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The life course cube: A tool for studying lives☆

Laura Bernardi[a,*], Johannes Huinink[b], Richard A. Settersten Jr.[c]

[a] NCCR LIVES, UNIL Geopolis, Quartier Mouline, Lausanne, 1015, Switzerland
[b] SOCIUM, University of Bremen, Mary-Somerville-Straße 9 28359 Bremen Germany
[c] College of Public Health and Human Sciences, Oregon State University, 2250 SW Jefferson Way Corvallis, OR 97331, USA

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ABSTRACT

This paper proposes a conceptualization of the life course as a set of behavioral processes characterized by interdependencies that cross time, life domains, and levels of analysis. We first discuss the need for a systematized approach to life course theory that integrates parallel and partially redundant concepts developed in a variety of disciplines. We then introduce the 'life course cube,' which graphically defines and illustrates time-domain-level interdependencies and their multiple interactions that are central to understanding life courses. Finally, in an appendix, we offer a formal account of these interactions in a language that can be readily adopted across disciplines. Our aim is to provide a consistent and parsimonious foundation to further develop life course theories and methods and integrate life course scholarship across disciplines.

1. Introduction

A wide array of substantive principles and methodological approaches fit under the umbrella of 'life course research.' These principles and approaches not only stem from sociology and psychology, but also from disciplines such as biology, economics, anthropology, and history, and from fields such as demography, criminology, epidemiology, and health and policy sciences.

It was sociologists who first originated the 'life course' perspective and gave it conceptual structure (1975, Cain, 1964; Clausen, 1972; Elder, 1974; Riley, Johnson, & Foner, 1972), just as psychologists did in originating the "life span" perspective (e.g., Baltes, 1968; Schaie, 1965). These classic ideas from the 1960s and 1970s especially sprung from research on aging, as gerontologists realized that to understand the final decades of life, one had to account for a long-lived past. But the two disciplines would generally enter their subject matter at different levels of analysis and focus on different outcomes and explanatory factors (see Dannefer, 1984; Diewald & Mayer, 2009; Settersten, 2009). Psychologists would focus more on internal and species level forces, and on intra and inter-individual variability in biogenetic, cognitive, motivational, volitional, and emotional phenomena. Sociologists would focus more on external forces, and especially social settings beyond interpersonal relationships, that regulate developmental tasks and opportunities; it would also focus on socially-structured life course inequalities related to race, class, gender, or other aspects of social life.

Meanwhile, related developments were occurring in other disciplines and fields, developments that would also inform life course and life span perspectives as ideas were cross-fertilized over time. A more complete telling of the evolution of life course studies has been narrated elsewhere (e.g., Elder, 1994; Mayer, 2004) and is beyond the scope of this paper. But particularly important in this regard have been preoccupations in demography with conceptualizing and measuring cohort effects (e.g., Ryder, 1965), in economics with life cycle theories of intertemporal choices (e.g., Modigliani, 1966; Loewenstein & Elster, 1992) and marginal utility (e.g., Gossen, 1998), in anthropology with evolutionary life history theory and its emphasis on the fundamental trade-offs between growth and reproduction and between quantity and quality of offspring (e.g., Kaplan, Hill, Lancaster, & Hurtado, 2000), in biology with the differentiated functioning of living organisms during distinct phases of their "life cycle" (e.g., Bogin & Smith, 2012), in social anthropology with theories of age structuring (Kertzer & Keith, 1984), in historical science with prosopography, life story, and oral history approaches (e.g., Harrison, 2009; Perks & Thompson, 2016), in criminology with delinquency careers (e.g., Sampson & Laub, 2003), and in epidemiology with modeling pathways connecting early life conditions and later health outcomes (e.g., Wadsworth & Kuh, 2016).

This is just a sampling of the many spaces in which the spirit of the life course perspective has thrived as it has evolved. Indeed, the field of 'life course' research has gained tremendous momentum in the last two decades, with few references in scientific articles to 'life course' in the

☆ Author order is alphabetical.

* Corresponding author.
E-mail address: laura.bernardi@unil.ch (L. Bernardi).

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1970s, slow growth in the 1980s and 1990s, and exponential surges in the 2000s and 2010s (Settersten & Angel, 2012). Another sign of the growing visibility of this paradigm is the flourishing number of journals, academic and research centers, and sections of professional organizations that now include 'life course' as part of their titles or descriptions.

Yet, precisely because life course scholarship is a multidisciplinary and interdisciplinary enterprise, there is a great need to integrate our disparate and complex research area. No matter what the discipline or field, central to a life course perