrate how providing opportunities for pro-environmental behaviors (such as cycling infrastructure) can lead to the rapid adoption of sustainable habits (e.g., cycling). Our results are relevant for urban designers and policy makers given that we illustrate how even minor changes in everyday environments can trigger longstanding behavioral change.

SUMMARY

To reach sustainability transitions, we must learn to leverage social systems into tipping points, where societies exhibit positive-feedback loops in the adoption of sustainable behavioral and cultural traits. However, much less is known about the most efficient ways to reach such transitions or how self-reinforcing systemic transformations might be instigated through policy. We employ an agent-based model to study the emergence of social tipping points through various feedback loops that have been previously identified to constitute an ecological approach to human behavior. Our model suggests that even a linear introduction of pro-environmental affordances (action opportunities) to a social system can have non-linear positive effects on the emergence of collective pro-environmental behavior patterns. We validate the model against data on the evolution of cycling and driving behaviors in Copenhagen. Our model gives further evidence and justification for policies that make pro-environmental behavior psychologically salient, easy, and the path of least resistance.

INTRODUCTION

From decades of research in social and ecological psychology, cognitive science, ecology, and cultural evolution, we know this much about human behavior: our niche affords varieties of behaviors;[1–4] behaviors modulate personal states, such as habits, skills, or attitudes;[3,5,6] personal states influence behaviors;[6,7] behaviors alter environments;[3,8,9] and behaviors are socially learned and transmitted.[10,11]

However, what seems much less understood is how all these processes work in tandem to shape the evolution of socio-cultural and socio-ecological systems. Understanding this is important given that we require systemic change in human behaviors, cultures, and habits to reach the Sustainable Development Goals, to mitigate climate change, and to guard biodiversity and the ecosystems we inhabit.[2,12] Given the widespread demand for sustainable systemic change, particularly in the social and political sciences, it is curious how little is understood about how to instigate non-linear systemic change by means of environmental or urban policy and design. If we wish to reach social tipping points in the adoption of sustainable behaviors, we arguably need to better understand the mechanisms of their emergence. Formal models can be useful in exploring these mechanisms.[12]

Reaching social tipping points is an elusive yet imperative target. Often the assumption appears to be that whatever instigates this transition should roughly follow an S-shaped curve:[13] we should reach peak emissions as soon as possible, follow this with an increasingly fast decarbonization or phase-out, and then arrive at a new phase state by mid- to late 21st century. Or alternatively, we should adopt new sustainable habits or technologies at an accelerating rate until we reach a sustainable state of behavior.

Recently, it has been proposed that the design of pro-environmental affordances (action opportunities) could present us with an efficient leverage point to reaching tipping points in social systems and that affordances can induce positive-feedback loops in the collective adoption of behaviors.[2,14] We define affordances here as the behavioral opportunities afforded by the environment to an organism (e.g., bicycles and bicycle lanes afford cycling; see Model Assumptions). Therefore, our motivation is to study how the introduction of pro-environmental affordances to a social system can have non-linear effects on the collective adoption of sustainable behavioral patterns. This is a politically important objective because illustrating how the introduction of environmentally friendly infrastructures can trigger social tipping points gives further justification for investing into the design of urban and everyday environments that make pro-environmental behavior psychologically salient, easy, and the "the path of least resistance and the default form of life."[2] Although predicting where or when pro-environmental tipping points emerge remains a difficult, if not impossible,[15] task, if we ever wish to reach them, it is important to understand the mechanisms underlying their emergence.

The research questions of this article are, where do the (politically feasible) leverage points lie in tipping collective behavioral patterns of a social system from one state to another, and more specifically, how can the composition of the "landscape of affordances"[4] of a socio-ecological niche affect the evolution and emergence of collective behavioral patterns? The landscape of affordances simply means the set of affordances available in an ecological niche[4] (see Environment Affords Behavior).

Our methodological approach is agent-based modeling. We argue that agent-based modeling is particularly suitable for dealing with our research questions given that agent-based models (ABMs) by definition are used to model agent-agent and agent-environment interactions and their evolution over time.[16] Our conceptual model also includes other characteristics particularly suitable for ABMs, such as heterogeneous populations and emergent collective behaviors arising from simple interactions.[16,17] Agent-based modeling has become a standard method for studying complex, dynamical, and adaptive systems,[16,17] presenting social and behavioral scientists with new avenues for studying human and social behavior from systems perspectives. We use NetLogo, a "low-threshold and no-ceiling" modeling software,[18] for modeling.

ABMs have previously been employed in studying the adoption of various sustainable behaviors and attitudes,[19] including models of norm transmission and evolution,[20,21] recycling,[22] traffic and transport,[23–25] farming,[26] energy and risk management,[27,28] and psychology.[29,30] Our contribution to this rapidly developing field is in developing a holistic systemic approach to the emergence of behavior as a subtle function of social, individual, and environmental factors by focusing explicitly on the emergent leverage points and tipping points. Our model illustrates both how system-level emergent phenomena constrain and enable individual and group behaviors and how individual and group behaviors can shape these constraints and affordances. Our results are relevant for urban designers and other policy makers interested in instigating collective pro-environmental patterns of behavioral change.

Here, we propose a dynamical and complex systems approach to the study of the cultural evolution of human behaviors. We develop an ABM to illustrate how self-reinforcing cultures of behavior can emerge from five interconnected processes, which together form an "ecology of human behavior," as hypothesized by Kaaronen.[2] First, ecological information in a physical and socio-cultural environment specifies affordances or psychologically salient opportunities for behavior. Second, behavior modulates the personal states of humans through processes of individual learning and habituation. Third, personal states—such as habits, intentions, and attitudes—shape behavior. Fourth, behavior alters the environment in non-random ways through processes of cultural niche construction. Fifth and finally, all behaviors occur in a social network and result in social learning and transmission (through, e.g., teaching or copying). Together, these five processes form a dynamical system, or "a system whose behavior evolves or changes over time."[31] We expand Kurt Lewin's equation (Equation 1),[32] a classic heuristic formula in social psychology where behavior (*B*) is a function (*f*) of the person (*P*) and their environment (*E*), to include the aforementioned five feedback loops. See Figure 1 and Table 1 for our conceptual model. Our approach allows us to study a social system's various leverage points, or "places in the system where a small change could lead to large shift" in the system's behavior.[33]

$$\text{Lewin's equation}: \; B = f(P, E) \qquad \text{(Equation 1)}$$

RESULTS

Overview

In this section, we present the results of our agent-based simulations, where behavior is assumed to be an emergent function of affordances, social learning, individual learning and habituation, personal states, and niche construction (see Figure 1 and Table 1). In our model, agents move in a landscape of affordances where they encounter either pro-environmental or non-environmental affordances and act upon them (i.e., behave pro- or non-environmentally; see Figure S17). Behaviors then lead to the development of habits, social transmission (learning or copying behaviors from others), and the modification of the landscape of affordances (i.e., cultural niche construction). In particular, we show how the composition of affordances in a socio-ecological system, such as infrastructures that afford pro-environmental behaviors, plays an essential role in shaping collective behavioral patterns. Our model illustrates how even linear increases in pro-environmental affordances can lead to the non-linear adoption of collective pro-environmental behavioral patterns. We refer the reader to the Experimental Procedures for a thorough description of our model and its multidisciplinary theoretical assumptions.

We proceed by first presenting an abstract version of the model with parameter values set as defined in Table S3. These

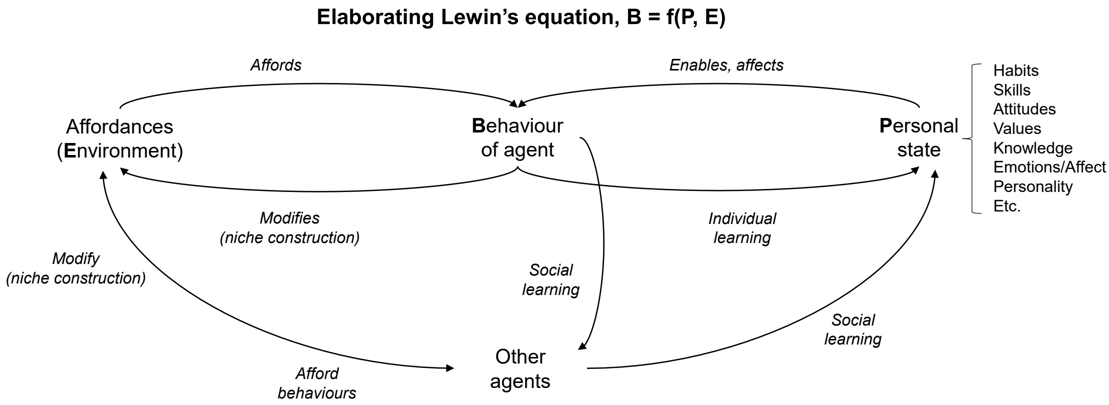

Figure 1. Conceptual Model
Elaboration on Lewin's equation. The figure implements several known feedback loops. The couplings form a socio-ecological system of human behavior.

are arbitrary parameter values; most parameter values are set at around halfway through the feasible parameter range, except that the rates of social learning and individual learning are set to values that reproduce macro-level output similarly to known social-learning patterns (i.e., S-shaped curves[11,45]). The rate of social learning is set slightly higher than that of individual learning (see Social Learning and Networks). Section Abstract Model Run thus demonstrates the general characteristics and mechanisms of the model by using abstract parameter values. In particular, the abstract version of the model aids in understanding the leverage points of the simulated system. We refer the reader to the Experimental Procedures for a description of the ABM and to the ODD Protocol and Sensitivity Analysis subsections (Figures S7–S16) of the Supplemental Experimental Procedures for a more complete picture of how each parameter affects the outcome of the model. See Table S2 for a list and definition of the model's parameters.

We then continue with empirical validation by fitting the parameter values to reproduce real-world macro-level patterns. We use the cultural evolution of cycling behaviors in Copenhagen as a case study. This empirical validation is intended to ensure "that the model generates data that can be demonstrated to correspond to similar patterns of data in the real world."[16]

Abstract Model Run

We run the model for 2,000 timesteps by measuring the variables of interest (pro-environmental and non-environmental behaviors) at the end of the model run (Figures 2 and 3) or producing time-series data by following pro-environmental and non-environmental behaviors at each timestep (Figure 4). We chose 2,000 timesteps as the arbitrary end of this model run given that this allows for considerable changes in behavior with the chosen parameter values (Table S3).

Figures 2A and 2B illustrate the end results of the model at timestep 2,000. Here, the initial proportion of pro-environmental affordances is varied from 0 to 1 with intervals of 0.01 and 30 simulation runs for each pro-amount value. This produces a total of 3,030 simulation runs. To illustrate the effects of niche construction (i.e., behavior altering the environment), Figure 2A plots the results with both rates of niche construction set at 10 (which corresponds to a 3% chance of niche construction following any behavior), and Figure 2B plots the results without any niche construction.

We can immediately notice that the system produces a tipping point, or a phase transition, when the initial proportion of pro-environmental affordances is around 0.5. When the initial proportion of pro-environmental affordances is above 0.5, the proportion of pro-environmental behaviors at the end of the model run increases drastically and vice versa. It is quite intuitive to understand why this happens. When the affordances in the environment bias the agents to behave in some way, this behavior becomes more probable than the alternative. Because of social learning and habituation, this bias in afforded behavior diffuses through the social network, altering personal states of the agents, modifying the environment through niche construction, and thus triggering a positive-feedback loop. A linear increase in affordances will have non-linear effects on the uptake of pro-environmental behaviors.

This produces an S-shaped curve, where the initial composition of affordances has a non-linear effect on the outcome of environmental behaviors (Figures 2A and 2B). Figure 3 produces k-means clusters of the pro-environmental behaviors of Figure 2A. The cluster analysis illustrates how drastic the phase transition from low to high proportions of pro-environmental behavior is when the initial composition of affordances is altered. The ellipses in Figure 3 contain roughly 95% of all data points.

Using global sensitivity analysis, Figure S15 illustrates how robust this tipping point is. Here, 300 near-random samples of parameter values are simulated (via Latin hypercube sampling[46]), whereby each is run five times with varying random seeds. Figure S15 thus illustrates that even when other parameters are allowed to vary freely (within a predefined range; see Table S1), the tipping point will emerge. This illustrates that in the system of social behavior, the non-linear effect of affordances on behavioral patterns is robust.

Notice that the same cannot necessarily be said of the effect of initial personal states on behavioral outcomes (Figure S16). For instance, the red box in the lower right corner of Figure S16 highlights cases where the agents, despite initially having high pro-environmental personal states, were mainly behaving non-environmentally at the end of the model run. This is most likely due to a lack of pro-environmental affordances, as well as the

Table 1. Model Assumptions

Description	Causality	Theories and Evidence (Non-exhaustive)
Ecological information specifies a variety of opportunities for behavior, or "affordances"	$E \rightarrow B$	ecological psychology and affordance theory,[1,4,34,35] behavior field theory,[35] and design theories[36]
Personal states affect behavior	$P \rightarrow B$	theory of planned behavior,[7] habituation,[37] and capability approach[38]
Behavior modulates personal states	$B \rightarrow P$	habituation,[37] individual (or asocial) learning,[11,39] cognitive dissonance and self-justification,[5,40,41] and the foot-in-the-door effect[40]
Behavior shapes the environment	$B \rightarrow E$	niche construction and cultural niche construction[9,10] and cumulative cultural evolution[42]
Behavior occurs in a social network with social learning, transmission, and cognition	$B_{(self)} \rightarrow P_{(others)}$, $B_{(others)} \rightarrow P_{(self)}$	social learning,[10,11,39] social cognition,[43] spread of innovation in social networks,[44] group conformity and social norms,[45] and cumulative cultural evolution[42]

This table elaborates on Lewin's equation (Equation 1), where behavior (*B*) is a function of person (*P*) and environment (*E*).

interference of other personal states on behavior. This is somewhat analogous to the attitude-action gap observed in environmental behavior.[2,47] Pro-environmental personal states do not translate into pro-environmental behavior if there are no opportunities to do so, and environmental design might prove to be a more reliable leverage point into pro-environmental behavioral change than attempts at altering personal states.[2]

Figure 4 plots time-series data with the parameter values specified in Table S3. Figures 4A and 4B plot the development of pro-environmental behaviors when initial pro-environmental affordances compose 50% of the affordance landscape. A total of 300 simulations were run for each plot. Figure 4A plots the data with niche construction, and Figure 4B plots them without niche construction. With both plots, the mean proportion of pro-environmental behavior remains stable over the model run. However, notice how the standard deviations (shaded area) increase with niche construction.

In Figures 4C and 4D the initial composition of pro-environmental affordances is altered to 60%. The minor (10%) change in the landscape of affordances has a drastic non-linear effect on the adoption of pro-environmental behaviors. As described above, this self-reinforcing process is mainly a product of social learning and habituation induced by the alteration of the affordance landscape.

Notice also how the curve in Figure 4C (with niche construction) is steeper than the curve in Figure 4D. Increases in niche construction rates seem to hasten the self-reinforcing effect on the adoption of behaviors.

Empirical Validation

Empirical validation (Figure 5), or testing that data produced by an ABM correspond to "empirical data derived from the real-world phenomenon," is an important step in modeling.[16] However, a common challenge with empirical validation is that "inputs and outputs in 'the real world' are often poorly defined or nebulous."[16] We acknowledge that this is the case with some parameters of the present model: finding reliable empirically grounded values for parameters such as the rates of social learning, individual learning, and niche construction is difficult if not impossible (see Discussion). However, regardless of this important caveat, we maintain that illustrating that the model can produce macro-level patterns resemblant of real-world data, with reasonable assumptions (see Experimental Procedures), is an important step in assessing the validity of the model.

We use the case of bicycling and driving habits in the city center of Copenhagen as a case study. Particularly since the 1990s, Copenhagen has seen a rapid increase in the proportion of cyclists. This change in transport habits has earned Copenhagen the title "City of Cyclists."[48] This change has not come for free, and it has been attributed not only to the emergence of a cycling culture but also to heavy investment into cycling infrastructure, such as cycling tracks, bridges, and a public bicycle scheme introduced in 1995.[48–50] Overall, Copenhagen has witnessed a considerable increase in affordances for cycling: people are increasingly satisfied with Copenhagen as a cycling city and with bicycle parking opportunities, and the amount of cycling tracks has increased considerably since the 1990s (Figure 6A).[49] There have also been decreasing amounts of seriously injured or killed cyclists, and in 2018, 77% of Copenhageners stated that they felt safe while cycling in traffic.[49]

We use the case of cycling in Copenhagen to illustrate how our model can produce realistic macro-level patterns of the evolution of pro-environmental behavior (cycling) and non-environmental behavior (driving). Although, as noted, parametrization is difficult, we know from available data that in 1970 driving was about four times more common than bicycling, and in 2018 the number of cyclists seemed close to overtaking the number of drivers (Figure 5A; data acquired from the City of Copenhagen through personal communication). The development of cycling also seems to resemble a cumulative distribution curve, which could indicate a strong presence of social learning (which is entirely expected of a human society; see Social Learning and Networks). We also know that affordances for cycling in Copenhagen have increased nearly linearly over time (see Figure 6A) and that the policy emphasis has been on constructing the environment to be cycle friendly.[49,50]

Using a genetic algorithm and manual tuning, we set the initial parameter values of the model as described in Table S4. We take one timestep of the model to represent 1 day and set the total model run to span 56 years or 20,440 timesteps (by assuming 365-day years). Although the model spans 56 years, it involves only one generation of agents. This is a simplifying modeling

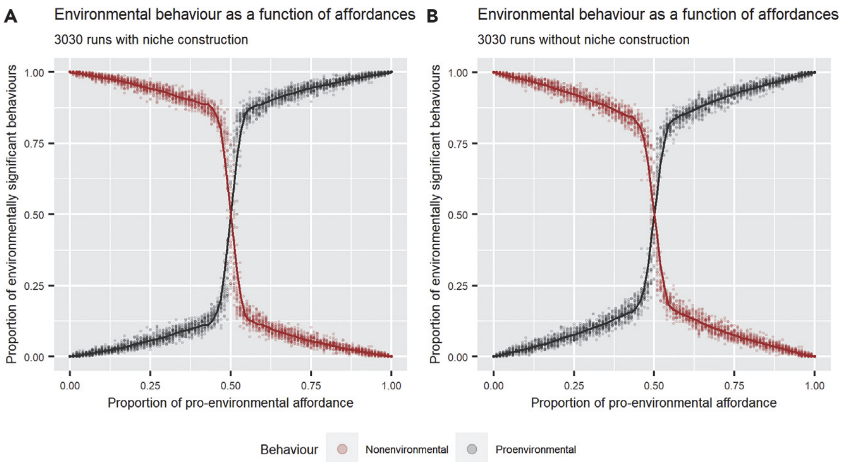

Figure 2. Pro- and Non-environmental Behavior as a Function of Initial Affordances

Results at the end of the model run from a total of 3,030 simulations (for each plot) with varying random seeds. The lines are smoothed conditional means or LOESS (locally estimated scatterplot smoothing) regressions with (A) niche construction and (B) without. Notice how the curves of (A) are steeper than those of (B): niche construction can amplify the positive-feedback loop.

choice that allows us not to deal with the thorny issue of how cycling behaviors (or personal states) would be inherited through generations. However, the model does include random mutations of personal states, which could be interpreted to simulate the random effects of intergenerational knowledge transfer (vertical cultural transmission).

Figure 5B presents the results of 300 runs of the simulation. As in real-world data (Figure 5A), at timestep 1 of the model run, the proportion of cyclists is roughly one-fourth of the proportion of drivers. However, as a result of feedback loops among pro-environmental niche construction, social learning, and individual learning, the proportion of cyclists rises at an accelerating rate, eventually almost overtaking the number of vehicle drivers by the year 2018 (or timestep 17,885). Although there is considerable variance between the model runs, the mean numbers of cyclists and drivers seem markedly similar to real-world patterns from Copenhagen, even when the model is left unsupervised after initial configuration (as is done with each run).

To illustrate what a single model run might look like, we manually selected a representative model run, illustrated in Figure 5C. Note, however, that many of the 300 model runs will see either a faster or slower adoption of cycling and driving habits (as indicated in Figure 5B). We allowed the simulations of Figure 5B to project to the future, illustrating an ever-increasing number of cyclists. However, we caution that this is not a prediction for the development real-world patterns in Copenhagen because obviously other major factors (many of which are inherently unpredictable) might influence or hinder this development. For instance, it has been speculated that the extension of the metro line in Copenhagen might reduce the number of daily cyclists.

Figure 5D depicts one factor that triggers the tipping point in the Copenhagen simulation: the rate of pro-environmental niche construction. It could be interpreted as suggesting that if the city had invested less into the development of cycling infrastructure, the accelerating rate of cyclists witnessed in the real-world data might not have taken off nearly at the rate that it did. That is, the composition of affordances over time, even if the development of affordances is close to linear (see Figure 6A for real-world data and Figure 6B for simulated data), can have non-linear self-reinforcing effects on the adoption of cycling behaviors.

DISCUSSION

If the assumptions of our model hold and systems of human behavior portray all five feedback processes defined in the Introduction and Experimental Procedures, our model gives further evidence for locating leverage points for collective pro-environmental behavioral change.

In particular, our model illustrates how (even minor) changes in the landscape of affordances can trigger non-linear (S-shaped) changes in collective behavioral patterns as a result of increased action opportunities, habituation, and social learning. This S-shape, or cumulative distribution curve, is known to signify social-learning patterns: "Hundreds of studies conducted by sociologists have repeatedly found that the spread of new technologies, practices, and beliefs follows an S-shaped cumulative distribution curve."[45]

Giving people increased opportunities to behave pro-environmentally can trigger a self-reinforcing feedback loop (recall Figure 1). Here, an increase in pro-environmental affordances leads to increased pro-environmental behavior, whereby people develop stronger pro-environmental habits, which in turn leads to social learning and transmission of behaviors through social networks, which might result in increased pro-environmental niche construction (i.e., construction of pro-environmental affordances), eventually reinforcing any existing habits and so on.

As illustrated by the case presented in our empirical validation, a responsive government can greatly facilitate this process. Designing urban environments to facilitate pro-environmental behavior patterns can play a central part in triggering tipping points in the adoption of pro-environmental behaviors, as has arguably been the case with the evolution of cycling cultures in Copenhagen (see Figures 5 and 6). Furthermore, our results suggest that as a result of potential tipping points, the design of urban environments to facilitate pro-environmental behaviors should continue even if the effects (i.e., adoption of pro-environmental behaviors) are not initially obvious. This is because it might only be after a certain threshold of affordances that the accelerating adoption of behaviors takes place (Figure 2).

Because other potential leverage points, such as changes in personal states, are less robust (Figure S16), our model suggests that tipping points in collective pro-environmental behaviors might be most efficiently triggered by changes in the physical form of environments. This is an interesting result because it is arguably also the physical environment that urban designers, policy makers, and other decision makers have most control

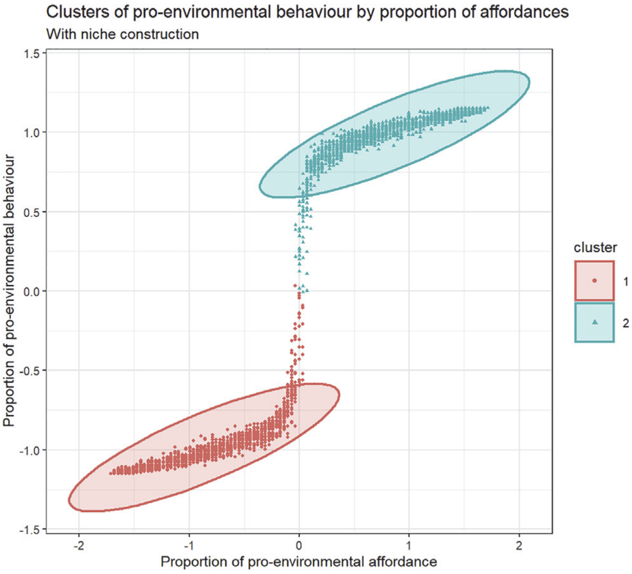

Figure 3. The Phase Transition

A k-means cluster plot of the pro-environmental behaviors of Figure 2A. Ellipses contain roughly 95% of all data points. The axes are standardized (standard deviations from the mean).

over, and leveraging environmentally significant behaviors by means of communication or information campaigning has proved to be notoriously difficult.[2,51,52] Perhaps a more reasonable information-oriented approach to collective behavioral change would be through the redesign of "general ecological information"[34] or the information in our everyday environments that specify the affordances within our niche (see Environment Affords Behavior). Through habituation, social learning, and social transmission of behaviors, the form of the physical environment can have more definitive, long-lasting, and widespread effects on our behavior than might generally be assumed.

The results also highlight the role of cultural niche construction in sustainability transitions. Whereas urban theorists such as Christopher Alexander[53] and Jane Jacobs[54] have for long noted the importance of self-organizing communities in the development of lively and resilient cities, our model shows how increasing the capacity of a society to construct its own niche can hasten the adoption of pro-environmental behaviors. Thus, letting communities evolve and self-organize can result in self-reinforcing sustainable behavioral patterns if such a community has pro-environmental personal states (note, however, that the converse is true if the community does not have pro-environmental personal states).

Overall, our model gives further justification for investment into the design of pro-environmental affordances. This is important given that many cities are currently considering investment into infrastructures that facilitate pro-environmental behavior. Our model suggests that making pro-environmental behavior as easy as possible, the default option for behavior, and the path of least resistance might have long-lasting and non-linear effects on the adoption of pro-environmental habits and effectively trigger tipping points in the sustainable cultural evolution of a social system.

Because of the large number of interconnected processes, each aspect of the present model was intentionally kept at a moderate level of complexity. This, we argue, keeps the model in the so-called "Medawar zone"[17] of complexity: not too simple (and thus neglecting essential mechanisms of the modeled system) but not too complex (and so becoming cumbersome and "bogged down in detail"). However, the model is open for further development and additions of more complex layers. These could, for instance, include more elaborate psychological decision-making processes (including social cooperation or competition[21]) and a higher variety of affordances and behaviors.

However, as we have stated above and as has been discussed by many others,[55–57] social scientific, cognitive, and psychological theories often do not provide enough detail to unambiguously specify algorithms to implement them. Even the same theories can produce different modeling outcomes as a result of variability in model architecture, choice of (numerical) representations, and empirical data or goals of the modeler, and minor differences in decision making can be amplified in the interactions of thousands of agents.[56,57] As is generally the case with complex systems, small changes in initial conditions can cause large variance in emergent end results.[57,58]

Moreover, social and psychological theories might altogether lack formal descriptions of mechanisms essential for modeling.[55] In the case of our model, precisely defining parameters such as the rate of niche construction poses particular challenges—not the least because complexity scientists such as Stuart Kauffman have suggested that the creative processes through which human cultures alter their material and technological world are fundamentally unpredictable and indescribable by law-like algorithms.[59] We acknowledge the need, where possible, for collaboration in the development of formal structures for implementing social scientific and psychological theories for ABMs, including systematic comparisons of models,[55] and believe the present model could be refined in particular through such interdisciplinary collaboration.

The model is also easily modified to include interactive elements, such as "policy buttons," which could trigger discrete changes in the landscape of affordances and personal states. This could, we imagine, also be used for educational purposes or co-creation with, e.g., policy makers or urban designers. We also acknowledge that the model could be further developed by the inclusion of other forms of empirical data, such as psychological data measured with surveys or geographical data[60] (or indeed both, e.g., with PPGIS[61] approaches).

Conclusion

In conclusion, our ABM illustrates how changes in the composition of affordances (action opportunities) in our everyday environments can trigger tipping points in the collective adoption of pro-environmental behaviors. Even near-linear increases in pro-environmental affordances can trigger the non-linear, self-reinforcing adoption of pro-environmental behaviors. These feedback loops emerge from the interconnected processes of habituation, social learning, and niche construction. We interpret this as giving further justification for the design and funding of everyday environments where the affordances for pro-environmental behavior are knowingly increased and thus make pro-environmental behavior the path of least resistance.

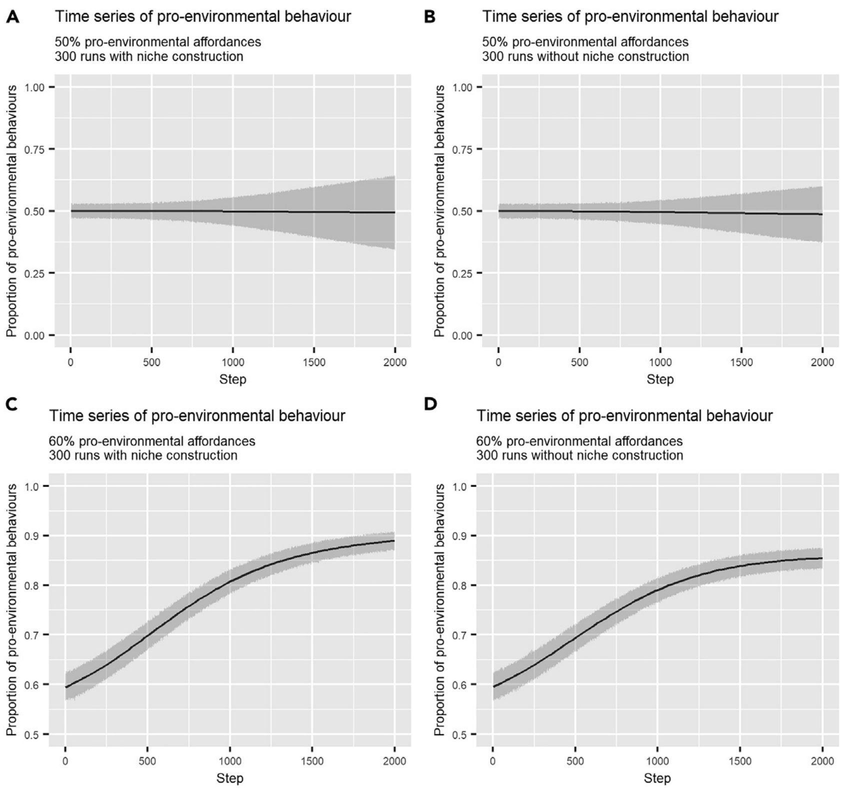

Figure 4. Time-Series Data

Mean time-series data of 300 model runs (for each plot) track the proportion of pro-environmental behavior over time. In (A) and (B), initial pro-environmental affordances are set at 50%. In (C) and (D), initial pro-environmental affordances are set at 60%. Niche construction is shown in (A) and (C) but not in (B) or (D). Shaded areas signify ±1 standard deviation. Lines are smoothed conditional means (generalized additive model [GAM]).

EXPERIMENTAL PROCEDURES

Model Assumptions

> In psychology one can begin to describe the whole situation [from which behavior emerges] by roughly distinguishing the person (*P*) and his environment (*E*). Every psychological event depends upon the state of the person and at the same time on the environment, although their relative importance is different in different cases. Thus we can state our formula [...] as $B = f(P, E)$. [...] Every scientific psychology must take into account whole situations, i.e., the state of both person and environment. This implies that it is necessary to find methods of representing person and environment in common terms as parts of one situation.[32]

The design of the model presented in the present paper expands on Kurt Lewin's equation (Equation 1).[32] Therefore, it proposes a systems approach to studying the emergence of behaviors by suggesting that, to explain behavior, we must account for the whole situations from which behaviors emerge.

Although it is a useful heuristic, Lewin's conceptual model alone does not provide enough detail for designing a reproducible formal computational model. Therefore, our model draws on a variety of fields, ranging from evolutionary ecology to cultural evolution to (social) psychology and cognitive science, to introduce various levels of detail to Lewin's equation. Namely, our model elaborates Lewin's model from a complex and dynamical systems perspective, where the cultural evolution of behavior within a society is understood as a product of several interconnected feedback loops. Thus, our model adds several causal links to elaborate on Lewin's formula (Table 1).

This model design is influenced by dynamical systems approaches to cognition and behavior.[3,31] That is, its focus is on studying how the human-environment system evolves *over time* and *as a whole* given ranges of initial conditions. According to Chemero[3] and Lewin,[32] the model assumes that focusing on only one of either personal states or the environment in insufficient for describing the emergence of behavior:

> Dynamical systems theory is especially appropriate for explaining cognition as interaction with the environment because single dynamical systems can have parameters on each side of the skin. That is, we might explain the behavior of the agent in its environment over time as coupled dynamical systems [...] It is only for convenience (and from habit) that we think of the organism and environment as separate; in fact, they are best thought of as forming just one nondecomposable system.[3]

Dynamical systems approaches to human behavior are readily available in the fields of ecological psychology[1,3,35] and (radical) embodied cognitive science.[3] Moreover, dynamical systems approaches to studying or modeling systemic change[12] and coupled human-nature systems[60] have been recently proposed in the context of socio-ecological systems theories. However, ecological psychology and cognitive science in particular have traditionally struggled with taking into account the social dimension.[62] To remedy this, the present article also models the dynamical human-environment system as a social one: no behavior is truly private in a socially connected world where organisms teach, copy, learn in social networks, and modulate their niche to shape its affordances.[10] The conceptual model underlying the ABM is illustrated in Figure 1. In the following sections, the theoretical and methodological assumptions of this model are elaborated (see Table 1 for a summary). For a more detailed conceptual model, see Kaaronen.[2]

Environment Affords Behavior

For any active organism, the environment affords a variety of behaviors. In ecological psychology, these opportunities for action have traditionally been called "affordances."[1,3,35] Affordances are commonly defined as the relations between the abilities of animals to perceive and act and features of the environment.[3,63] That is, an affordance is the functional meaning of an environment for an organism. A chair, for instance, affords the function of sitting for humans, whereas a bicycle affords cycling. Affordances are specified to an organism through the availability of ecological information.[1] Ecological information is "the set of structures and regularities in the environment," such as patterns of light or sound reflected by the physical environment, "that allow an animal to engage with affordances."[34]

It is important to emphasize that an affordance is a relational construct, or a relation between capabilities and the environment.[3] For instance, a bicycle path will only afford bicycling for a person who knows how to cycle. The basic logical structure of an affordance can therefore be defined as "affords-ϕ (environment, organism), where ϕ is a behaviour."[63]

Ecological psychologists have thus focused on the functional meaning of environments for animals, particularly humans. A central tenet of ecological psychology is that in our immediate experiential and phenomenological world, we do not generally perceive our environment as functionally meaningless. For instance, when we perceive a chair, we do not merely perceive

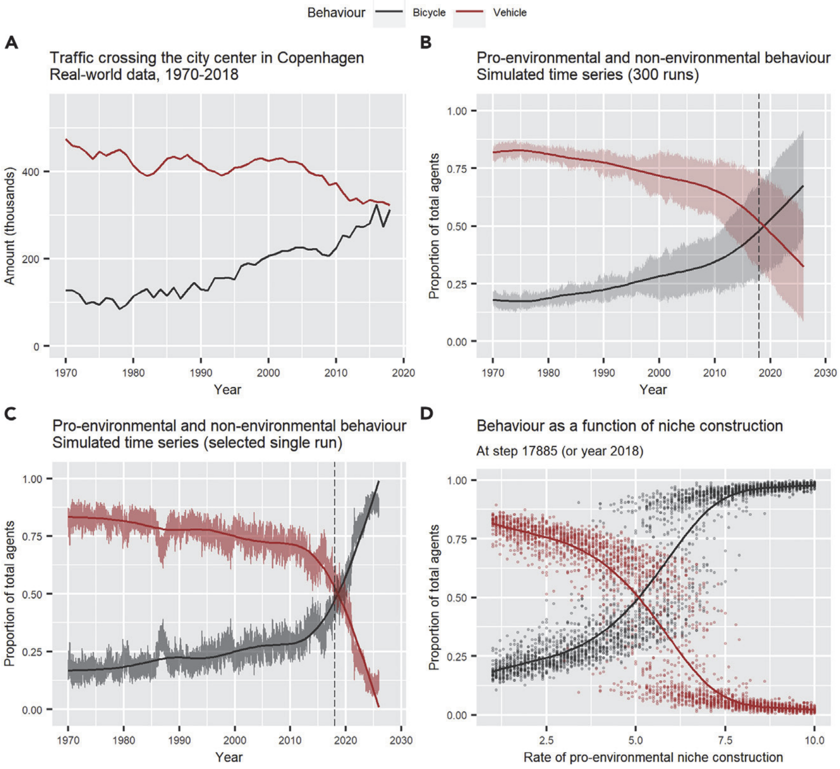

Figure 5. Empirical Validation

Real-world and simulated data of cycling and driving patterns in Copenhagen. Shown are (A) real-world data from 1970 to 2018 and (B and C) simulated time-series data, the latter of which have a dashed vertical line at the year 2018. 300 simulation runs with a ribbon of ±1 standard deviation are shown in (B), and a single representative simulation run, manually selected from (B), is shown in (C). Results at year 2018 (timestep 17,885) when the rate of niche construction is varied are illustrated in (D). Lines in (B)–(D) are smoothed conditional means (GAM). In (D), notice the phase transition between niche construction rates of roughly 5 and 7, similar in logic to the tipping point illustrated in Figures 2A and 2B.

a static object; rather, we perceive an opportunity for sitting.[64] In other words, (some of) the primary things we perceive are affordances.[1]

Rietveld and Kiverstein[4] have argued that humans inhabit a particularly rich and resourceful "landscape of affordances." That is, we have designed and fitted our environments—urban environments in particular—with a large variety of opportunities for action. This notion of a landscape of affordances is crucial for the present model given that the model's grid (Figure S17) effectively represents a landscape of affordances.

Recently, affordance theory has been applied particularly in assessing the functional meaning of urban form, e.g., the provision of sustainable affordances in urban environments[2,65] and the child friendliness of affordances in urban and rural environments,[14] and it has also found foothold in sense-of-place research.[66] What these approaches have in common is the attempt to study or model the psychologically meaningful dimensions of the material environment and the influence of the physical environment on human behavior.[67]

Moreover, research in ecological and environmental psychology has suggested that a "positive interaction cycle" could emerge between humans and environments when affordances are readily available.[14] That is, an increase in affordances for behavior *B* will increase the probability of actualizing behavior *B*, which in turn increases the probability for engaging with affordances for behavior *B* in the future (as a result of increased motivation, learning, habituation, and other factors; see Behavior Modulates Personal States). Similar feedback loops have been proposed by Chemero[3] and Kaaronen.[2]

Behavior Modulates Personal States

The ways in which we behave—or whatever affordances we act upon—often influence how we behave in the future. This is because humans learn from individual behavior (individual or asocial learning), form habits, and have a tendency to adjust their attitudes and values to their behavior, among an innumerable variety of other cognitive, psychological, and neural factors.

A habit is an automatic behavioral response to environmental cues and is believed to develop through the repetition of behavior in consistent contexts.[6] Particularly with commonly encountered cues (or affordances), a habit leads to the frequent performance of a behavior *B*, and habits are often strong enough to override any conscious or intentional regulations for that behavior.[6] We have a tendency to behave in the ways in which we are used to behaving or the ways in which our environment prompts us to behave, sometimes even regardless of our intentions or desires. In everyday life, this is almost self-evident: our behavioral patterns are far from random, and to give some examples, we often shop for the same items as we have shopped for before, use familiar routes and modes of transport, and so on. The process of gaining habits, or a "behavioral response decrement that results from repeated stimulation," is called habituation.[37]

Other fields of (social) psychology and cognitive science have illustrated how we have a tendency to modulate our internal states (such as attitudes and values) to our behavior. For instance, research in cognitive dissonance theory illustrates how through processes of self-justification, we have a tendency to adjust our attitudes and beliefs to conform with our current, past, or recent behavior.[5,40,68] More recent approaches to cognitive science, such as predictive processing, also support the notion that we have a tendency to adjust our internal models of the world to minimize prediction error or to keep our internal models of the world in tune with our past and current behavior.[68,69] If these internal states are predictors of behavior *B* (see Personal States Affect Behavior), this would also imply (all other things being equal, and on average) that behavior *B* would increase the future probability of behaving in that way.

Moreover, behavior can result in a wide variety of individual learning.[11,39] This is fairly uncontroversial: if a person enacts behavior *B* (e.g., cycling) regularly, they might improve their cycling skills and thus engage in that behavior more often in the future. For instance, Kyttä[14] has suggested that repeated engagement with familiar affordances can result in increased motivation to interact with them in the future.

Thus, crudely, it could be asserted that on average and in the long run (and all other things being equal), behaving in a way *B* at time *t* would increase the probability of performing behavior *B* at time t_{+1}, mediated through changes in the personal state *P* (which include individual learning and habituation, among other cognitive processes).

Personal States Affect Behavior

The notion that the personal state of a human has an effect on behavior is perhaps the most familiar assumption of the present model. We like to think of our behavior as being guided by our attitudes, values, subjective norms, and so on. Indeed, a branch of psychology dealing with the "theory of

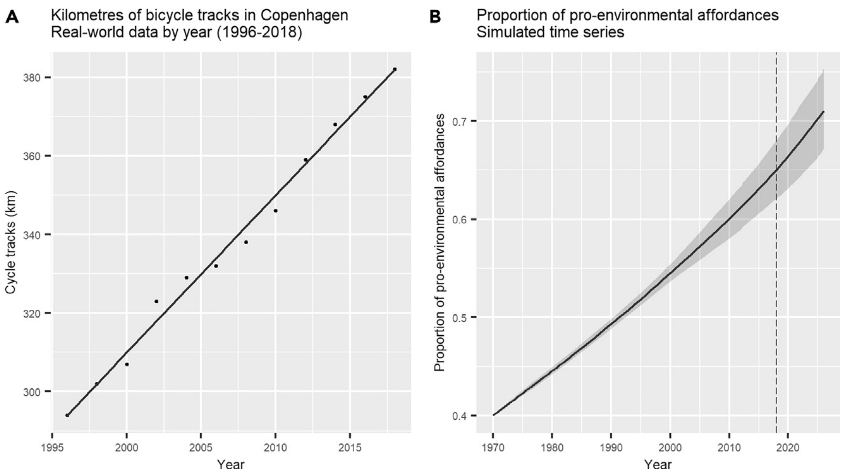

Figure 6. Development of Bicycling Affordances in Copenhagen

(A) Real-world data of kilometers of bicycle tracks in Copenhagen from 1996 to 2018 with a linear regression fit for illustrative purposes.

(B) The proportion of pro-environmental affordances over time in 300 simulation runs with smoothed conditional mean (GAM). The shaded area signifies ±1 standard deviation, and the vertical dashed line is at year 2018.

planned behavior'' deals explicitly with this;[7] it proposes that behavior can be predicted from ''attitudes toward the behavior, subjective norms [an individual's perception about a behavior], and perceived behavioral control.''[7]

However, there exist a wealth of behavioral patterns that are not predicted by attitudes or subjective norms. This has been studied extensively in the context of the attitude-action gap.[47,70] For instance, possession of environmental knowledge and environmental awareness does not necessarily translate into pro-environmental behavioral patterns.[47,71] This discrepancy might be a result of old habits or, simply, the lack of given and easily accessible action opportunities or affordances.[2]

For these reasons, in the present text, the personal state (*P*) of an organism is defined as the totality of an organism's properties that dispose it to behaving in a particular way. More precisely, in the present model, the *P* of an agent corresponds to the probability of interacting with a certain type of affordance. Therefore, the personal state as referred to in this paper is much more than just a conception of attitudes, subjective norms, or values—it is an umbrella term that also includes adopted habits (even unconscious ones), personality, learned sensorimotor skills, (tacit and explicit) knowledge, capabilities,[38] and so on.

Behavior Shapes the Environment

Not only do affordances influence human behavior, but we also actively shape the affordances within our ecological niche. This process, ''whereby organisms, through their activities and choices, modify their own and each other's niches,'' is called niche construction.[8] Although the roots of niche construction theory lie in evolutionary ecology,[9] niche construction theory has more recently gained interest in cognitive science[3,69,72] and cultural evolution.[8,10] For present purposes, it suffices to understand niche construction as the construction of non-random biases on behavioral selection pressures.[9]

Through the process of niche construction, we design our environment to afford a large variety of behaviors that reinforce our daily habits and routines.[69] Recent theories in cognitive science suggest that, in general, niche construction occurs to make the environment more predictable—that is, we tend to design our environment so that it conforms to our cognitive models.[69,73] As Veissière et al. argue,[74] niche construction ''can be viewed as the process whereby agents make their niche conform to their expectations'' (see also Constant et al.[72]). Thus, the behavioral selection pressures caused by niche construction would then generally serve to reinforce past behaviors.

In the context of the present model, niche construction could include urban design (e.g., implementation of bicycle paths as a response to increased demand), household design (e.g., fitting one's household with eco-friendly affordances, such as recycling bins), or other forms of self-organizing social activities (e.g., providing a community with more autonomy in designing their niche from the bottom up; see Alexander[53]).

Social Learning and Networks

Any description of human behavior that does not account for social learning and transmission would be radically incomplete. Therefore, in the present model, all behavior is assumed to emerge in a social network. This is because humans are, above all, social learners, and our social capabilities are arguably the feature that sets us most apart from other species.[10,75]

Social learning is the process through which learning is ''facilitated by observation of, or interaction with, another individual or its products.''[11] In a social network, behaviors and information spreads through a process known as social transmission, where ''the prior acquisition of a behavioral trait T by one individual A, when expressed either directly in the performance of T or in some other behavior associated with T, exerts a *lasting positive causal influence* [emphasis added] on the rate at which another individual B acquires and/or performs T.''[11]

Social learning and social transmission form a cornerstone of studies of cultural evolution.[10,11] This is simply because ''much behavioral variation between societies can be explained in terms of cultural transmission: people acquire knowledge, customs, attitudes, values, and so on from other members of their society.''[45] In fact, the social intelligence hypothesis[76] goes as far as to propose that, particularly in the case of humans, social learning is more common and influential than individual learning.

For the purpose of this model, this implies that whenever an agent engages with an affordance and behaves successfully, it will exert lasting positive causal influence on its local social network, increasing their probability to behave similarly.

Model Design

Concluding from the previous sections, we can now define Lewin's equation's parameters more precisely (see Table 1). Behavior is a function of person and environment (Equation 1), where, first, the environment (*E*) is a landscape of affordances consisting of a distribution of opportunities for behavior. Second, behavior (*B*) at time *t* occurs from successful interaction with affordances (*E*) and can lead to non-random modification of the environment (*E*), altering the selection pressures for behavior at t_{+1}. Third, a personal state (*P*) corresponds to the probability of engaging with an affordance and is modulated by behavior (*B*). Fourth, all behavior (*B*) occurs in a social network where behaviors affect the personal states (*P*) and thus behaviors of others.

Although by no means exhaustive, this conception provides a coherent framework for designing a formal model around Lewin's equation. We now proceed to a description of the ABM itself. A more detailed description of the model's procedures and mechanisms can be found in the ODD Protocol subsection of the Supplemental Experimental Procedures. The ODD Protocol also includes Unified Modeling Language diagrams (Figures S1, S5, and S6) and further elaboration of network structure (Figures S2–S4).

In the spirit of pattern-oriented modeling,[17] we rely on ''multiple patterns observed in real systems to guide design of model structure.'' We have designed the model in accordance with multiple micro-level patterns, from which realistic macro-level patterns emerge.

The subsection Sensitivity Analysis in the Supplemental Experimental Procedures also includes two kinds of sensitivity analyses: local one-factor-at-a-time (OFAT) sensitivity tests,[77] where the model's sensitivity to each parameter is analyzed individually (Figures S7–S13), and global sensitivity tests (Figures S14–S16), where all free parameters are allowed to vary with the use of Latin hypercube sampling.

Model Setup

Affordances

The grid of this model represents a landscape of affordances.[4] This model has two types of affordances: a pro-environmental affordance, where pro-environmental "refers to behavior that harms the environment as little as possible, or even benefits the environment,"[78] and a non-environmental affordance, where non-environmental refers to an environmentally harmful activity.

In its abstract form, the model is indifferent to what these affordances precisely are. What is important for the model design, however, is that these behaviors are dependent. For instance, if the pro-environmental affordance is understood to represent an opportunity for "cycling," engaging with this affordance should have an effect on the probability of engaging with the non-environmental affordance (e.g., "driving"). The abstract categorization into binary affordances (non-environmental and pro-environmental) is not a necessity for the model design, but it makes for more simple interpretation. Considering that modeling the whole of the landscape of affordances in any given human niche would be practically impossible, this limitation is also a pragmatic one.

The model represents affordances as patches within NetLogo's Cartesian grid. See Table S2 for a brief definition of the model's parameters and the Discussion for thoughts on how the model could be extended to include more behaviors in the future. The model's setup procedure generates a landscape of affordances, where the initial proportion of pro-environmental affordances is assigned by the parameter "pro-amount."

Networks

In model setup, agents are spawned on the grid at random locations (the default value for the "number-of-agents" is 300). During the generation of agents, links are generated to connect the agents, creating a Klemm-Eguíluz network.[79] The Klemm-Eguíluz model was chosen because it represents two characteristics we know to characterize social systems: societies have hubs (the network degree distribution follows a power law distribution, i.e., it has scale-free properties), and societies have highly clustered local communities (social networks have high clustering coefficients).[79] Although our ABM also supports the Erdős-Rényi model[80] (random network), the Barabási-Albert model[81] (scale-free network with low clustering), and the Watts-Strogatz small-world model[82] (highly clustered network without scale-free properties), the Klemm-Eguíluz model was chosen because it combines the best aspects of the latter two models: scale-free properties and high clustering. The code for creating the Klemm-Eguíluz model was adapted with permission from Caparrini's[83] Complex Networks Toolbox. All links in this model are undirected such that information flows both ways.

The model is quite robust against variation in network density, although extreme values will create more polarized outcomes in model behavior. In the following simulations, we set the Klemm-Eguíluz model parameter μ to 0.9 and *m*0 to 5 (see Caparrini[83] for a concise definition of these parameters and Klemm and Eguíluz[79] for a more detailed account). This creates a network with a long-tailed degree distribution and a high global clustering coefficient. With these parameter values, the model relatively rarely creates agents with more than 150 direct connections. Although it is notoriously difficult to operationalize a realistic network density, the chosen network structure does respect the suggested upper cognitive limit of the degree of stable social relationships, or Dunbar's number,[84] which suggests that humans are cognitively incapable of maintaining over 150 social relationships.

Personal States

Each agent is assigned two initial personal states, "pro-env" and "non-env." The former defines the probability of interacting with a pro-environmental affordance, and the latter defines the probability of interacting with a non-environmental affordance. Personal states are initially sampled from a normal distribution with a mean defined by the parameters "initial-pro" (for pro-env) and "initial-non" (for non-env) and a standard deviation of 0.15. A standard deviation of 0.15 (in the range of 0–1) is roughly in line with data on standard deviations of environmental attitudes and self-reported behaviors. For instance, Chan[85] reports standard deviations ranging from 0.75 to 0.8 for self-reported pro-environmental behaviors on a five-point scale.

Because personal states are probabilities, they are bounded within the range [0, 1]. Each agent is given individual upper bounds and lower bounds for their personal states. The bounds are drawn from normal distributions with means of 0.2 (lower) and 0.8 (upper) and a standard deviation of 0.05. This allows for some agents to adopt more extreme habits than others, which is in line with empirical observations; for instance, some people might be more prone to adopting strict vegan habits than others who adopt, at most, part-time vegetarian or flexitarian eating habits. Note that the personal states need not add up to 1; it is possible, for example, that a person would actualize the affordance of driving (when encountering a driving affordance) with a probability of 0.55 while also actualizing an encountered cycling affordance with a probability of 0.55.

Model Processes

Overview

The Go command launches the model. Agents move in a random walk around the landscape of affordances. During each tick (timestep), the agents have a chance of interacting with the affordance (patch) they are currently on. For example, if an agent is on a pro-environmental affordance and currently has a pro-env value of 0.5, it has a 50% chance of interacting with that affordance. Each agent must behave somehow during each tick. Therefore, if an agent does not interact with an affordance successfully, it will move one step forward and try again by repeating this procedure until it interacts successfully with an affordance it encounters. Successfully interacting with an affordance represents one instance of behavior. Behaviors are tracked through the global variables "pro-behavior" and "non-behavior," which are reset at the beginning of each tick. This allows us to track the total amount of pro-environmental and non-environmental behaviors at the end of each timestep.

Individual Learning

Successful behavior launches a series of procedures. First, behaving leads to individual learning and habituation. If, for instance, an agent behaves pro-environmentally at time *t*, it will set its personal state pro-env to "pro-env$_{(t)}$ + asocial-learning" and its non-env to "non-env$_{(t)}$ − asocial-learning," where "asocial-learning" is the rate of individual learning and habituation. The sequence is identical for non-environmental behavior. It is important that an increase in pro-env leads to a decrease in non-env (i.e., they are not independent) because otherwise the model would practically always converge to a state where each agent possesses a maximum possible value for both pro-env and non-env. The decrease can simply be understood as the decay of an acquired habit when a given behavior is not practiced.

Social Learning

Second, behavior leads to social learning and transmission. If an agent behaves non-environmentally at time *t*, it will ask its network neighbors (the agents it is directly linked to) to set their non-env to "non-env$_{(t)}$ + social-learning" and its pro-env to "pro-env$_{(t)}$ − social-learning," where "social-learning" is the parameter for the rate of social transmission. Again, the sequence is identical for pro-environmental behavior.

Niche Construction

Third, behaving can lead to niche construction. For example, if an agent behaves pro-environmentally, it can flip one of the patches in its Moore neighborhood (its surrounding eight patches) to a pro-environmental affordance (thus increasing the likelihood of encountering a pro-environmental affordance in the future and effectively making the environment more predictable; see Behavior Shapes the Environment). The procedure is identical for non-environmental behavior. The probability for niche construction is defined by the parameters "construct-pro" (for pro-environmental niche construction) and "construct-non" (for non-environmental niche construction).

Other Processes

Finally, if mutations are turned on, on each tick agents have a chance of mutating their pro-env and non-env values by a slight amount. This is analogous to external influence or the influence of factors not captured by the model. This produces more jagged data more resemblant of real-world observations. We use mutations only in empirical validation. All behaviors in the model are sequential: an agent completes the full set of actions before passing on control to the next agent. The order of agents is read randomly on each tick.

DATA AND CODE AVAILABILITY

All data (.CSV) and code (R) used for analysis are available on GitHub: https://github.com/roopekaaronen/affordance. The agent-based model (NetLogo) with code is available at https://www.comses.net/codebases/c2feceb8-d9c4-4637-8f27-fda49c7dc4f3/releases/1.2.0/.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.01.003.

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AUTHOR CONTRIBUTIONS

R.O.K. was the main contributing author for the manuscript, model, and analysis. N.S. supervised the project and oversaw the development of the manuscript, model, and analysis.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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One Earth, Volume *2*

Supplemental Information

Cultural Evolution of Sustainable Behaviors: Pro-environmental Tipping Points in an Agent-Based Model

Roope Oskari Kaaronen and Nikita Strelkovskii

Supplemental Experimental Procedures

Software

In this research article and NetLogo (version 6.1.0) model, we use NetLogo's native BehaviorSpace tool for parameter sweeping, and NetLogo's BehaviorSearch for Genetic Algorithms [1]. We use R [2] and R Studio [3] and R packages tidyverse [4], factoextra [5], Hmisc [6], plyr [7], RColorBrewer [8], reshape2 [9], gridExtra [10] and nlrx [11] for data analysis and visualisation.

ODD Protocol

The following model description follows the ODD (Overview, Design concepts, Details) protocol for describing agent-based models [12,13].

1. Purpose

This model illustrates the cultural evolution of pro-environmental behaviour patterns. It shows how collective behaviour patterns evolve from interactions between agents and agents (in a social network) as well as agents and the affordances within a niche. More specifically, the cultural evolution of behaviour patterns is understood in this model as a product of:

1. The landscape of affordances (action opportunities) provided by the material environment,
2. Individual learning and habituation,
3. Social learning and network structure,
4. Personal states (such as habits and attitudes), and
5. Cultural niche construction, or the modulation of affordances within a niche.

More particularly, the model illustrates how changes in the landscape of affordances [14] can trigger nonlinear changes in collective behaviour patterns. The model also shows how several behavioural cultures can emerge from the same environment and even within the same network.

The model is an elaboration of Kurt Lewin's [15] heuristic equation, $B = f(P, E)$, where behaviour (B) is a function (f) of the person (P) and the environment (E). The model introduces several feedback loops (1–5 above) to Lewin's equation, and thus provides a framework for studying the evolution of dynamical and complex behavioural systems over time. The model should be considered an abstract model, since many of its parameters are unspecifiable due to limits to current understanding of human (social) behaviour. However, the model can be tuned to replicate real-world macro patterns, and be used as a sandbox environment to locate tipping points in social systems. In the present manuscript, for example, we use the model to reproduce real-world patterns of bicycle and car use in Copenhagen.

2. Entities, state variables, and scales

The model includes three types of agents: human individuals, represented by mobile circle-shaped agents (or 'turtles' in NetLogo lingo), affordances (static patches that occupy grid cells) and links (which connect agents in a social network).

Individuals: Agents represent a single human being, located within a broader collective social network and ecological niche. Each individual has two personal states. These personal states correspond to the individual's probability of engaging with a specific kind of affordance. Affordances are opportunities for action provided by the environment. The two personal states in this model are *pro-env* and *non-env*. The former, *pro-env*, defines the probability of an individual to engage with pro-environmental affordances, and the latter, *non-env*, defines the probability of an individual to engage with non-environmental affordances.

The personal states of individual agents are sampled from a normal distribution with mean values *initial-pro* (for *pro-env*) and *initial-non* (for *non-env*), and SD 0.15. This standard deviation is roughly in line with empirical data related to environmental attitudes and self-reported behaviours [16]. Owing to the model's probabilistic representation of human behaviour, the values of *pro-env* and *non-env* must be bounded between 0 and 1. More specifically, the model assigns individual boundaries for the *pro-env* and *non-env* of each agent. The bounds are sampled from a normal distribution with mean values 0.2 (lower bound) and 0.8 (upper bound), with SD 0.05.

Individuals are coloured based on their personal states. This is purely cosmetic, but it aids in noticing changes in personal states. If *pro-env* > *non-env*, the agent is coloured black. If *non-env* > *pro-env*, the agent is coloured red.

Links: Individual agents are embedded in a social network which is connected by links. The model supports four types of networks: the Klemm-Eguíluz model (highly clustered scale-free network), the Watts–Strogatz model (small-world network), the Barabási–Albert model (scale-free network with preferential attachment) and the Erdős–Rényi model (random network). All network edges (links) are undirected (bidirectional).

The default network choice is the Klemm-Eguíluz model [17]. The Klemm-Eguíluz algorithm generates a network based on a finite memory of the nodes (agents), creating a highly clustered and scale-free network (see Figures S2–S4). The Klemm-Eguíluz model was chosen since it represents two features we know to characterize social systems: Societies have hubs (the network degree distribution follows a power law distribution, i.e. it has scale-free properties) and societies have highly clustered local communities (social networks have high clustering coefficients) (ibid.). See Klemm and Eguíluz [17] and Caparrini [18] for descriptions of how Klemm-Eguíluz model works, as well as Prettejohn et al. [section 3.4 in 19] for useful pseudocode. We set the default Klemm-Eguíluz model's parameter *m0* (initial number of agents) to 5 and μ (probability to connect with low degree nodes) to 0.9.

Figure S1. Class diagram (UML).

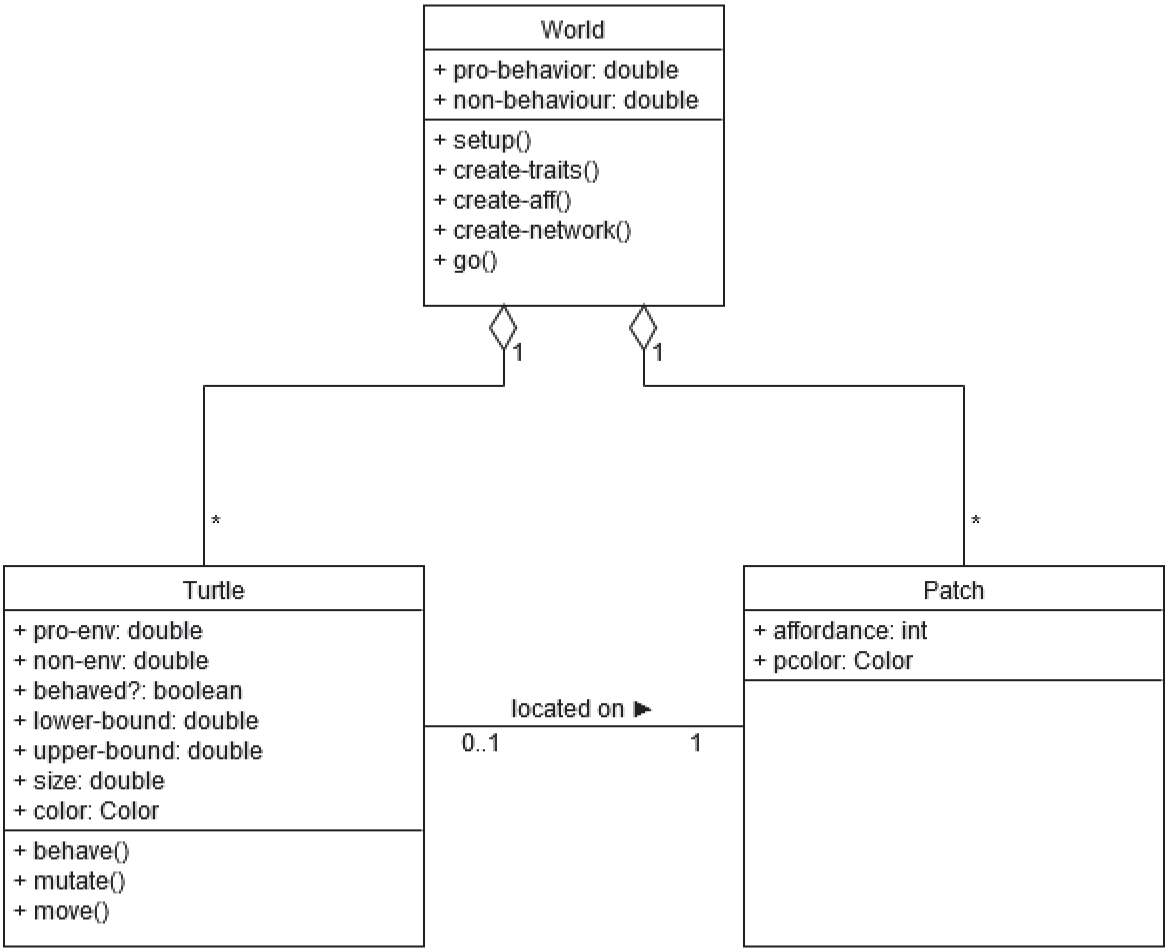


Figure S2. Network degree distribution. A representative plot of the network degree distribution from a single model run with 300 agents. Notice how some agents have amounts of links that greatly exceed the mean (black dashed line) and median (red dashed line).

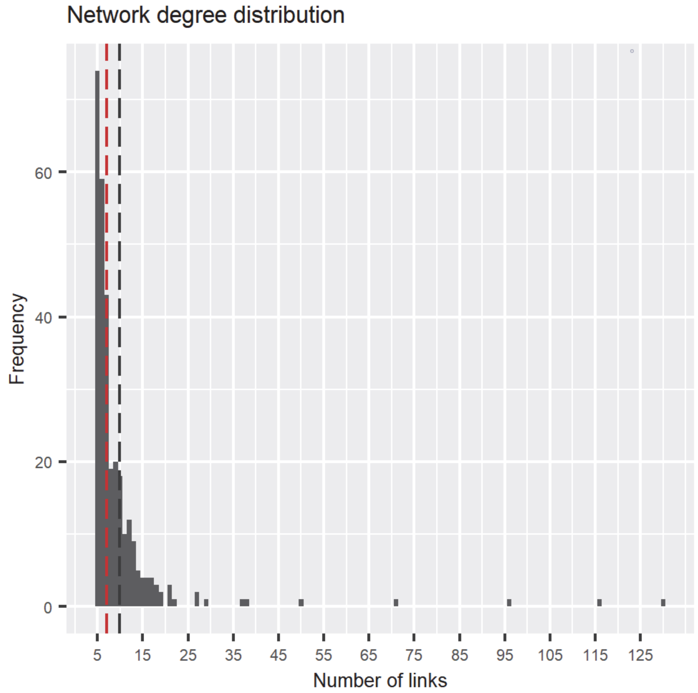


Figure S3. Cumulative network degree distribution. 1000 simulations (total of 300,000 agents) on a logarithmic scale. Notice the scale-free density distribution and relative infrequency of agents with above 150 direct links. Mean links are signified by the black dashed line and median by the red dashed line.

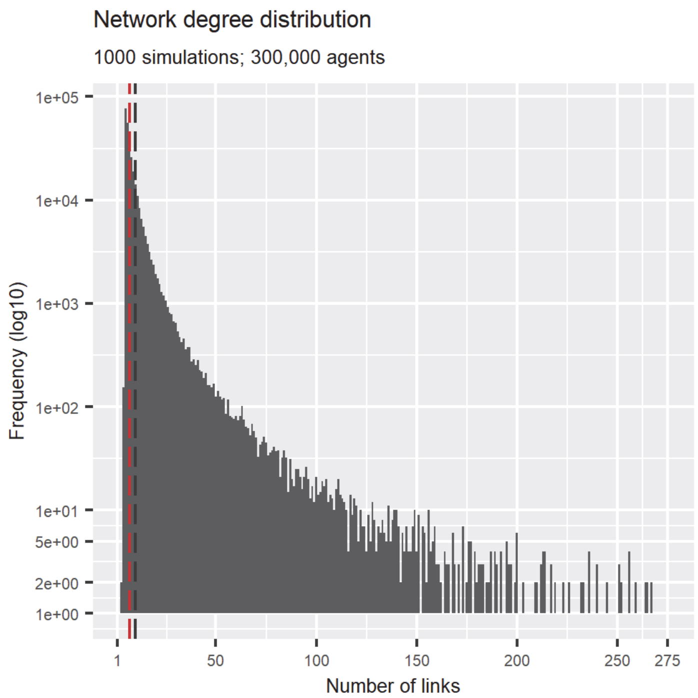
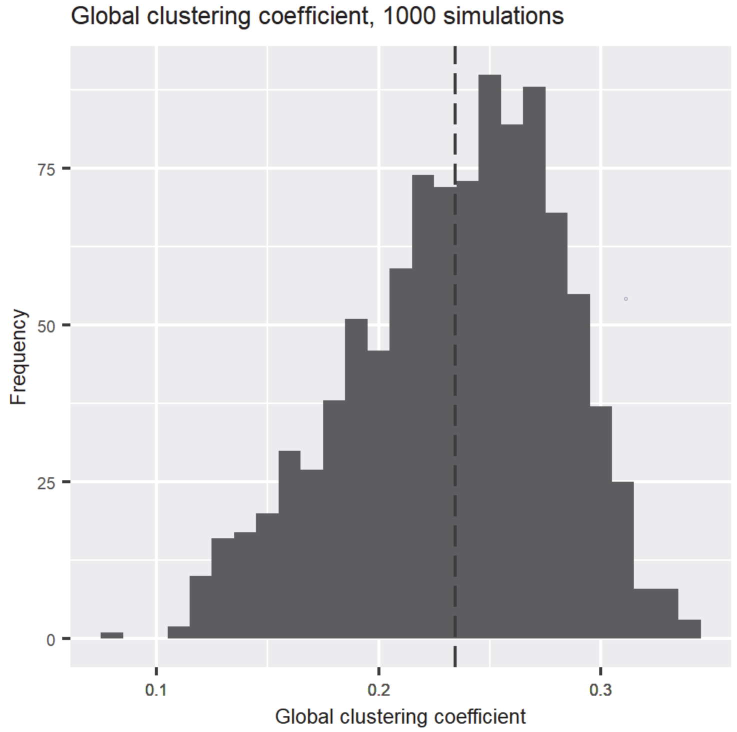


Figure S4. Global clustering coefficients. Histogram with 1000 runs with 100 agents. Global clustering coefficients are calculated based on triplets of nodes. Triplets are three nodes which are connected either by two (open triplet) or three (closed tripled) edges (links). The global cluster coefficient is the number of closed triplets in a network divided by the total number of triplets. Dashed line is at the mean global clustering coefficient, 0.24.



Patches (environment): Patches represent the action-opportunities, or affordances, within the environment. An affordance is the functional relevance of the environment for an individual. The model has two affordances: One represents an opportunity for pro-environmental behaviour (represented by a violet patch) and one represents an opportunity for environmentally harmful behaviour (sky-blue patch). The latter are from here on referred to as non-environmental affordances. The affordances of the environment are therefore binary in this model, even though nothing prevents the addition of more kinds of affordances. Affordance-patches occupy the two-dimensional grid of the model. The grid wraps horizontally and vertically (i.e., it is torus-shaped). The total area of the grid is an arbitrary 201x201 patches.

Scales: The model can be adapted to represent different spatial and temporal scales. One time-step can be understood to either represent one instance of behaviour per agent, or a collection of behaviours. In the abstract version of the model, the spatial and temporal scales are not specifically defined. In empirical validation, the spatial area of the model represents the city centre of Copenhagen, with each tick representing one day.

3. Process overview and scheduling

The submodels of the model are described in more detail and pseudocode in the *Submodels* section. In this section, we describe a brief process overview.

Setup: The model begins with a setup phase where the patches, agents and links are created. Ticks are reset after the setup, so all setup processes occur before the first timestep.

First, the social network (agents and links) is created. This will create a network with individuals specified by the parameter *number-of-agents*.

Second, each agent is assigned two personal states, *pro-env* and *non-env*.

Third, affordances are created. Affordances are binary patches-own variables: value 0 signifies a non-environmental affordance, and value 1 a pro-environmental affordance. First, all patches are assigned with a non-environmental affordance (and coloured sky-blue). Subsequently, the proportion of patches designated by the parameter *pro-amount* are turned into pro-environmental affordances. Therefore, the parameter *pro-amount* corresponds to the initial proportion of pro-environmental affordances within the total landscape of affordances.

Go: The 'Go' procedure is the heart of the model.

First, agents behave. If the agent is on a pro-environmental affordance, it will interact with it with the probability of P(*pro-env*). For example, if an agent's personal state *pro-env* is 0.5, it has a 50% chance of interacting with a pro-environmental affordance.

Likewise, if the agent is on a non-environmental affordance, it will interact with it with the probability of P(*non-env*). Again, if an agent's personal state non-env is 0.7, it has a 70% chance of interacting with a non-environmental affordance.

A while-loop ensures that each agent behaves once every turn. Each agent owns a binary value, *behaved?*, which signifies whether it has behaved, or actualized an affordance, during the current tick. If *behaved?* is TRUE, the agent will stop attempting to behave after completing the behaviour commands (including steps 1–5 below).

Once an agent behaves successfully, a sequence of procedures launched in the following order.

1. If the agent behaved pro-environmentally (i.e., it actualizes a pro-environmental affordance), it will increase its current personal state *pro-env* by the amount of *asocial-learning* and decrease its current *non-env* by the amount of *asocial-learning*.

   Conversely, if the agent behaved non-environmentally (i.e., it actualizes a non-environmental affordance), it will increase its current *non-env* by the amount of *asocial-learning* and decrease its current *pro-env* by the amount of *asocial-learning*.

2. If *niche-construction* is TRUE (niche construction is turned on) and if the agent behaved pro-environmentally, with probability *construct-pro* it will ask one of the eight patches in its Moore neighbourhood to turn into a pro-environmental affordance (which is then coloured in violet). *construct-pro* therefore defines the rate of pro-environmental

niche construction. The procedure is identical for non-environmental niche construction (following non-environmental behaviour), whose rate is defined by *construct-non.* Rates of niche construction are controlled for number-of-agents. This way, adding more agents to the simulations does not add to the rate of overall niche construction. This is necessary because the area (grid) of the model is held constant.

3. If *networks* is TRUE and if the agent behaved pro-environmentally, it will engage in social learning with its network neighbours (the agents to which it is directly connected to by a link). Following pro-environmental behaviour, the agent will ask its network neighbours to increase their current *pro-env* by the amount specified by parameter *social-learning*, as well as to decrease their current *non-env* by the amount specified by parameter *social-learning*. Again, the procedure is similar after non-environmental behaviour, except this results in an increase of *non-env* and decrease of *pro-env* by the amount of *social-learning*.

4. The agent will bound its personal states *pro-env* and *non-env*. If the agent's personal state is above its upper bound or below its lower bound, it will set its personal state to its upper and lower bound, respectively.

5. If mutate? Is TRUE, at each tick, the pro-env and non-env of all agents have a chance of mutating. The default probability for mutation (*mutate-prob*) is 0.005, and the default rate for mutation (*mutate-rate*) is 0.05. The probabilities for increasing or decreasing pro-env and non-env values (of all agents) are equal, i.e. mutation is not biased to any direction.

After each behaviour or attempt to behave, agents move in a random forward direction between 45 degrees right and 45 degrees left from their current heading. In one tick (timestep) agents will continue moving until they have behaved, i.e. until they have successfully interacted with an affordance.

The aforementioned steps are sequential: An agent completes the full set of actions before passing on control to the next agent. The order of agents is read in a random order on each tick.

4. Design concepts

Basic principles.

The model design elaborates on social psychologist Kurt Lewin's [15] heuristic equation: $B = f(P, E)$. Here, behaviour (B) is a function (f) of the person (P) and its environment (E).

The model adds five dimensions of detail into Lewin's equation.

1. The environment affords a variety of opportunities for action, or affordances ($E \rightarrow B$).
2. Behaviour modulates personal states through processes of habituation and individual learning ($B \rightarrow P$).
3. Personal states, such as habits and intentions, drive behaviour ($P \rightarrow B$).
4. Behaviour shapes the environment through processes of niche construction ($B \rightarrow E$).
5. Feedback loops 1–4 all occur within a social network where behaviour is transmitted via social learning ($B_{myself} \rightarrow P_{neighbors}$ and $B_{neighbors} \rightarrow P_{myself}$).

These assumptions are elaborated in detail in the manuscript's section Model Assumptions.

The basic principles can be summarized as follows: Through processes of individual and social learning as well as niche construction, any behaviour at time t will have an effect on the behaviour of an agent and other agents at time $t+1$. The model therefore presents a dynamical systems approach to the emergence of human behaviour, where the unit of study is a tightly coupled human-environment system – a dynamical system which evolves over time and can behave in nonlinear ways due to positive feedback-loops.

Emergence.

The model produces a complex and dynamical system which exhibits several kinds of emergent behaviour.

Firstly, the model displays nonlinearities in the development of behavioural cultures (collective behaviour habits). The behaviour of the agents in the network can be steady for long periods of time, only to be followed by abrupt phase transitions into new states (this is illustrated in more detail in the Results section of the manuscript).

Second, the model illustrates how two different behavioural cultures can emerge from the same environment, and even in the same social network. This is a macro-level pattern that is known (from studies of cultural evolution) to occur in real-world societies [20].

Third, the model has several leverage points. For instance, a small change (e.g., 5–10%) in the initial composition of affordances in the landscape can have radical effects on the evolution of the behavioural cultures. Thus, in a way which is typical to complex emergent systems, the model is sensitive to initial conditions, which makes its evolution difficult to predict at certain parameter ranges.

Fourth, whilst the model always starts with a random composition of the affordance landscape, this landscape gets more structured over time as individuals construct the niche around them.

Adaptation.

Through processes of individual and social learning, agents adapt their personal states to their behaviour and to their immediate social environment. Moreover, agents construct their environment to be more predictable by constructing niches which are in line with past behaviour.

Objectives.

Agents engage in active attempts to behave successfully (actualize an affordance) and to create an environment where past behaviour patterns are increasingly more likely.

Learning.

The model includes two learning processes, individual and social learning. Individual (asocial) learning occurs after behaviour and affects only the agent who behaved. Individual learning is thus a product of individual behaviour. Social learning occurs in the social network an agent is embedded in.

The rates of individual and social learning depend on the chosen representation of behaviours and time-units. Realistic rates of individual and social learning are therefore difficult to specify. However, by studying real-world patterns, it might be possible to infer reasonably accurate rates of social and individual learning (see section Empirical Validation of the manuscript).

Prediction.

Agents do not estimate future conditions or consequences of their decisions.

Sensing.

Agents sense the (colour of the) patch they are currently on as well as their network neighbours and neighbours' behaviour. Agents also sense their physical vicinity, i.e. the patches in their Moore neighbourhood (the 8 patches surrounding the patch they are currently on).

Interaction.

After behaving, agents interact with their network neighbours. This involves both influencing the network neighbours as well as being influenced by each network neighbour (both defined by the rate of *social-learning*). Niche construction also influences the behaviour of other agents, and is thus an indirect form of social interaction.

Stochasticity.

The following processes rely on random sampling:

The initial personal states of agents are sampled from a normal distribution (see section 2 of ODD protocol above). The initial configuration of affordances on the grid is random (the proportion of pro-environmental affordances, however, is fixed by the parameter *pro-amount*). The movement of agents on the grid is a random walk through the landscape of affordances. Each instance of behaviour and niche construction makes use of a floating random number generator. The model supports the use of a fixed random seed for replicability (if *random-seed?* is TRUE, a random seed can be fixed with the *rseed* parameter).

Collectives.

Individuals belong to a social network and construct their niche, as defined above. Individuals take part in shaping the collective network and niche which, in turn, shapes their behaviour.

Observation.

Observation generally involves tracking mean or specific values over time. The most relevant variables are the global variables *pro-behavior* and *non-behavior*, which track the total amount of pro-environmental and non-environmental behaviour during each tick.

Parameter sweeps are conducted via NetLogo's native BehaviorSpace tool.

5. Initialization

The initialization of the model is allowed to vary among simulations. Since many values, such as the personal states of agents, are randomly sampled, each model run will differ from the next even when run with the same parameter values.

However, the model supports the use of a fixed random seed for replicability (if *random-seed?* is TRUE, a random seed can be fixed with the rseed parameter).

The initial state of the model at $t = 0$ will depend on the parameters *initial-pro, initial-non, pro-amount* and the network parameters (*networks*, *network-type*) as defined above.

In the abstract version of the model, the initial states are arbitrary. The abstract model can be used to study the dynamics and sensitivities of the model's general structure.

In empirical validation, the initial states of the model are tuned to reproduce real-world patterns, or the cycling and driving habits of people in central Copenhagen.

6. Input data

The model does not use input from external sources such as data files or other models.

7. Submodels

In the following, the processes mentioned in *Process overview and scheduling* (above) are described in more detail in pseudocode, flowcharts (UML diagrams) and natural language. Pseudocode is written by editing NetLogo code to resemble natural language. Whilst the descriptions below are comprehensive, please also refer to the fully annotated model code for details. The following section documents the *SETUP* submodels (*Social network, Personal states and Affordances*) and the *GO* submodels (*Behavior* and *Mutate*). *Behavior* includes descriptions of the processes of individual learning, niche construction and social learning.

SETUP

Social network

Since fully a full description of the Klemm-Eguíluz model would require a chapter-length analysis, we refer the reader to Caparrini's Complex Networks Toolbox [18] for a description of the Klemm-Eguíluz small-world-scale-free network (we adapted, with permission, Caparrini's code for the present model). A full pseudocode description of the Klemm-Eguíluz model is openly accessible in Prettejohn, Berryman and McDonnell's [19] chapter '3.4 Klemm and Eguílez

Small-World-Scale-Free Network'. A full mathematical description of the model is also available in Klemm-Eguíluz' original work [17].

Personal states

Personal states are created in the model setup. In pseudocode,

```
to set personal states
for each turtle in the list of all turtles [
  Set pro-env: sample a random value from a normal distribution with
  mean of initial-pro and a standard deviation of 0.15.
  Set non-env: sample a random value from a normal distribution with
  mean of initial-non and a standard deviation of 0.15.
  Set lower-bound: Set a lower bound for non-env and pro-env from a
  random normal distribution with mean 0.2 and SD 0.05.
  Set upper-bound: Set an upper bound for non-env and pro-env from a
  random normal distribution with mean 0.8 and SD 0.05
  ]
  end
```

Affordances

Affordances are patches-own variables. Affordances are created with the following procedure (pseudocode):

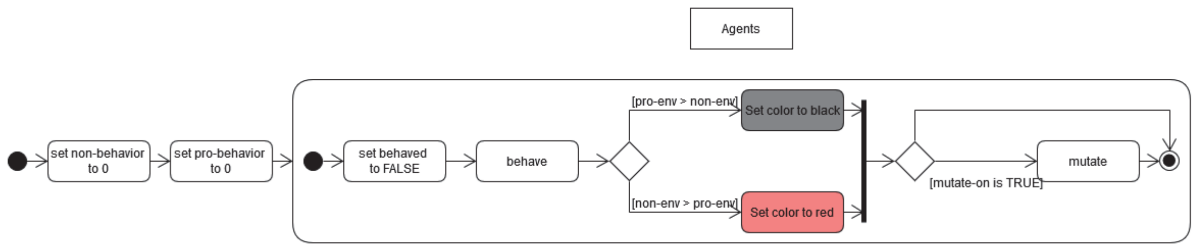
```
to create affordances
let total-patches be total count of patches
  ask all patches [
     set affordance to 0 ;; non-evironmental affordance
```

```
      set color to sky-blue ]
  ask n-of (total-patches * pro-amount) patches [
      set affordance to 1 ;; pro-environmental affordance
      set color to violet]
end
```

GO

The go-procedure begins with each agent resetting their global *pro-behavior* and *non-behavior* variables to 0 (these global variables measure the total pro- and non-environmental behaviours of all agents at the end of each tick). Then, agents set their *behaved?* variable (turtles-own variable) to FALSE. The *behaved?* variable ensures that each agent behaves (either pro- or non-environmentally) only once during a tick. After this, agents behave.

Figure S5. Go procedure, activity diagram (UML).



Behavior

This submodel is the heart of the model. It defines how agents interact with the environment and other agents. Since the procedure is identical for both pro-environmental and non-environmental behaviours, only pro-environmental behaviour is described here. To implement non-environmental behaviour, simply duplicate the code and replace 'pro-environmental' (value 1) patch with ‘non-environmental’ (value 0), ‘violet’ with ‘sky-blue’, and *pro-env* with *non-env* (and vice versa, *non-env* with *pro-env*). The processes of habituation, niche construction and social learning are included in this submodel, and are described below in pseudocode.

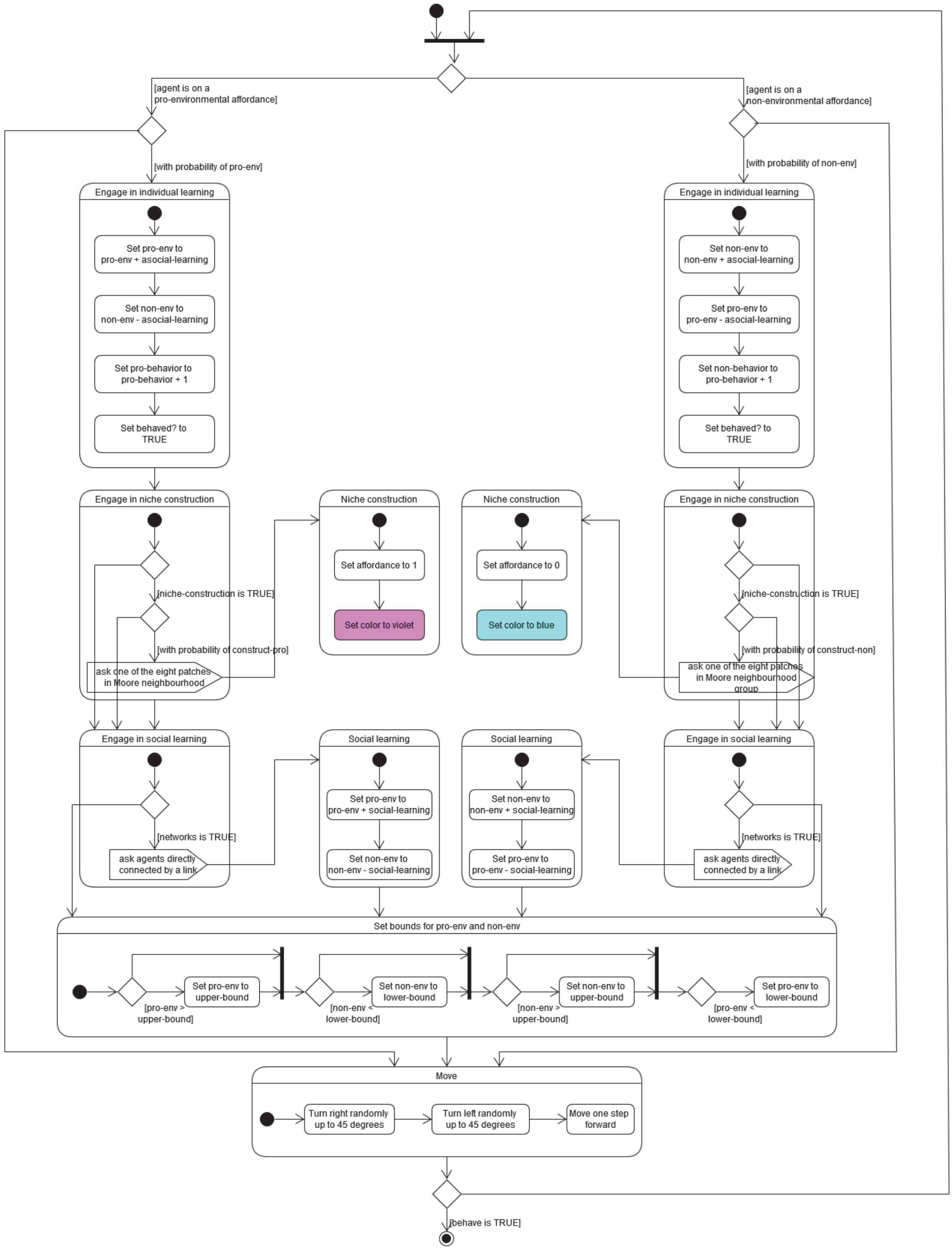
```
to behave
 while behaved? is FALSE [ ;; Start of while-loop
      if the patch the agent is currently on is pro-environmental
      and random-floating number in range [0,1] is smaller than
      pro-env [
;; Engage in individual learning
      set pro-env to (pro-env + asocial-learning)
      set non-env to (non-env - asocial-learning)
      set pro-behavior to (pro-behavior + 1)
      set behaved? to TRUE
;; And still complete the following commands (we are still in the
while-loop)

;; Engage in niche construction
if niche-construction is TRUE [
      if random-floating number in range [0,1] is smaller than
      (construct-pro / number-of-agents) [
         ask one-of patches in Moore neighborhood [
            set affordance to 1
            set color to violet ]
               ]
            ]
```

```
;; Engage in social learning
if networks is TRUE [
      ask link-neighbors [
        set pro-env to (pro-env + social-learning)
        set non-env to (non-env - social-learning)
            ]
      ]
]

;; Set bounds for pro-env and non-env
if pro-env > upper-bound [set pro-env to upper-bound]
if non-env < lower-bound [set non-env to lower-bound]
if non-env > upper-bound  [set non-env to upper-bound]
if pro-env < lower-bound [set pro-env to lower-bound]

;; Finally, move.
turn right randomly up to 45 degrees
turn left randomly up to 45 degrees
move one step forward
] ;; End of while-loop, and end the behave procedure
end
```

Mutate

```
to mutate

if mutate-on? = TRUE [

let mutate-probability 0.005

let mutate-rate 0.05

if random-floating number in range [0,1] is smaller than mutate-probability [

    ask turtles [ set pro-env to (pro-env + mutate-rate)]]

if random-floating number in range [0,1] is smaller than mutate-probability [

    ask turtles [ set non-env to (non-env - mutate-rate) ]]

;; ...and so on for all four possible configurations (mutation is not biased to any direction.)

if random-floating number in range [0,1] is smaller than mutate-probability [

    ask turtles [ set non-env to (non-env + mutate-rate) ]]

  if random-floating number in range [0,1] is smaller than mutate-probability [

    ask turtles [ set pro-env to (pro-env - mutate-rate) ]]

]

end
```

Figure S6. The 'behave' submodel, activity diagram (UML).



Sensitivity Analysis

Local Sensitivity Analysis: OFAT Testing

We begin by testing our model's sensitivities based on one-factor-at-a-time (OFAT) sensitivity analysis. OFAT sensitivity analysis 'consists of selecting a base parameter setting (nominal set) and varying one parameter at a time while keeping all other parameters fixed' [21]. It is therefore referred to as a local sensitivity analysis method. For local sensitivity testing, we use the parameter values as defined by Table S3 (the abstract model run), since its output is arguably more intuitive to understand (than the parameter values used for empirical validation), and it is much less computationally demanding. For data visualisation, we use raincloud plots [22], which illustrate the distribution of data points (in this case, the proportion of pro-environmental behaviour at the final timestep, 2000) and a boxplot with medians and ± 1 standard deviations. Since the mechanism for initial-pro and initial-non, as well as construct-pro and construct-non, are identical, only the pro-environmental variants of these parameters are analysed. This produces a total of 7 plots, shown below.

Figure S7. Sensitivity test 1. The model is especially sensitive to the initial proportion of pro-environmental affordances. This is, however, expected on the basis of results such as Figures 2A and 2B. At extreme values such as when pro-amount is larger than 0.75, most agents will behave pro-environmentally.

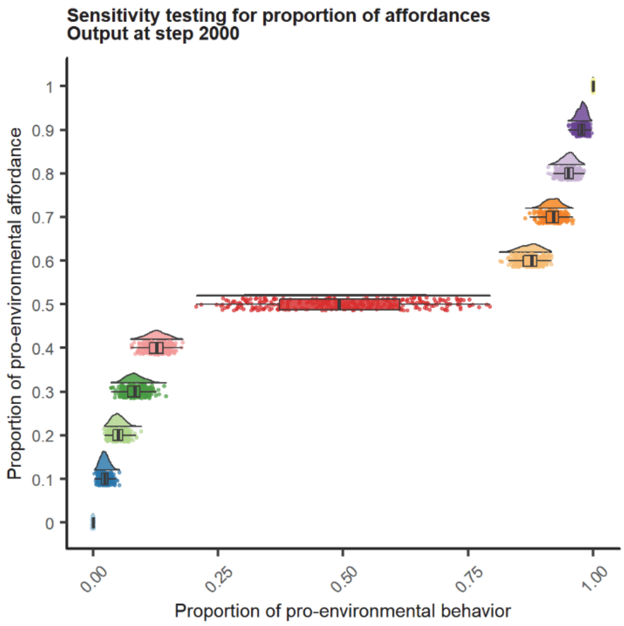


Figure S8. Sensitivity test 2. The model is particularly robust against changes in the rate of individual (asocial) learning.

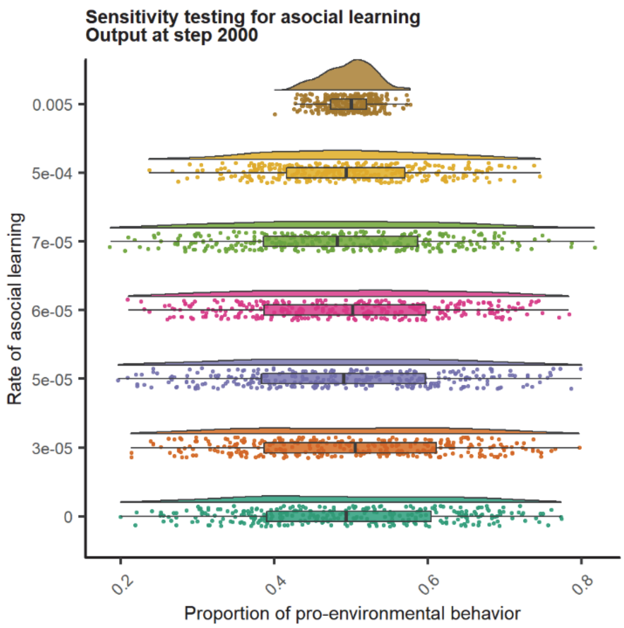


Figure S9. Sensitivity test 3. Higher rates of pro-environmental niche construction will lead to more extreme results in the adoption of pro-environmental behaviour. This effect was also seen and explained in the Results section of the present manuscript.

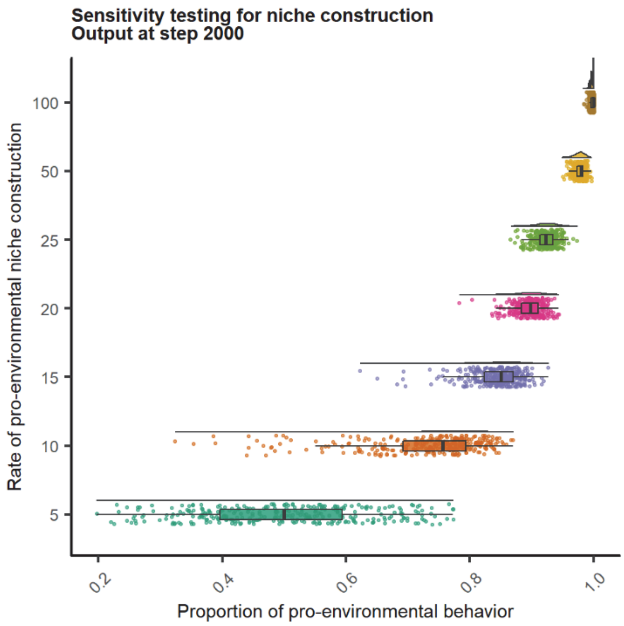


Figure S10. Sensitivity test 4. The network density (minimum degree of connection, or *m0* in the Klemm-Eguíluz model) has a notable effect on outcomes in pro-environmental behaviours. The reasoning is intuitive: When networks are denser, more social learning and transmission occurs, which leads to more polarized end results as the society of agents converges into a uniform behavioural unit or culture (notice how the density distribution of degree connection 20 approaches what seems like a bimodal distribution).

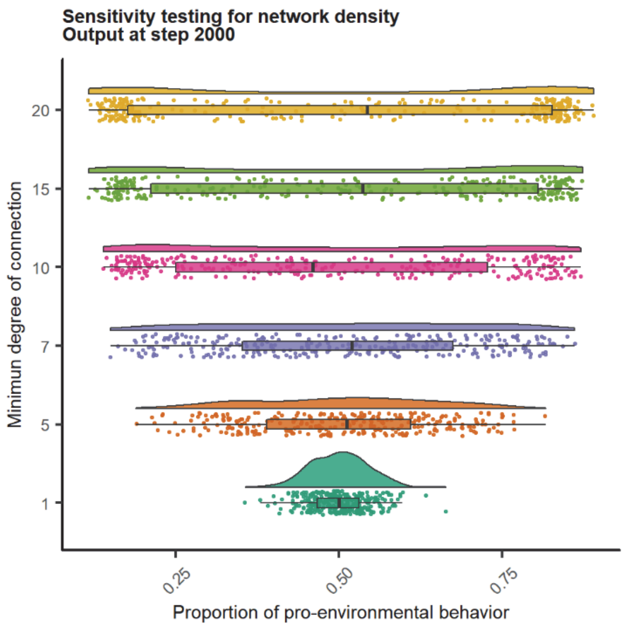


Figure S11. Sensitivity test 5. Importantly, the model is robust against the total number of agents. Due to computational constraints, we do not run the model with over 1000 agents. When the model has over 100 agents, the results are similar. The default value for number-of-agents, 300, can thus be justified.

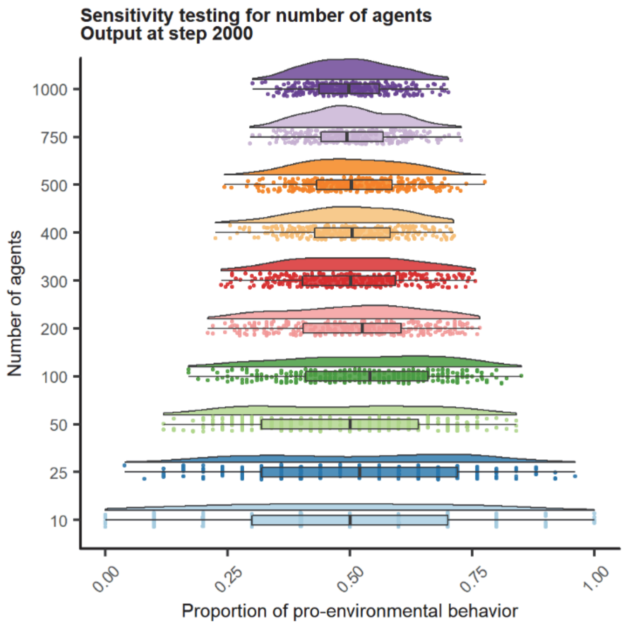


Figure S12. Sensitivity test 6. The effect of initial pro-environmental personal states on the outcome of the model is considerable, and similar in logic to the initial composition of affordances (Figure S7). Notice, however, that in global sensitivity testing, this effect is shown to be less robust when other parameters are allowed to vary.

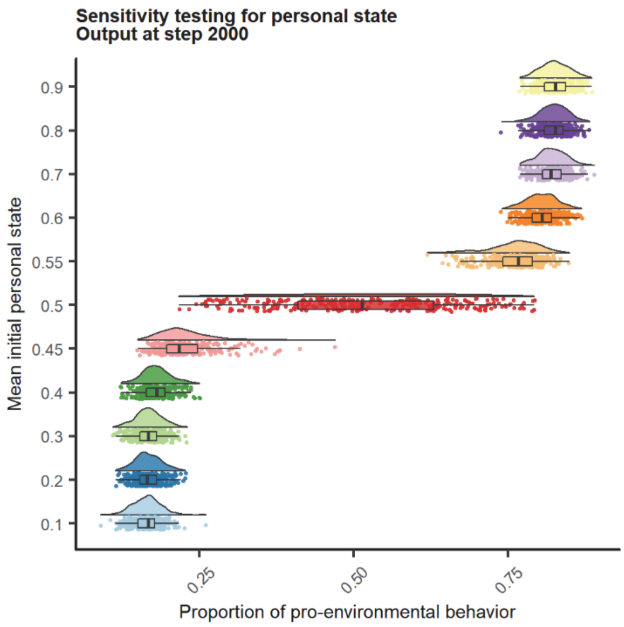
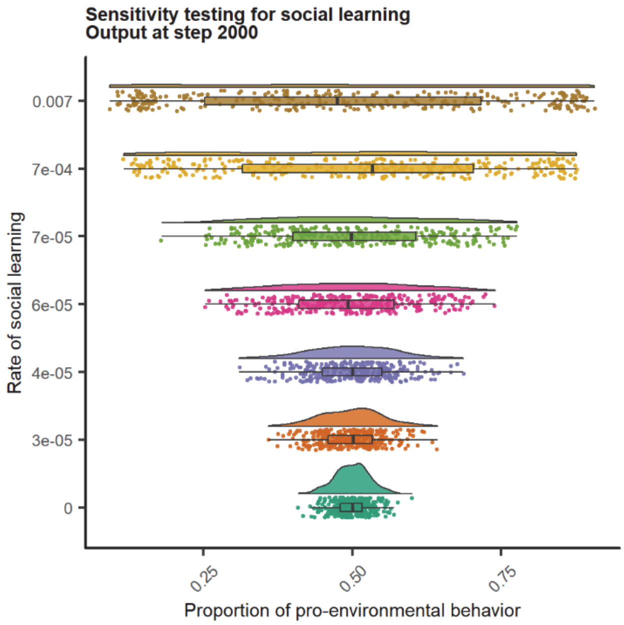


Figure S13. Sensitivity test 7. Similarly to Figure S10 (network density), the rate of social learning has a considerable effect on model outcomes, particularly at extreme values (i.e., ten- or twentyfold to the rate used in the Results section). The model is quite robust against more moderate changes in the rate of social learning. Again, the reasoning is intuitive: The more the rate of social learning is increased, the more social transmission occurs, which leads to more polarized end results as the society of agents converges into a uniform behavioural unit or culture.



Global sensitivity analysis: Latin hypercube sampling

We use Latin hypercube sampling (LHS) as our method for global sensitivity analysis. LHS ensures that each of the model's input variables have all portions of their distribution represented by input values [23]. LHS is simply a K-dimensional extension of Latin square sampling (ibid.), and is commonly used for global sensitivity testing [24]. See e.g. [24] or [23] for more details on LHS. We use the R package nlrx [11] to generate our Latin hypercube samples. We sample our input values from the ranges specified in Table S1. The values were selected on the basis of the OFAT sensitivity tests. We excluded extreme parameter values (which would lead to very predictable and extreme model results, such as when pro-amount is close to 1), but still allow the model to run on a wide range of input values.

Table S1. Parameter ranges for global sensitivity analysis.

Model parameter	**Range**
number-of-agents	[100, 1000]
social-learning	[0.0002, 0.0008]
asocial-learning	[0.0002, 0.0008]
pro-amount	[0.33, 0.66]
initial-pro	[0.33, 0.66]
initial-non	[0.33, 0.66]
construct-non	[0, 10]
construct-pro	[0, 10]
network-param	[3, 7]
mu	0.9

Figure S14. Sensitivity test 8. 300 parameter sets are sampled from the ranges specified in Table S1. The model is run 5 times on each parameter sample, with a different random seed. The lines in this plot illustrate the range of the outcomes of each parameter sample, from min value to max value. Overall, the model has a clear tendency of converging to a state of either high or low pro-environmental behaviour. This is unsurprising, given the results seen in Figures 2–4. This effect will be less drastic if the model is run for less than 2000 ticks or if the range of parameters such as pro-amount is decreased.

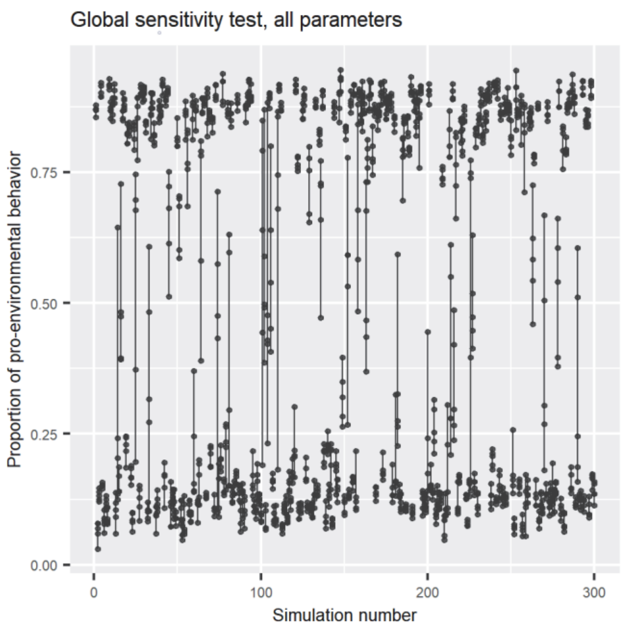


Figure S15. Sensitivity test 9. Even when all other parameters are allowed to vary freely, the nonlinear effect of pro-environmental affordances on pro-environmental behaviour remains. This figure therefore illustrates that the phase transition effect seen in Figures 2A and 2B is very robust.

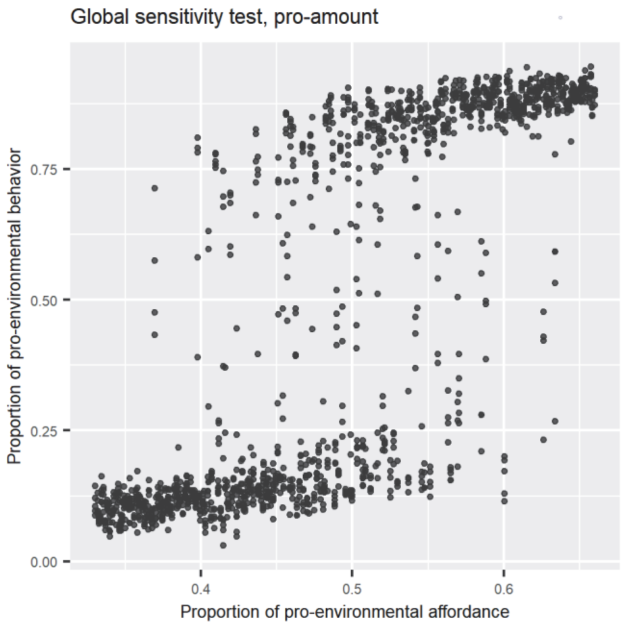
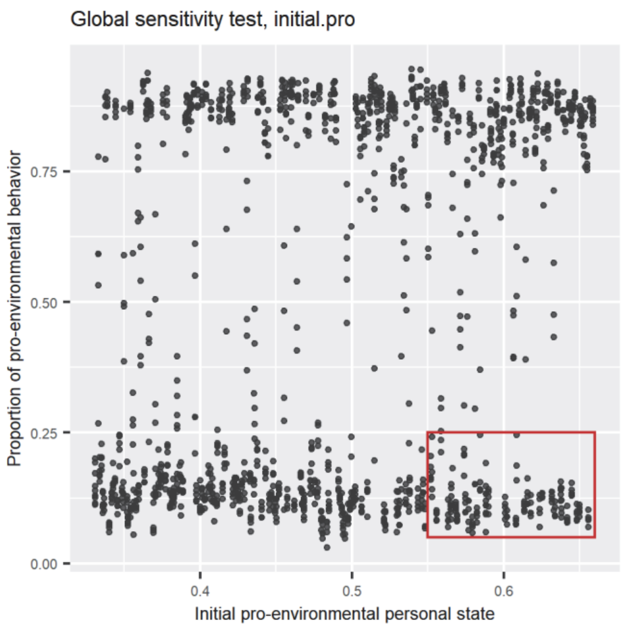


Figure S16. Sensitivity test 10. When other parameters are allowed to vary, initial-pro (the mean initial pro-environmental personal state) has a less apparent effect on behaviours than seen in Figure S12 (where an OFAT test was run on initial-pro). Notice how initial pro-environmental personal states often do not translate into sustained pro-environmental behaviour (highlighted by the red box). This is most likely because of either a lack of pro-environmental affordances, or the interference of a high initial-non value (i.e., counteracting personal states).



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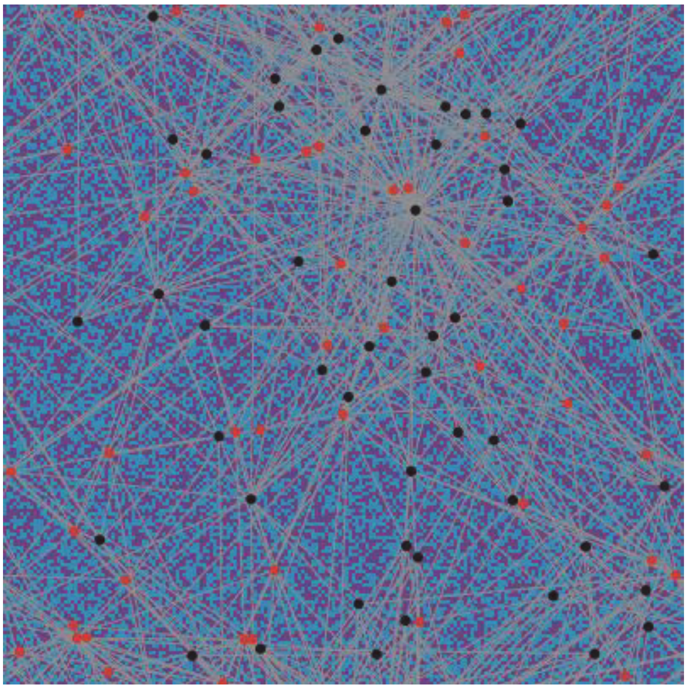
Supplemental Figures

Figure S17. A screenshot of the spatially explicit NetLogo model. Here, 100 agents (circle-shapes) are connected to each other in a Klemm-Eguíluz network. Agents coloured in black are more pro-environmentally than non-environmentally disposed, and vice versa for agents coloured in red. The network is represented with grey links connecting the agents. Notice how some agents are much more connected than others. The environment consists of two kinds of patches, pro-environmental affordances (violet) and non-environmental affordances (sky-blue). Agents move around the grid in a random walk. The torus-shaped world wraps around horizontally and vertically.



Supplemental Tables

Table S2. Parameters. The model's parameters, descriptions of parameters, and ranges of possible parameter values.

Model parameter	Description	Possible range
number-of-agents	Total number of agents.	[1, 1000]
social-learning	Rate of social transmission of behaviour.	[0, 1]
asocial-learning	Rate of individual learning and habituation.	[0, 1]
pro-amount	Initial proportion of pro-environmental affordances in the landscape of affordances.	[0, 1]
initial-pro	Defines the initial pro-environmental personal state, pro-env, which is the probability of interacting with pro-environmental affordances when encountered.	[0, 1]
initial-non	Defines the initial non-environmental personal state, non-env, which is the probability of interacting with non-environmental affordances when encountered.	[0, 1]
construct-non	Probability of constructing a non-environmental affordance.	[0, number-of-agents]
construct-pro	Probability of constructing a pro-environmental affordance.	[0, number-of-agents]
network-param	*m0* in the Klemm-Eguíluz model [17]. Defines the initial complete graph in the network generating algorithm.	[1, number-of-agents]
mu	μ in the Klemm-Eguíluz model [17]. Probability of connecting with low degree nodes. Alters the clustering coefficient of the network. [18]	[0, 1]

Table S3. Parameter values for the abstract model run.

Model parameter	**Value**
number-of-agents	300
social-learning	0.00007
asocial-learning	0.00005
pro-amount	[0, 1]
initial-pro	0.5
initial-non	0.5
construct-non	0 or 10
construct-pro	0 or 10
network-param	5
mu	0.9

Table S4. Parameter values for the Copenhagen simulation.

Model parameter	**Value**
number-of-agents	300
social-learning	0.00007
asocial-learning	0.00005
pro-amount	0.4
initial-pro	0.2
initial-non	0.8
construct-non	0
construct-pro	5
network-param	5
mu	0.9

IV

Mycological Rationality:
Heuristics, Perception and Decision-Making in Mushroom Foraging

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Cover photo: Chanterelles (*Cantharellus cibarius*, left) and funnel chanterelles (*Craterellus tubaeformis*, right). Photograph by author.

Abstract

How do mushroom foragers make safe and efficient decisions under high degrees of uncertainty, or deal with the genuine risks of misidentification and poisoning? This article is an inquiry into ecological rationality, heuristics, perception, and decision-making in mushroom foraging. By surveying 894 Finnish mushroom foragers with a total of 22,304 years of foraging experience, this article illustrates how socially learned rules of thumb and heuristics are used in mushroom foraging. The results illustrate how traditional foraging cultures have evolved precautionary principles to deal with uncertainties and poisonous species, and how foragers leverage both simple heuristics and complex cognitive strategies in their search for, and identification of, mushrooms. Foragers also develop selective attention through experience. The results invite us to consider whether other human foraging cultures might use heuristics similarly, how and why such traditions have culturally evolved, and whether early hunter-gatherers might have used fast and frugal heuristics to deal with uncertainty.

Keywords: bias, bounded rationality, cognition, cultural evolution, ecological rationality, expertise, foraging, heuristics, mushroom hunting, perception, risk, selective attention, tacit knowledge, uncertainty

Note: The heuristics and rules discussed in this text should NOT be used as a guide for identifying mushrooms. Always consult a local expert and multiple information sources before picking or eating wild mushrooms.

1 Introduction

mycology (noun)

the scientific study of fungi

Cambridge dictionary (2019).

Imagine a forager in the wild. The hazy and damp forest is cluttered with a range of autumnal colours, fallen leaves and rotting foliage. The forager is confronted with dozens, or even hundreds, of barely identifiable or visible mushrooms, only a fraction of which are suitable for human consumption. Here, a single misidentification can lead to organ failure or death. Yet still, the forager is accompanied by even children and adolescents who fare surprisingly well at the task, and the foragers are carrying hefty baskets filled with seasonal delicacies. How do they succeed in this?

One could assume the answer to be something as follows: "When encountering a mushroom in the wild, foragers use complex sets of rules and cognitive procedures to aid identification, and systematically weigh the risks or costs of poisoning against the benefits of good catch." However, recent research in ecological rationality invite us to consider another possibility: the use of simple rules of thumb, or "fast and frugal" heuristics, in decision-making (Todd and Gigerenzer 2012; Marewski, Gaissmaier, and Gigerenzer 2010; Gigerenzer and Todd 1999). The general message from three decades of research in ecological rationality suggests that good judgments do not necessarily require complex cognitive processes, and that, particularly in environments with high degrees of uncertainty, people often resort to simple heuristics when making decisions. Moreover, in such environments, simple rules might systematically outperform more complex judgments (Marewski, Gaissmaier, and Gigerenzer 2010; Todd and Gigerenzer 2012; Kozyreva and Hertwig 2019).

In this research article, mushroom foraging in Finland is studied as a case of ecological rationality. 894 mushroom foragers, with a total of 22,304 years of foraging experience, were surveyed about their foraging rules and habits, with a variety of quantitative and qualitative questions. This article argues that the theory of ecological rationality can help us understand the practice and success of mushroom foragers, and also discusses limitations of the framework in understanding the often-complex identification processes. The research questions of the present manuscript are:

1. How do mushroom foragers make (ecologically rational) decisions?
2. What, if any, (fast and frugal) heuristics do mushroom foragers use when identifying mushrooms or making judgments about edibility?

Furthermore, this research article explores how foragers leverage recurrent and reliable perceptual cues in their environment when searching for mushrooms, how foragers develop selective attention, and how culturally acquired knowledge is central to the process. This article thus also contributes to the understanding of the cultural evolution of foraging practices and preserves traditional knowledge into scientific literature. Next to quantitative analysis, this article employs a variety of qualitative approaches to study foraging strategies and heuristics. This is a response to Herbert A. Simon's (2000, 35–36) call for further focus on verbal protocols, written records and natural language when studying decision-making processes.

This article accompanies a previous autoethnographical and phenomenological study (Kaaronen 2019). The present text contributes to taking research on ecological rationality "into the wild," assessing how well simple cognitive rules can be used to make decisions in noisy and uncertain real-world contexts. The results also invite the reader to consider how the verbally transmitted art of mushroom foraging might have evolved culturally through social learning, and how earlier hunter-gatherer societies may have employed similar cognitive strategies to survive in high-uncertainty environments. The results contribute to a broader understanding of how traditional cultures have managed to bound uncertainty in socio–ecological systems, and invite us to consider whether there are lessons to be learned for contemporary management of uncertainty.

This article is structured as follows. Firstly, in section 2, the reader is briefly introduced to the culture of mushroom foraging in Finland. Second, in section 3, the main theoretical framework, ecological rationality, is outlined. Section 4 describes the methods, and section 5 the results. Section 6 is dedicated to a more thorough analysis of both the quantitative and qualitative results, and discusses the findings in more detail, also pointing directions for further research. Section 7 concludes. Data and R code are available at https://github.com/roopekaaronen/mushroom/.

2 Context: Mushroom Foraging in Finland

All mushrooms are edible—but some only once.

Proverb

Mushroom foraging is considered traditional Finnish cultural heritage. The practice of mushroom foraging has been transmitted, mainly verbally, from one generation to the next, and even today most foragers learn the practice from their family or relatives. The precise origins of mushroom foraging in Finland are unknown, but it is believed to have been influenced by varying foraging cultures from Russia and Sweden. The popularity of foraging is at least partly due to public education, which has taught the people to survive in times of food shortage. Mushrooms are mainly foraged for food, although they are also used for other purposes, such as dyeing. Mushroom foraging is also considered by many a recreational activity. (Elävä perintö 2019.)

Some 5400 fungal species grow in Finland, of which at least a few hundred are suitable for regular human consumption (Korhonen 2015). The annual growth of mushrooms in Finland ranges from 1.5 to 4 billion kilograms, of which humans harvest 2 to 10 million kilograms. Mushrooming is a highly popular activity, and an estimated over 40% of adult Finns go mushroom hunting on a yearly basis (Metsäntutkimuslaitos 2010). Mushrooming is considered an "everyman's right", which entitles "everyone in Finland to enjoy outdoor pursuits regardless of who owns or occupies the area" (Ministry of the Environment 2019).

Although mushroom foraging is mainly taught verbally and in practice, mushroom identification books are also popular. The first known Finnish mushroom identification book was published in 1863 (Hisinger 1863). Since then, mushroom books have gained wide popularity, and are today a staple in Finnish households and summer cottages. Mushroom identification books include detailed instructions for safe identification of mushrooms. Such instructions range from taxonomical features to perceptual cues, which include descriptions of a wide range of visual, olfactory, haptic and gustatory cues for mushroom identification (Korhonen 2018; 2015).

Among the Finnish fungi grow dozens of poisonous species, of which at least six are deadly. Many of the deadly species grow abundantly. Whilst mushroom related fatalities and serious accidents do occur every now and then, they are rare. Between 1969 and 2017, a total of nine people were recorded to have died of mushroom poisoning in Finland, with five people receiving a mushroom poisoning related liver transplant (Maaseudun tulevaisuus 2017). Accidents are generally attributed to misidentification, where a poisonous mushroom is confused for an edible one. For instance, a deadly *Amanita virosa* (Fig. 1) might resemble a highly valued mushroom of the *Agaricus* genus (including the cultivated portobello and champignon mushrooms found in supermarkets worldwide).

Mushroom foraging is an activity characterised by high degrees of uncertainty. Mushroom development is highly variant, and local populations or individuals might exhibit unusual colour, shape, or size for the species. Different conditions in humidity, moisture, weather or soil quality can have a considerable effect on how the fruiting bodies of fungi appear, and mushrooms can grow in unexpected patches or environments. Young mushrooms also generally differ greatly in their features from fully grown ones, often increasing the difficulty of identification (see, e.g., Fig. 1). (Korhonen 2015.)

Figure 1. A collage of fruiting bodies of the deadly poisonous *Amanita virosa*, commonly known as the destroying angel. Pictured are two grown mushrooms (above) and two photos of a young mushroom (below). Notice how similar particularly a young *A. virosa* (bottom left) can look to a typical champignon. Bottom right illustrates an exhumed young *A. virosa*, with an onion-like bulb at the base, typical to the species. *A. virosa* can also be recognized by the hanging ring on its stem (seen in the two pictures on top) and its completely white colour. *A. virosa* is one of the most poisonous mushrooms in the world—one cap is enough to kill an adult human. It grows in abundance in Finland. Photographs by author.

3 Ecological Rationality

The rationality of heuristics is not logical, but ecological.

(Gigerenzer 2008b, 23.)

Today, the notion that rationality is bounded is a fairly uncontroversial one. Polymath Herbert A. Simon, in as early as the 1950's, noted that in real world contexts, rational decision-making is limited by the tractability of the decision problem, uncertainty, cognitive limitations, as well as time and resources available to make a decision (Simon 1957). Therefore, humans are not supernatural beings "possessing demonic powers of reason, boundless knowledge, and all of eternity with which to make decisions"—unlike some formal models of rational inference would assume (Gigerenzer and Todd 1999, 5). Instead, we are *satisficers*[1]: We have a tendency of seeking solutions for decision-making problems which are not perfect, but good enough for practical purposes.

In recent decades, the notion of bounded rationality has been revived in a descendant of Simon's work in the research program of *ecological rationality.*[2] Ecological rationality places the decision-maker back into their ecological context. Broadly defined, ecological rationality can be understood in terms of cognitive success in the world, or the fit between the mind and the environment (Kozyreva and Hertwig 2019; Gigerenzer and Todd 1999; Todd and Brighton 2016). Thus, an action is ecologically rational if it is cognitively successful given a certain environmental context.

More specifically, the aim of ecological rationality is "to explicate the mind–world interactions underlying good decision making" (Todd and Gigerenzer 2007, 167). Here, Simon (1990, 7) used his famous analogy of scissors: "Human rational behaviour is shaped by a scissors whose blades are the structure of task environments and the computational capabilities of the actor." We cannot simply use one blade of the scissors to cut successfully. Rather, both environmental structures and cognitive capabilities must be leveraged to make a sharp decision.

The study of ecological rationality generally involves finding out which cognitive and environmental structures work together to form a reliable pair of scissors (Todd and Gigerenzer

[1] Simon's neologism from "satisfying" and "sufficing".
[2] For comprehensive reviews, see e.g. (Gigerenzer and Todd 1999; Todd and Gigerenzer 2012; Kozyreva and Hertwig 2019).

2012, 15). Thus, ecological rationality deals with how the minds of organisms compensate for their bounded cognitive resources by exploiting the structures and regularities of information in the task environments in which they are applied. From an ecological point of view, rational behaviour can therefore be understood as the adaptive capacity of an organism to achieve its intentions "under the constraints and affordances posed by both the environment and its own cognitive limitations" (Kozyreva and Hertwig 2019).

To understand ecologically rational decision-making, it is helpful to distinguish risks from uncertainties (Gigerenzer and Selten 2002). Risks deal with decision-making when all relevant alternatives, consequences and probabilities are known. In such situations, quantitative methods such as statistical thinking and cost-benefit analyses are useful. However, in the messy and noisy real-world, all alternatives, consequences and probabilities are rarely known. These are *uncertain* environments, and dealing with uncertainty requires more robust and generalizable decision-making rules, such as precautionary principles (e.g., how to avoid risk of ruin), expertise, intuition and heuristics (Gigerenzer and Selten 2002).

Heuristics form a central part of ecologically rational decision-making (Gigerenzer and Todd 1999). Heuristics are satisficing "rules of thumb," which, for instance, employ simple stopping rules for searching through sequences of available alternatives, or use one-reason judgments to make inferences. Ecologically rational heuristics are also often "fast and frugal," using very little information to make reliable judgments.

Heuristics are not decision-making strategies which would traditionally be understood as optimal.[3] They are, however, able to operate within tight bounds of time, knowledge and computational capacity. In fact, satisficing search heuristics or fast and frugal heuristics do not even seek to achieve optimality. Instead, by exploiting statistical regularities, or *ecological validities* (Brunswik 1956), within the environment, or by relying on habits and culturally acquired rules, ecologically rational individuals are able to circumvent the optimisation process altogether (Kozyreva and Hertwig 2019; Gigerenzer and Selten 2002).

[3] Typically, an optimisation model operates by defining a problem so that it allows an optimal solution to be found, and then proves the existence of strategies for optimising the criterion of interest (Gigerenzer and Todd, 1999, p. 24).

Moreover, contrary to the highly influential *heuristics and biases* school of behavioural economics (Tversky and Kahneman 1974), proponents of ecological rationality do not consider the use of heuristics as a necessary trade-off between effectiveness and reliability. Commonly, this "accuracy-effort trade-off" is framed so that more information or computation always leads to more accurate inferences, and that use of heuristics implies a loss of accuracy (Gigerenzer and Todd 1999; Todd and Gigerenzer 2012). Whilst Kahneman and Tversky (1974) famously associated the use of heuristics with systematic and predictable errors, or *biases*, ecological rationalists would generally disagree with such an unfavourable conception of heuristics.[4]

By studying how organisms behave in the real world, research on ecological rationality has worked to uncover the often successful, domain-specific simple heuristics which cognitively bounded humans employ particularly when faced with uncertainty in decision-making (Todd and Gigerenzer 2007, 167). It is thus the task of ecological rationality to uncover the "adaptive toolbox" of the mind (Todd and Gigerenzer 2012). The tools in this toolbox are heuristics, which are tuned to specific environmental regularities and designed for task-specific problems (Marewski, Gaissmaier, and Gigerenzer 2010, 106; Todd and Brighton 2016).

Ecological rationality operates particularly well in uncertain environments (Kozyreva and Hertwig 2019). This is because, in uncertain environments with high variance, organisms must not only gain information but learn to *ignore* information (Todd and Brighton 2016). In other words, sometimes *less* information might be *more*—the so-called "less-is-more effect" (Goldstein and Gigerenzer 2008). For instance, it might not be rational for a mushroom forager, encountering an edible white mushroom in a supermarket, to infer there is something about white mushrooms that makes them edible. This is known technically as the *bias–variance* dilemma. Simply, in uncertain environments it might be more adaptive to be systematically biased (i.e., use biased heuristics) than to suspect oneself to variant and error-prone learning, since this prevents the *overfitting* of cognitive or behavioural rules to adapt to random fluctuations and idiosyncracies (Marewski, Gaissmaier, and Gigerenzer 2010; Brighton and Gigerenzer 2012).

[4] Note that this does not imply that proponents of ecological rationalism presume heuristics are immune to errors: "Individuals can certainly be led to use particular heuristics in inappropriate environments and consequently make errors, as the heuristics-and-biases research tradition emphasized" (Todd and Gigerenzer, 2007, p. 168).

This selective ignorance, research in ecological rationality suggests, increases “novelty robustness,” or the capacity of organisms for handling previously unencountered uncertainties (Brighton and Gigerenzer 2012, 40; Todd and Brighton 2016). Organisms can guard against uncertainty by preferring coarse and biased behaviour rules, which are less sensitive to change and variance than more complex cognitive processes. In uncertain environments, simplicity can often be key to robustness and resilience. Thus, the use of heuristics is likely a cultural evolutionary adaptation: The tendency for humans to be ecologically rational, often preferring simple decision heuristics to more complex cognitive computations, has the “twin advantages of speed and accuracy in particular environments” (Todd and Gigerenzer 2007, 167; 2012).

Ecological rationalists have identified several empirical cases where simple heuristics might outperform more complex decision-making (Todd and Gigerenzer 2012). One well-documented case is catching a ball in mid-air flight (Hamlin 2017). One could assume that this involves complex computations and multidimensional mental gymnastics (such as solving complex differential equations[5]), working out the ball’s trajectory and acceleration, and factoring in other environmental factors such as wind. However, real human behaviour may be much simpler. To catch a ball high up in the air, “one simply has to fixate it, start running, and adjust the speed of running such that the angle of gaze remains constant”—this is the *gaze heuristic* (Marewski, Gaissmaier, and Gigerenzer 2010, 103). As is often the case with ecological rationality, good judgments do not always require complex cognition (Marewski, Gaissmaier, and Gigerenzer 2010). Some other well-documented heuristics are described in Table 1.

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[5] Richard Dawkins (1989, 96) in (Todd and Gigerenzer 2012, 5) writes: “When a man throws a ball high in the air and catches it again, he behaves as if he had solved a set of differential equations in predicting the trajectory of the ball. He may neither know or care what a differential equation is, but it does not affect his skill with the ball. At some subconscious level, something functionally equivalent to the mathematics calculation is going on.”

Table 1. Some well-documented heuristics in the ecological rationality literature.

Heuristic	Description	Examples
Recognition heuristic	If one alternative out of two or more options is recognised, infer that the one recognized ranks higher on the given criterion. (Todd and Gigerenzer 2012; Goldstein and Gigerenzer 2002)	Predicting Wimbledon 2005 tennis results by mere player name. Recognition-based predictions were "equal to or better than predictions based on official ATP rankings and the seedings of Wimbledon experts" (Scheibehenne and Bröder 2007).
Take-the-best heuristic	When inferring which of two alternatives has higher value on a given criterion, 1) "search through cues in order of validity", 2) "stop search as soon as a cue discriminates", 3) "choose the alternative this cue favors" (Todd and Gigerenzer 2012).	In 20 real-world data sets, the take-the-best heuristic came close to or beat (particularly in generalizing to new data) the performance of more complex and computationally demanding algorithms (including multiple regression) (Czerlinski, Gigerenzer, and Goldstein 1999).
1/N heuristic	When investing, allocate money equally to each of N funds.	Has outperformed many optimization policies (Gigerenzer 2008a; DeMiguel, Garlappi, and Uppal 2009).

Since humans have navigated their way through complex and unpredictable environments "long before probability and decision theory established new rules of rational behaviour," it is reasonable to assume that successful cognitive strategies to cope with uncertainty in the real world are not necessarily rooted in such complex rules rooted in probabilities and utilities (Kozyreva and Hertwig 2019, 8). Indeed, the results of this article illustrate how mushroom foragers use several cognitive shortcuts to make novelty robust and resilient decisions in high-uncertainty environments, and rarely seem to resort to probabilistic reasoning or utility calculation. The following results therefore uncover the "adaptive toolbox" of mushroom foraging.

4 Methods

A link to an online survey was shared on Finnish mushroom foraging societies on their social media platforms. These groups are relatively popular and active, and the largest group has over 30 000 members. 894 unique responses were registered during April–June 2019. Participants were recruited with informed consent (see section Research Ethics). The survey charted the foraging practices and experience of respondents as well as the heuristics (or rules of thumb) they use for foraging. Demographic information was also collected. The survey was conducted in Finnish. All questions and some qualitative responses in this manuscript have been translated to English by the author.

Mushroom foraging heuristics were surveyed by asking the following open questions[6]:

1. What rules of thumb do you use pertaining to **safe foraging**?
2. What rules of thumb do you use pertaining to the **identification of edible or poisonous mushrooms**?
3. What rules of thumb do you use pertaining to **identifying good foraging patches or finding mushrooms**?

Respondents were encouraged to answer with as many rules of thumb (Finnish: *nyrkkisääntö*, "fist-rule") as they could come up with. Responses were analysed using inductive content analysis (Elo and Kyngäs 2008). This involved an initial process of identifying recurrent themes or patterns in the data, after which the themes were classified systematically. Emergent themes and patterns (recurring rules of thumb and heuristics) were coded and their frequencies analysed. Note that since the questions were open, the true use of mentioned heuristics is likely to be more common than the number of their instances in the dataset (since respondents might not, e.g., have remembered that they use a particular heuristic at the time of response, or were otherwise unable to explicate a rule they use).

The foragers were also presented with a search task. Two pictures were presented, one of a mossy coniferous forest (Fig. 7), and another of a drier birch forest (Fig. 9). Both pictures are from

[6] Open questions were preferred since there exists little previous literature on the subject to inform sufficiently detailed closed questions.

Finland, but the location and time of the photoshoot were not specified in the task. Foragers were asked the question “What mushroom species would you search for in the terrain in this picture?”, with an open response field. The aim of this task is to illustrate how little ecological information foragers can utilise to direct their search for mushrooms. Obvious ecological cues in Fig. 7 include spruces, moss and a sloped terrain. Ecological cues in Fig. 9 include birch trees, grass, hay, and a dry and illuminous, perhaps pastural or otherwise human-modified, landscape. To enable computational processing, the species or genera mentioned (nouns) were stemmed to their nominative singular case (since Finnish has fifteen noun cases). Other words were excluded from the dataset. Although the question asked for species, many answers were on the higher taxonomic rank of genus or family (e.g., boletes, milk-caps) or in folk taxonomy. These were chosen to be included in the analysis. In translation, English or common names were preferred to binomial (Latin) names when available, since respondents rarely responded in scientific nomenclature.

For statistical analysis, I use descriptive statistics and data visualisation to depict the demographics of respondents as well as an exploratory correlation plot to analyse relations between foraging strategies and preferences. Along with the search task, a simple linear regression is also performed to test the effect of foraging experience on the number of species identified.

Data analysis was done with R (R Core Team 2019). R-packages used included the tidyverse packages (Wickham 2017), corrplot (Wei and Simko 2013), Hmisc (Harrell Jr and Dupont 2008), likert (Speerschneider and Bryer 2013), tm (Feinerer 2018), RColorBrewer (Neuwirth 2014), (Wickham 2012, 2), plyr (Wickham 2011), ggpubr (Kassambara 2017), gridExtra (Auguie and Antonov 2017), and qdap (Goodrich, Kurkiewicz, and Rinker 2018).

5 Results

5.1 Descriptive Statistics and General Foraging Habits

Respondents were asked the following series of demographic and general foraging questions, with close-ended and multiple-choice items.

Table 2. Gender distribution of respondents.

Female	757	84.7%
Male	124	13.9%
Other or do not wish to tell	13	1.5%
Total	**894**	**100%**

Table 2 illustrates the gender distribution of the respondents. 84.7% of respondents were female. This gender distribution is partly a product of the higher representation of females in the population of mushroom foragers. According to Finnish statistics in 2010, 44.7% of Finnish females foraged for mushrooms on a yearly basis, whilst the share was 35.9% for men (Metsäntutkimuslaitos 2010).

Respondents were asked where they learned to forage from (Table 3). The most common response (n = 609, 68.1%) was from their parents. Note that the share of learning from the internet is particularly likely to be biased here, since the participants were recruited from online groups.

Table 3. Who or where did you learn to forage from? (Select all that apply.)

Parents	Grandparents	Other relatives	Books	Internet	Course	Other[7]
609	182	149	576	311	142	209
68.1%	20.4%	16.7%	64.4%	34.8%	15.9%	23.4%

The respondents' motive for foraging was also surveyed (Table 4). Interestingly, the most common answer was "for fun or hobby" (n = 777, 86.9%). "For food" was the second most common with 770 (86.1%) mentions (recall, however, that mushrooms are also picked for dyeing, beverages and

[7] Answers included friends, spouses, colleagues, school, among others.

other uses). The results suggest that foraging is considered much more than food collection, and is an important form of leisure activity, nature connection, and social life.

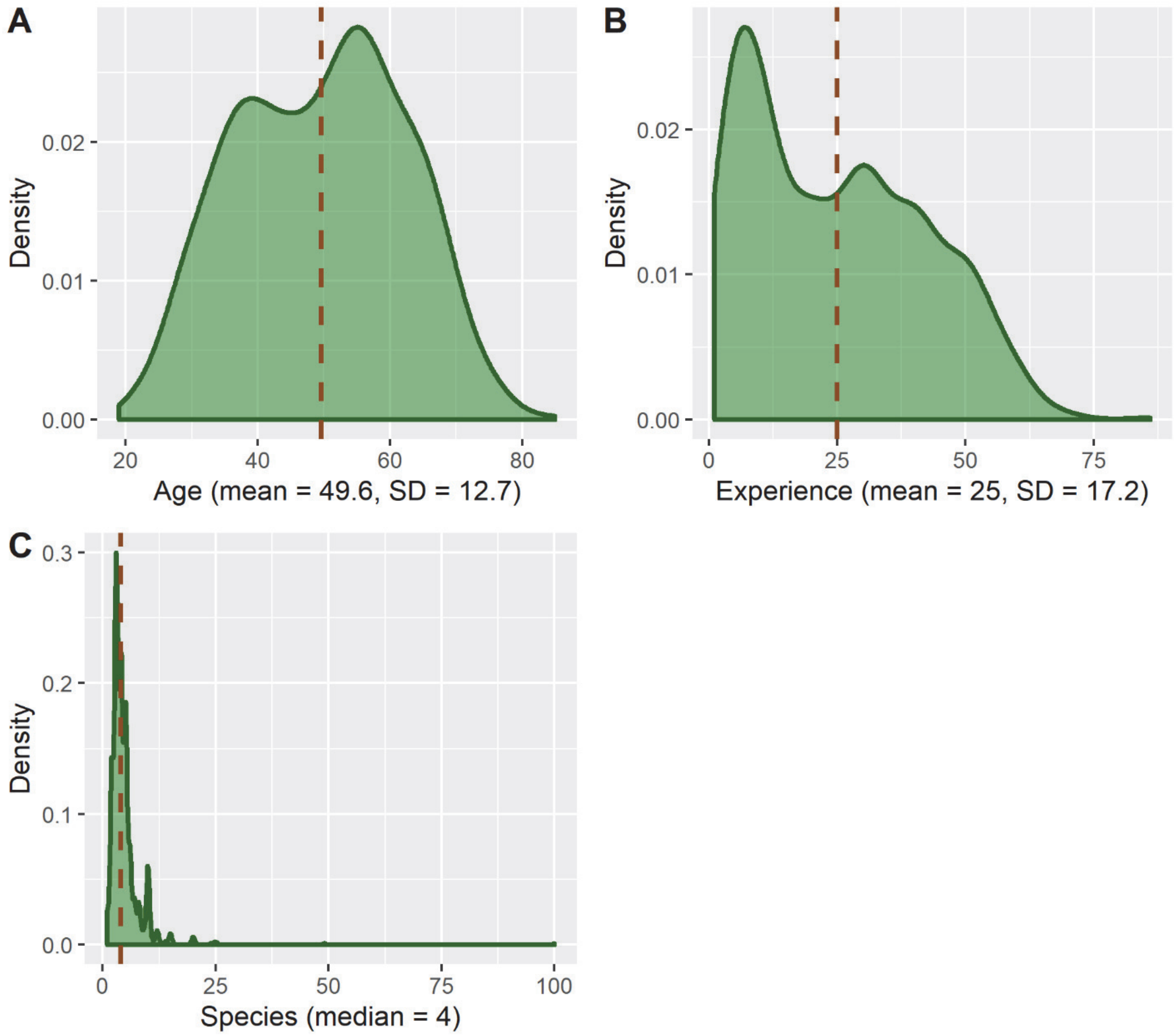
Table 4. Why do you forage? (Select all that apply.)

Food	Fun/hobby	Research or science	Relax	Nature experience	Exercise	Social activity
770	777	49	707	726	514	288
86.1%	86.9%	5.5%	79.1%	81.2%	57.5%	32.2%

The mean age of the respondents was 49.6 years (Fig. 2A), which is considerably higher than the mean age of Finns, 42.3 years (Tilastokeskus 2019). The foragers surveyed were highly experienced (Fig. 2B), with a mean experience of 25 years of foraging (although note the peak in foragers with under 10 years of experience). The survey reached a total of 22,304 years of mushroom foraging experience. Foragers were also asked how many species of mushrooms they forage on their average trip (Fig. 2C). The distribution is highly skewed, with most foragers focusing on under 5 species at a time. Some foragers, however, reported up to 49 or even 100 species (including one forager with 60 years of experience).[8]

[8] Whilst these are technically feasible, particularly since foraging societies include experts such as mycologists, there is also a chance that the higher-end answers mistook "species" for individual mushrooms, or that of a typo.

Figure 2. Descriptive statistics. A: Age density distribution with mean age of foragers. B: Experience density distribution with mean experience (years) of foragers. C: Figure 3. Density distribution of number of species picked on one foraging trip with median.



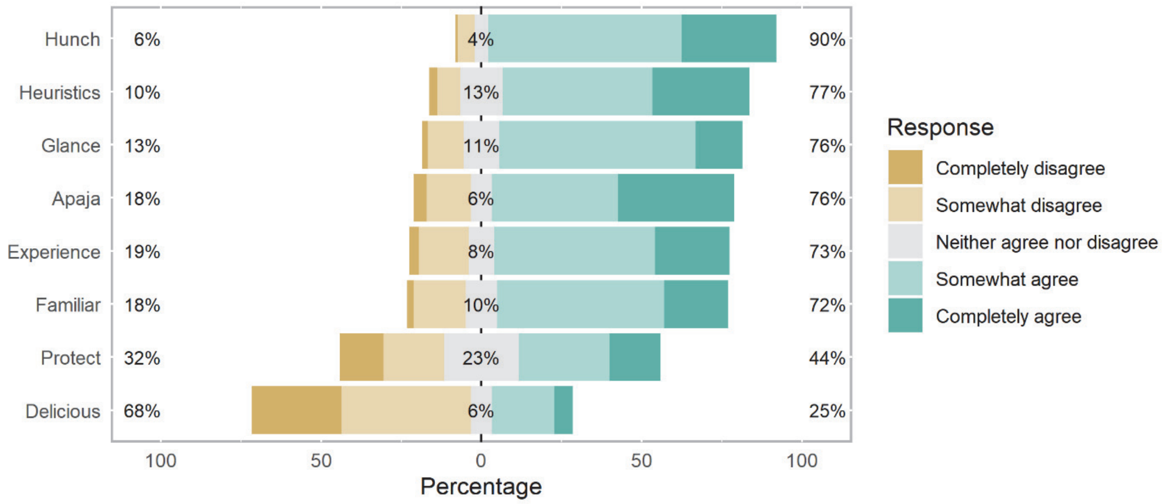
Foragers were presented with eight statements to survey their mushroom hunting experience and strategies on a five-point Likert scale. The statements were:

1. When I go mushroom foraging, I have a strong hunch of which mushrooms I expect to find. [Referred to as **Hunch** hereafter.]
2. I often make use of rules of thumb when I forage. [**Heuristics.**]
3. With a quick glance of a given terrain, I know which mushrooms could grow in the area. [**Glance.**]

4. I keep the knowledge of good mushroom hunting patches (*apaja*) to myself or my close ones. [**Apaja**. Translation note: The Finnish word *apaja* does not directly translate into English. In this context, it means an area that is known or expected to reliably and recurrently grow (specific species/genera of) mushrooms.]
5. I consider myself an experienced mushroom forager. [**Experience**.]
6. I mainly forage in familiar terrain. [**Familiar**.]
7. I would rather protect a forest where I forage than other forests which I visit. [**Protect**.]
8. If I search for a specific delicious or precious species of mushroom, I don't pick other species. [**Delicious**.]

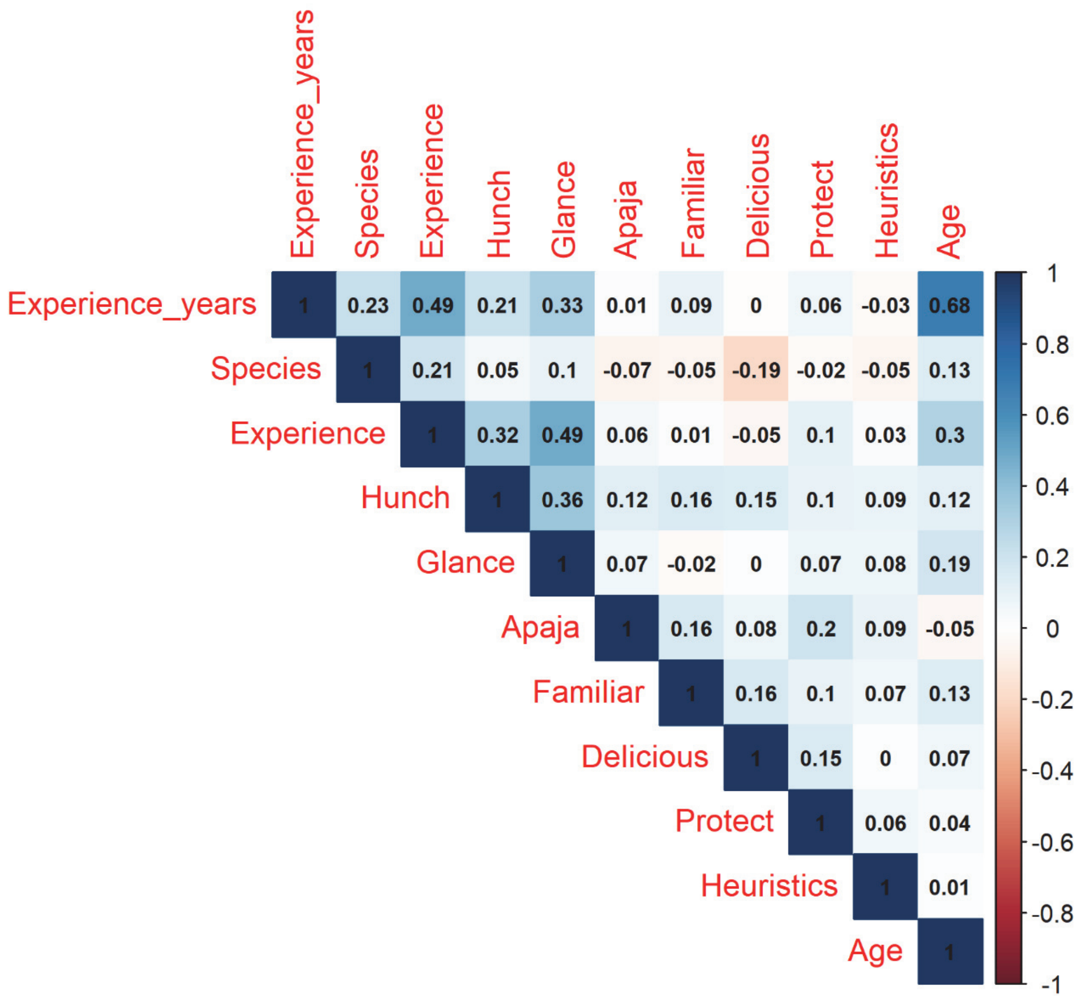
Results are shown in diverging stacked bar charts in Fig. 3.

Figure 3. Diverging stacked bar charts of the eight general foraging questions asked. The table illustrates percentages of respondents who agree with (right), disagree with (left), and are neutral regarding (centre) the statement.



An exploratory correlation plot (with Pearson correlation coefficients, Fig. 4) was produced from the eight questions above as well as the variables age [**Age**], experience in years [**Experience_years**], and average number of species picked [**Species**]. Acknowledging that an exploratory correlation plot should be interpreted with caution, some interesting relations seem to exist particularly between the experience variables ([**Experience**] and [**Experience_years**]) and having hunches (**Hunch**: r = 0.32 and 0.21, respectively) and anticipations (**Glance**: r = 0.49 and 0.33) of what mushrooms one expects to find. Perhaps most interesting for the context of the present article, however, is that the use of heuristics [**Heuristics**] does not appear to be correlated with the experience variables (r = 0.03 and -0.03). That is, heuristics are used by experts and novices alike.

Figure 4. An exploratory correlation plot with Pearson correlation coefficients.



5.2 Heuristics: The Adaptive Toolbox of Mushroom Foraging

In the following section, the results of the three open foraging heuristic questions are analyzed. The reported heuristics are defined in Tables 4–6 with counts of their mentions by respondents,[9] with representative examples from the qualitative data. **Note: the following results should not be used as a guide for mushroom foraging. Heuristics are only applicable in the context from which they are reported from, if even there.**

A total of 22 recurrent rules for safe foraging were identified (Table 4). Overall, foragers had little trouble with this question. The heuristic "Only pick mushrooms you can identify (with certainty)" was by far the most common with 525 instances.

Table 4. What rules of thumb do you use pertaining to **safe foraging**?

Description of rule or heuristic	**Examples**	**Count (N = 894)**
Only pick mushrooms you can identify (with certainty).	Only pick those mushrooms that you can identify with certainty. Don't pick mushrooms that you can't recognise.	525
Carry sufficient equipment, including: identification book, gumboots, mushrooming knife, matchsticks, map, etc.	A first-aid kit is carried in the backpack. A water bottle to prevent dehydration. Phone charged with prepaid and an emergency application installed. Dress for the weather.	102
Identify an edible mushroom, or specifically an edible milk-cap (*Lactarius*), by the latex ("milk") the mushroom exudes when cut. If it bleeds white "milk", the mushroom is judged edible (and if not, it might be poisonous).	All milk-caps that excrete milky sap are edible.	81
Only eat mushrooms you can identify with certainty.	I don't eat those mushrooms that I can't be 100% sure I've identified. .	77
Keep different species or genera of mushrooms in different containers (since, e.g., some are non-edible or even deadly before blanching, some are picked for colouring, etc.).	I sort mushrooms by the species into paper bags as soon as I pick them into my basket. .	68

[9] Each respondent is allowed to only have one instance of any given heuristic, even if they had mentioned it twice (or more).

Completely avoid or be very cautious with white mushrooms (due to similarity with *Amanita virosa*).	I do not pick completely white mushrooms. Be extra careful with white mushrooms.	61
Carry unidentified or uncertain mushrooms in a different container.	I carry a separate bag where I pick those mushrooms that I want to examine more.	56
When identifying a mushroom, consult multiple information sources, including other people, books and online communities.	I take uncertain mushrooms to be identified by an acquaintance. As a tool for identification I use the internet, books and hobbyist forums.	52
Learn to identify new mushrooms one or a few species at a time (or per year).	Learn one new species at a time. I learn one new species each year.	38
Only pick mushrooms from clean environments/far from roads.	I don't pick mushrooms next to big roads.	37
Be aware of your starting point and/or surroundings, beware of getting lost.	I avoid being lost by observing my route. I get my direction from the sun. On cloudy weather I try to remember the form of the terrain.	37
Learn to identify (the most common) poisonous mushrooms and lookalikes.	Each spring I learn the most poisonous mushrooms in Finland.	32
Tell others where you are going/where you are.	I always tell my family where I am going mushroom foraging.	30
Keep your mushrooming knife in its case or in the basket when foraging.	Always place the mushroom knife in the basket when you don't need it.	20
Forage in familiar terrain and areas.	I forage in familiar terrain.	20
Use other senses (smell, touch, taste when appropriate) to ensure successful identification.	A mushroom should always be looked/smelled/felt for many identification cues. One is not enough to define a species.	19
Identify the mushroom in its natural terrain, and/or ensure it is not close to poisonous mushrooms.	Aim to identify mushrooms in the terrain, don't wait until you are home.	18
Identify the mushroom once more at home, or when cleaning or preparing the mushroom.	I go through the picked mushrooms once more when I unpack my catch.	17
Pick, identify and maintain whole mushrooms without breaking them (until preparation).	I pick whole mushrooms, so they are easy to identify.	17
Do not forage alone.	I don't go mushroom foraging alone, I have a bad sense of direction.	16
Make sound (to scare off wildlife such as bears, wolves or snakes).	Make sound in the forest, so that animals give way.	15
Boletes (Boletales spp.) are not poisonous.	A bolete won't kill you.	14

A total of 19 rules for identifying edible or poisonous mushrooms were identified. These rules are listed in Table 5. Note that the answers have some overlap with the heuristics reported in Table 4. A particularly common answer with 229 instances was identifying an edible mushroom, or specifically an edible milk-cap (*Lactarius*), by the latex ("milk") the mushroom exudes when cut (see Fig. 12). The heuristic is that if the mushroom (or milk-cap) bleeds white "milk", it is judged edible—and if not, it might be poisonous (e.g., a fenugreek milk-cap, *Lactarius helvus*). Other common heuristics were picking only mushrooms one can identify with certainty (166 instances), and encouraging extra caution with or complete avoidance of white mushrooms (112 instances; recall the discussion on *A. virosa* and white mushrooms above and in Fig. 1).

Table 5. What rules of thumb do you use pertaining to the **identification of edible or poisonous mushrooms**?

Description of rule or heuristic	**Examples**	**Count (N = 894)**
Identify an edible mushroom, or specifically an edible milk-cap (*Lactarius*), by the latex ("milk") the mushroom exudes when cut. If it bleeds white "milk", the mushroom is judged edible (and if not, it might be poisonous).	If a milk-cap excretes white milk, it is edible (an easy rule even for a child). If a milk-cap excretes colourless sap, it is poisonous.	229
Only pick mushrooms you can identify (with certainty).	I only pick those mushrooms that I recognise with certainty.	166
Completely avoid or be extra cautious with white mushrooms (due to similarity with *Amanita virosa*).	I do not pick any white mushrooms.	112
When identifying a mushroom, consult multiple information sources, including other people, books and online communities.	If you don't recognise a mushroom you pick, utilise many different sources to figure out the species with certainty.	60
Pay attention to the smell of the mushroom.	The smell is an important part of mushroom identification next to how it looks. The curry milk-cap smells like curry.	57
Boletes (*Boletales* spp.) can be identified by the spongy pores ("tubes") underneath their caps. (N.B. Related to heuristic below.)	Boletes have tubes. Boletes that look normal are usually edible, but I don't pick those boletes that I can't recognise. Tubes (…) give the impression that it can't be a very poisonous species.	53
Boletes (*Boletales* spp.) won't kill you (but not all are edible). (N.B. Some mildly poisonous boletes grow in certain southern regions of Finland but are rare overall.)	Boletes and russulas don't include poisonous species (in my areas), there are just worthless ones and they can easily be distinguished by tasting.	40
Learn to identify (the most common) poisonous mushrooms.	There aren't that many extremely poisonous mushrooms in Finland. Once you can identify those, you won't get yourself killed.	33

Learn to identify the (poisonous) lookalike species of edible mushrooms (and/or take caution when foraging mushrooms with lookalikes).	I remember the identification cues of those edible mushrooms that look like poisonous ones with precision.	28
Avoid webcaps (*Cortinarius*) or do not pick them at all.	I don't pick any webcaps, even though they include edible ones.	28
Amanita (which are often poisonous) generally have bulbs in their stems.	Amanita have a bulb on their stem.	27
No heuristics suffice for identifying an edible mushroom (or distinguishing an edible from a poisonous one).	There are no rules of thumb to distinguish a poisonous mushroom from an edible one if they look a lot like each other. I suppose this is a rule of thumb, too: There are no rules of thumb to pick mushrooms, you must know them.	25
Pay attention to the terrain and natural environment when identifying a mushroom.	Identify a mushroom in the environment it grows in.	20
Only eat mushrooms you can identify with certainty.	I do not taste or eat unknown mushrooms.	18
Distinguish a porcini (*Boletus edulis*) from a lookalike but non-edible bitter bolete (*Tylopilus felleus*) by the netlike pattern ("fishnet stockings") on its stalk (bitter boletes have darker patterns).	A bad girl wears black stockings.	17
Be cautious with mushrooms with a ring (skirt) around their stalk (many poisonous *Amanita* have this).	If it has a ring, I won't pick it.	15
Completely avoid or be extra cautious with red mushrooms (due to similarity with *Amanita muscaria*).	I do not pick any white or red mushrooms at all.	10
Completely avoid or be extra cautious with mushrooms with spotted caps (many poisonous *Amanita* have spotted caps).	No mushrooms with spots.	10
Learn to identify new mushrooms one or a few species at a time (or per year).	I only learn one new mushroom species at a time.	7

Figure 5. Some foragers report they completely avoid red and/or spotted mushrooms. This is generally due to similarity with the (in)famous poisonous fly agaric (*Amanita muscaria*) pictured below. Some foragers also mentioned they would not identify a fly agaric from the spots alone, since these might be washed away by rain, emphasizing that individual cues often do not suffice for safe identification. Notice also the bulb at the lower stem of the toadstool, and that the ring on the stem (typical to *Amanita*, see Fig. 1) has not yet developed for these young individuals. Photograph by author.

Verbally defining a good foraging patch (Table 6) proved to be a trickier task. 17 heuristics were identified. The most common instances were search heuristics related to finding some of the most valued mushrooms (funnel chanterelles, chanterelles, *Gyromitra esculenta*, and boletes), and identifying (symbiotic or mychorrizal[10]) associations between fungi and plants, such as "chanterelles grow near birch trees" (108 instances) or "funnel chanterelles grow near spruces" (49 instances).

However, a tendency among the respondents was to answer that rules of thumb are less useful in this domain, and that identifying a good foraging patch involves so many dimensions that a single rule of thumb would be insufficient. Many reported relying on expertise and intuition instead of explicit rules of thumb:

- *"Mushrooms are found in so many places that there are no rules of thumb for good foraging patches."*
- *"I can't put my finger on it, it is instinctive."*
- *"I am an instinctive forager. I do not identify consciously what factors are in place when I feel the intuition."*
- *"Mostly I recognise foraging patches intuitively, without rules of thumb. (…) I believe this owes to my experience of foraging every autumn with my grandparents when I was one to fifteen years old."*
- *"I don't know. My instinct drives me just like it drove my father back in the days. I haven't given it much thought, but I rarely miss the target."*
- *"It is difficult to describe with words. The general outlook [of the forest]. My instinct drives me to the right places."*

This tacit knowledge (Polanyi 2009; 1969) in foraging is particularly interesting, since despite the troubles with explicating what makes a good foraging patch (and a relatively low count of

[10] Encyclopaedia Britannica (2019) defines mychorrizal relationships as follows: "Mycorrhiza is a non-disease-producing association in which the fungus invades the root to absorb nutrients. Mycorrhizal fungi establish a mild form of parasitism that is mutualistic, meaning both the plant and the fungus benefit from the association. [...] By sharing the products it absorbs from the soil with its plant host, a fungus can keep its host alive."

heuristics reported in this domain), respondents had little trouble with identifying what grows where in the search task (section 5.3 below), and seemed to be using at least some of the explicitly mentioned heuristics in Table 6. For instance, whilst only a total of 154 funnel chanterelle-related instances were mentioned in the heuristics for finding mushrooms (e.g., that funnel chanterelles grow in mossy, sloped terrain with spruces, see Table 6 and Fig. 6), a total of 692 respondents mentioned they would search for funnel chanterelles in the terrain depicted in Fig. 7, which portrays very little ecological information other than mossy terrain, spruces and sloped terrain. It might well be that mushroom foragers "know more than they can tell" (Polanyi 2009) in recognising good foraging patches, as some foragers indeed explicitly stated.

Table 6. What rules of thumb do you use pertaining to **identifying good foraging patches or finding mushrooms**?

Description of rule or heuristic	**Examples**	**Count (N = 894)**
Chanterelles (*Cantharellus cibarius*) grow near birch trees.	A chanterelle yearns for a birch tree. Chanterelles thrive by birches.	108
Forage in familiar areas known to have good catch (particularly since many species grow in the same spot for consecutive years).	Since a little child I have visited the same places. I can find what I'm searching for there. Mushrooms have a habit of growing in the same places year after year.	107
Gyromitra esculenta (a false morel) grows in recently logged forests.	I search for false morels in felled areas where the ground surface has been broken. One should search for false morels in areas that were logged a couple of years ago.	71
Funnel chanterelles (*Craterellus tubaeformis*) grow in mossy terrain.	A funnel chanterelle terrain can be recognised from a thick layer of moss.	66
Funnel chanterelles grow near spruces.	Funnel chanterelles thrive in spruce forests.	49
A general preference towards old forests.	Generally, the older the forest the more mushrooms.	46
Mushrooms (in general) are best found in mossy terrain.	A thick and moist terrain implies a good *apaja*.	41
Funnel chanterelles can be found on sloped terrain.	Funnel chanterelles thrive in sloped terrain.	39
Search for mushrooms near (forest) paths.	Some good edible mushrooms seem to grow more near paths.	35
Boletes (particularly pine boletes, *Boletus pinophilus*) grow by pine trees.	Boletes can be found in boreal pine forests.	23
A general preference towards sloped terrain.	Often slopes are good places.	22

Milk-caps (particularly rufous milk-caps) grow in dry heath forests.	One should search for rufous milk-caps in dry heath forests.	21
If you find one mushroom (particularly funnel chanterelles and chanterelles), you are likely to find more of the same in the immediate vicinity.	Once you see one funnel chanterelle, it is likely that you are standing on an abundance of them.	16
A general preference towards spruce forests.	Old mossy spruce forests draw me towards them.	16
Look for terrain that looks similar to previously proven foraging patches.	At a new area, I aim to compare the terrain to places I am familiar with. This is how I deduce possible species I might encounter.	13
Trust in instinct (and not explicable rules of thumb) when foraging.	I can't make use of rules of thumb at all. I trust intuition, it often helps me to find boletes, chanterelles and especially funnel chanterelles.	13
Identify a good foraging patch by its smell.	A certain smell of mushrooms guides me to stop at the right places. I believe it is a mixture of moisture and something else.	8

Figure 6. Three search heuristics in one picture: A funnel chanterelle thrives in mossy terrain, often grows near spruces (notice the spruce cone) and rarely grows alone (notice the smaller funnel chanterelle in the background). Photograph by author.

5.3 Search and Environmental Cues

Two pictures were presented for the search task (Figs 7 and 9). The pictures were chosen to portray relatively little ecological information (Gibson 1979; Bruineberg, Chemero, and Rietveld 2018), but a sufficient amount of cues to direct search. Overall, the respondents replied to the open question “What mushroom species would you search for in the terrain in this picture?” with little difficulty, and a rich amount and diversity of answers were recorded.

This task illustrates how little ecological information foragers need to shape their expectations of catch as well as direct their search and attention (see section 6 for further discussion). This gives some flesh to the previous finding that 76% of foragers agreed with the statement “With a quick glance of a given terrain, I know what mushrooms could grow in the area.” The answers clearly differ between the two landscapes—e.g., the most common answer for Fig. 7 (692 instances for funnel chanterelle) was mentioned only six times for Fig. 9. There was considerable consensus with the most popular mushrooms associated with each picture.

Below are bar charts (Figs 8 and 10) of the top 15 mushroom species or genera mentioned for each picture. Overall, Fig. 7 proved to be a more promising and diverse foraging patch (3199 instances of mushrooms mentioned with 89 different species or genera) than Fig. 9 (1656 and 79, respectively). The overall sentiment seemed among the mushroom foragers was that the birch forest is a much inferior foraging patch to the mossy coniferous forest, e.g.: *”I would not forage for mushrooms in this terrain, although I might find boletes. It somehow looks much too dry.”*

Figure 7. This picture of a coniferous forest includes some clear cues for mushroom hunting: Spruces, fallen (decaying) trees, and a mossy and sloped landscape. Photograph by Janne I. Hukkinen with permission.

Figure 8. Bar chart of the top 15 mushrooms identified in the search task for Fig. 7 (coniferous forest).

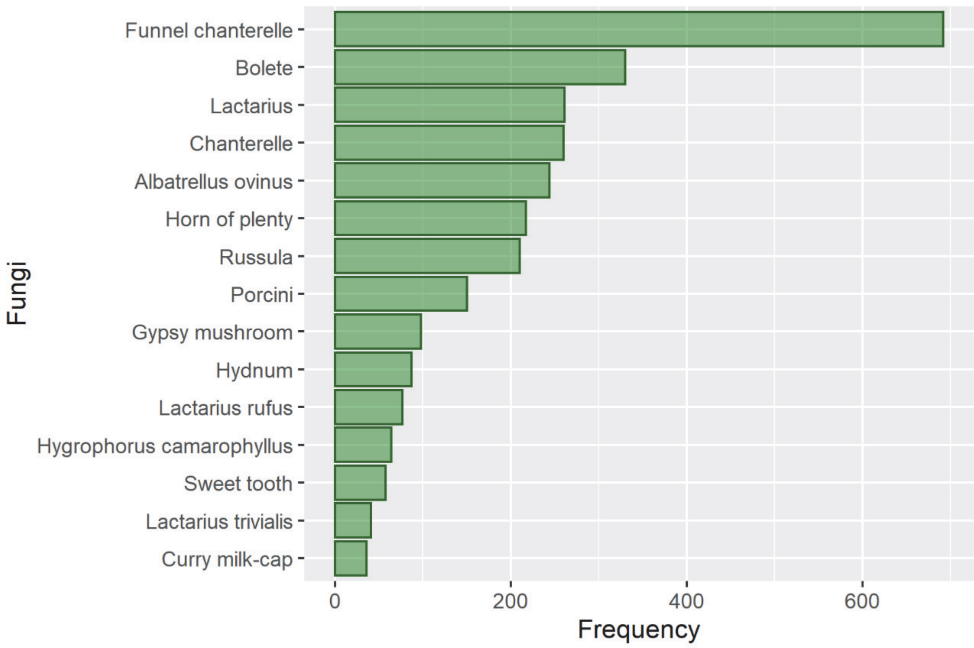
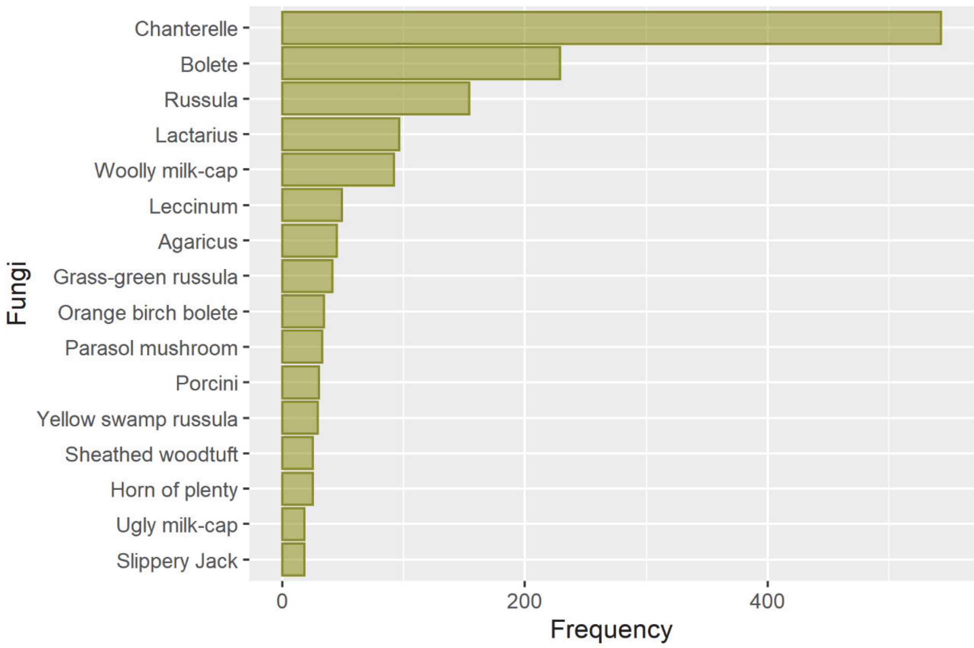


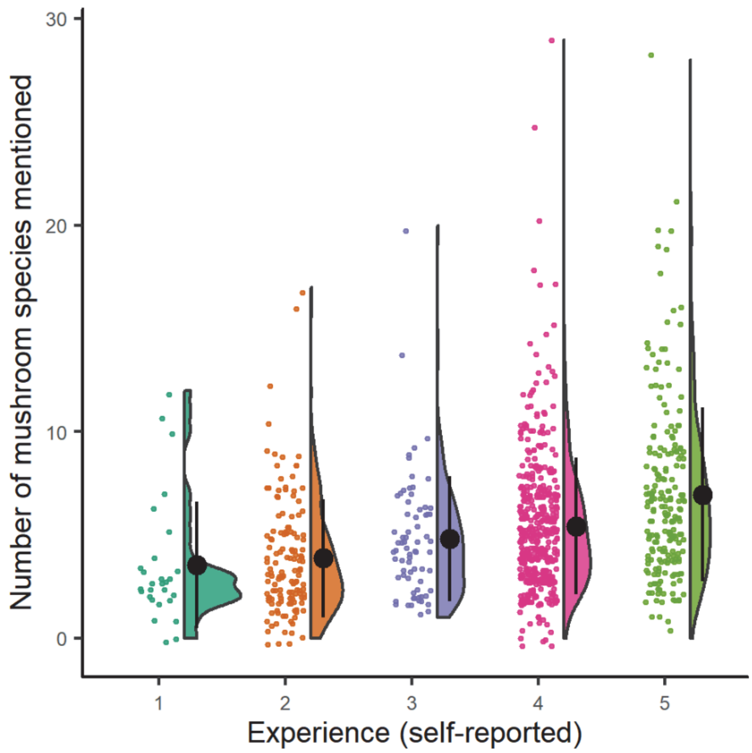
Figure 9. The cues for mushroom foraging in this birch forest include birches, grass, hay, light, dryness and a possibly pastural landscape. Photograph by Janne I. Hukkinen with permission.

Figure 10. Bar chart of the top 15 mushrooms identified in the search task for Fig. 9 (birch forest).



Experienced foragers reported a higher total number of mushroom species or genera (in the two pictures combined). A simple linear regression was calculated to predict the number of mushroom varieties mentioned based on self-reported experience ($\beta = 0.08$, 95% CI [0.06, 0.10], $p < 2.2e\text{-}16$, adjusted $R^2 = 0.075$). This is illustrated in the raincloud plot (Allen et al. 2018) in Fig. 11. The results suggest that more experienced foragers have more refined expectations of what mushrooms they expect to encounter in a presented terrain. This provides further evidence for the correlations found between variables **Experience** and **Glance** ($r = 0.49$) in Fig. 4. That is, experience predicts higher capacity to "hunt by expectation" (Kamil and Bond 2006, see discussion).

Figure 11. A raincloud plot of self-reported experience measured against the number of mushroom species or genera mentioned in Figs 7 and 9 (combined). Plot includes means (black points) with 95% confidence intervals for each of the experience levels (measured on a five-point scale), as well as all individual data points and density distributions.



6 Discussion: Heuristics, Precautionary Principles and Selective Attention

> *"But what about poisonous and dangerous mushrooms! Not a word has been spoken of them," said the guest. "We do not worry about them," came the answer, "but leave all mushrooms to themselves, which we cannot recognise. Only this way can we be certain of them".*
>
> Quote from the first Finnish mushroom identification guide (Hisinger, 1863).

The results provide evidence for the hypothesis that mushroom foragers use heuristics when identifying, making edibility-judgments of, and searching for mushrooms. 77% of foragers report that they often use rules of thumb when foraging. Moreover, some of the most common reported instances are fast and frugal heuristics, such as "only pick the mushrooms you recognise" or "avoid white mushrooms altogether," whilst others utilised one-reason judgments to make inferences regarding edibility (e.g., the "white milk" of milk-caps of genus *Lactarius*).[11] These heuristics differ notably from risk or utility calculation (or other optimisation procedures), since, for instance, by rejecting whole subsets of mushrooms, foragers do not even attempt at valuing a large amount of encountered species.

With some caveats, the results also can be read to give support for the "less is more effect" (Goldstein and Gigerenzer 2002) in mushroom foraging. The rationale here is that suspecting oneself to *less* information—e.g., ignoring unrecognised or white mushrooms—can lead to better judgments in uncertain environments, where even one mistake can prove to be deadly. However, a caveat is that some of the reported one-reason heuristics presuppose other more complex identification processes. For instance, distinguishing an edible milk-cap was reported by many to be possible by utilising a single cue (bleeds white milk when cut, see Fig. 12), but using this heuristic presupposes a possibly more complex cognitive task of recognising mushrooms that belong to the (somewhat distinctive) genus of milk-caps (*Lactarius*). This is also an interesting

[11] The dataset also included many rather unique and complex mnemonics for foraging, such as the following: *"On boletes: Bad girls have black fishnet stockings (bitter bolete), and good girls have white stockings (porcinis). Nice aunty boletes wear an orange beret and brown, linty socks. [Cortinarius caperatus] is a Northern chap sitting by a bonfire: frost on his cap, an aurora-shaped scarf above his collar, and when young, a total prick [a reference to its phallic shape when young]."* Variance in mnemonics like this could be expected from a practice that is inherited mainly via vertical cultural transmission (from parents or grandparents) (Mesoudi 2011, 60).

finding for ecological rationality theory, since it illustrates how fast and frugal heuristics can be used in tandem with more complex, possibly higher order, cognitive processes.

Whilst the "white milk" heuristic relies on the sufficiently strong (and culturally tested) ecological validity (Brunswik 1956) of the cue ("white milk" correlates strongly enough with "not poisonous" to guide safe decisions), some reported that they treat even this heuristic with scepticism:

- *If a mushroom bleeds milk it MIGHT be edible. Even then it must first be identified.*

Figure 12. A milk-cap (genus *Lactarius*), cut from the near edge. The white latex (or "milk") it bleeds is clearly visible on the gills and the cap of the fruiting body. Photograph by author.

Another important finding is the purpose which the most common heuristics seem to serve. Other than the very common "white milk" heuristic and the common "boletes have spongy pores (and are usually not poisonous)" heuristics, the most common rules of thumb do not pertain to *identifying* an edible mushroom, but rather to *ruling out* subsets of possibly poisonous mushrooms, e.g., white or unrecognized[12] mushrooms.

This can be understood as a process of uncertainty reduction or risk aversion—a precautionary principle of sorts. By *a priori* ruling out those mushrooms that have a possibility of being deadly, and by only focusing on a limited amount of recognized mushroom species, mushroom foragers are considerably reducing the amount of cognitive processing needed to make safe decisions. To maintain the levels of uncertainty at a bearable level, many foragers also report a slow pace of learning new mushrooms.

Interestingly, this precautionary principle has previously been suggested to be an efficient and ecologically rational foraging strategy in a simulation model. Bullock and Todd (1999, 533) found that precautionary foraging strategies are essential particularly in an environment with lethal mushrooms: "Since the consumption of a poisonous mushroom is fatal [...], every successful strategy there must proceed by rejecting subsets of mushrooms on the basis of cues which tend to make correct rejections." The survey data in the present study confirm that real foraging societies indeed use (fast and frugal) heuristics particularly to reject subsets of mushrooms. Two foragers describe these precautionary measures as follows:

- *All mushrooms are poisonous until proven otherwise.*
- *If any uncertainty remains [after initial identification], the mushroom joins the alders [is thrown into the woods].*

This tendency to reject subsets of mushrooms can also be understood in terms of the bias–variance dilemma: When mushroom foraging, it might be safer (and, in the long run, more efficient) to be systematically biased rather than suspecting one's decisions to high variance (e.g., considering a broader variety of mushrooms). An example of this bias could be the heuristics "avoid white mushrooms" or "only pick the mushrooms you recognise," which bias the forager to not pick

[12] This is also the subject of a common Finnish mushroom foraging joke, which was also mentioned by some respondents: "First learn to recognise all the poisonous mushrooms, and then eat only the mushrooms you recognise."

several edible delicacies, but guard the forager against the extreme event of poisoning or death. This, effectively, can lead to novelty robust decisions (Brighton and Gigerenzer 2012; Todd and Brighton 2016). These cognitive biases are culturally acquired adaptive foraging strategies that have likely evolved over decades or centuries of social learning. For instance, the "recognition" heuristic used here can be dated to at least 1863 (see the epigraph of this section) and is likely to be much older.

The "recognition" heuristic used by mushroom foragers (only pick those you recognise) is somewhat similar to the "recognition heuristic" studied in ecological rationality (Pachur et al. 2011). However, instead of using "recognition" as a positive cue for edibility (as the "recognition heuristic" would imply), mushroom foragers are using the recognition heuristic in the inverse: "non-recognition" is a cue for non-edibility, but recognition does not imply edibility.

This bias is ecologically rational, since calculating the benefits of eating a possibly poisonous or unknown mushrooms makes little or no sense if it might be the last thing you ever eat (i.e., potential costs are infinite). Foragers thus find themselves in what is called an asymmetrical (concave[13]) payoff function (Taleb 2012). Benefits of eating a white mushroom are bounded (even deliciousness has its limits!), but potential costs are infinite (death by poisoning). Thus, the biased heuristic of avoiding white mushrooms, for example, makes ecologically rational sense, and has culturally evolved for good reason.[14] Interestingly, the precautionary principle is often recommended to be used in similar policy situations: When uncertainty is high and when costs can expand to infinity (i.e., risk of ruin), taking even minor risks should be avoided (Taleb et al. 2014).

As discussed above in section 3, ecologically rational decision-making is always context-specific, a product of the fitness between the mind and the environment. Indeed, foragers reported using several environmental cues as heuristics, leveraging statistical regularities in their environment to

[13] For instance, imagine "Gain/Loss" on the y-axis and "Edibility" on the x-axis of a graph. After a certain threshold, an increase in edibility brings only limited gain. A decrease, however, can lead to infinite loss. This is asymmetry also evident in the popular mushroom rankings in Finnish foraging guidebooks (Korhonen 2018; 2015): *** (delicious), ** (good), * (edible), ○ (not edible), † (mildly poisonous), †† (very poisonous), ††† (deadly). The losses from a move from † (stomach aches, etc.) to ††† (death) is much larger than the gains of a move from * (edible) to *** (delicious). Hence any foraging rules should put a non-negotiable bound on not moving below, e.g., ○ or *.

[14] Research in cultural evolution has also documented in detail cases where inherited cultures "outsmart" individuals, or the "collective brain" phenomenon (Henrich 2015; Muthukrishna and Henrich 2016). Curiously, the surveyed data also provided cases which suggest that some foragers use precautionary heuristics even though they were unaware why exactly they are doing so. For instance, one forager writes: "*I do not pick white mushrooms. I don't know why.*"

guide their search. These included associating specific mushroom species with particular trees (owing to mychorrizal relationships) or terrain types, as well as foraging in familiar or recognised patches. Moreover, the nature of ecologically rational decision-making implies that the used heuristics are applicable only in the environments where the foragers applied them. Indeed, foragers often reported that the heuristic they use applies to their local forest. For instance,

- *No poisonous boletes grow* ***in my foraging patches****, so all boletes can be picked except for those which have red straws. That one is the bitter bolete and is not edible.*

Interestingly, cases are known where familiar heuristics used in *unfamiliar* contexts have led to fatalities. For instance, reports exist of tourists or foreigners using a heuristic associating whiteness with edibility (likely due to their familiarity with champignons) when mushroom foraging in Finland—the exact opposite of one of the most common heuristics reported in this study, "avoid white mushrooms"—which has led to several *A. virosa* poisonings (Hämeen Sanomat 2018). Another example is the recent case of refugee mushroom poisonings in Germany (Connolly 2015). Here, refugees had likely used familiar foraging rules from their Mediterranean home countries, where they had foraged for the bearded Amanita (*Amanita ovoidea*), and had mistakenly eaten the poisonous death cap (*Amanita phalloides*) in their new home in Germany.

It should be noted that many respondents (at least 25) expressed their scepticism regarding the use of heuristics alone for identifying an edible mushroom:

- *Such rules of thumb do not exist, and one should learn to identify mushrooms by the species. Of course, white milk helps to identify a milk-cap as a milk-cap, and the web of a webcap as a webcap, and so on. But I would say they are pieces of the recognition puzzle, parts of identification wholes that help one towards the right evaluation, not rules of thumb.*
- *There are no rules of thumb to distinguish a poisonous mushroom from an edible one if they are very much alike.*
- *Never trust a single cue.*
- *Identifying a mushroom species is hard to describe in words. It is born from experience and practice. Next to looks and smell, it is affected by how the*

> *mushroom feels on your fingers and how it breaks when bent, how and where it grows, and the whole impression, which you recognise intuitively and near-instantly.*

These are similar to typical pieces of advice in mushroom foraging guides, e.g.: “Never grasp on one identification cue when defining a species, but view the mushroom as a whole” (Korhonen 2015, 12, translated by author). In other words, whilst rules of thumb or fast and frugal heuristics can be efficiently utilised in identification, particularly when ruling out certain subsets of mushrooms, they might not (and likely do not) suffice alone to make inferences about edibility, and seem to be generally accompanied by prior knowledge and experience, tacit knowledge, use of multiple senses and information sources, recognition of the foraging patch, etc. That is, identification in the messy real-world is rarely an algorithmic process with clearly defined steps. This raises some questions regarding how well well-defined algorithmic heuristics such as take-the-best (Gigerenzer and Goldstein 1999) or the recognition heuristic (Pachur et al. 2011) might fare in the wild.

The survey results give the impression of mushroom foraging as a highly intuitive practice. 90% of respondents report that they have a “strong hunch” of the mushrooms they will find prior to going on a foraging trip, and 76% report that they can anticipate what mushrooms grow in an area from a quick glance (the latter is also supported by the results of the search task in section 5.3). Foraging seems to be characterised by non-explicable “tacit knowledge” (Polanyi 2009; 1969), and many foragers reported experiencing highly selective perception and attention during foraging.

Whilst this “selective industry” of the mind is by no means a new notion in psychology (James 1892), to the authors knowledge it has not been studied extensively in human foragers. Selective attention has been better described in other animals, where animals “increase the accuracy with which some stimuli are detected” whilst effectively ignoring others (Kamil and Bond 2006). This is often associated with the development of a “search image,” which biases animals to perceive some cues over others, or “hunting by expectation,” forming an association between particular areas and particular reward rates (Kamil and Bond 2006). The results in section 5 provides evidence for how human mushroom foragers hunt by expectation and gives insights on how foragers might develop search images to focus on particular species. Particularly, the results suggest that experienced foragers have a higher capacity to hunt by expectation, or at least a higher variety of expectations. Selective attention in mushroom foraging could prove to be a fruitful area of future studies in perceptual psychology, cognitive science and human behavioural ecology. This selective perception/attention was described particularly well by some participants:

- *I have hunted mushrooms since I was a child, and* ***my eye has been calibrated to mainly notice the few edible and beautiful or interesting mushrooms****.* ***Others I do not see****.*
- *After finding the first mushroom, you usually start finding more* ***once your eye gets used to it****.*

Overall, the present study points many avenues for future research. For studies on decision-making and perception, it presents opportunities for further research in heuristics, selective attention and precautionary principles. Looking ahead, it invites the reader to consider how traditional forms of uncertainty management might be applicable in our modern, technological, and risk-calculative world. For instance, with the surge of AI and mobile (computer vision) applications for identifying plants and mushrooms, it is reasonable to ask whether these new applications deal with uncertainty as robustly as culturally evolved traditional heuristics. Looking to history, the results invite us to consider possible means by which other traditional or historical hunter-gatherer groups might have used fast and frugal heuristics to facilitate safe foraging, and also point toward further research in how foraging societies and practices evolve culturally. These possibilities could be particularly relevant for research in cultural evolution, evolutionary psychology, and archaeology.

7 Conclusion

This research article surveyed 894 Finnish mushroom foragers about their foraging strategies and heuristics. Most mushroom foragers (77%) make common use of heuristics (rules of thumb), and often resort to “fast and frugal” one-reason decision-making when foraging. The present article gives ample evidence of mushroom foragers using decision-making strategies that are ecologically rational, as well as illustrates how foragers use ecologically valid environmental cues to guide their search. Simple heuristics are particularly used to rule subsets of unknown and potentially poisonous mushrooms out of consideration (e.g., by avoiding unrecognised or white mushrooms). Heuristics for identifying edible mushrooms are also common, but it is dubious whether simple heuristics alone suffice for judgments of edibility, since even the use of simple heuristics is often preceded by more complex cognitive processes, such as identifying the genus or family of the mushroom. The overall picture of mushroom foraging is one of a delicate practice characterised by rich cultural knowledge, expertise, intuition, and tacit knowledge. For instance, the results revealed that experienced foragers have significantly more refined expectations of what mushrooms they expect to find in given terrain. This article also illustrates how heuristics can play an important role in the cultural evolution of safe foraging practices, particularly by bounding the amount of uncertainty the foraging society deals with in decision-making.

Data Availability Statement

Anonymous data (CSV, .txt) and code (R) for data-analysis are available on GitHub: https://github.com/roopekaaronen/mushroom/

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Research Ethics

Research was conducted in full compliance with the Finnish ethical principles of research with human participants (https://www.tenk.fi/en/ethical-review-in-human-sciences) and in accordance with the declaration of Helsinki. All participants were recruited with full informed consent. No minors were surveyed. Participants are not identifiable from answers. The research design did not require an ethics approval statement from the human sciences ethics committee (Finnish National Board on Research Integrity TENK). A statement is only required if the study design contains any of the following (Finnish National Board on Research Integrity, Ethical review in human sciences):

“a) Participation in the research deviates from the principle of informed consent,

b) the research involves intervening in the physical integrity of research participants,

c) the focus of the research is on minors under the age of 15, without separate consent from a parent or carer or without informing a parent or carer in a way that would enable them to prevent the child’s participation in the research,

d) research that exposes participants to exceptionally strong stimuli,

e) research that involves a risk of causing mental harm that exceeds the limits of normal daily life to the research participants or their family members or others closest to them or

f) conducting the research could involve a threat to the safety of participants

or researchers or their family members or others closest to them.”

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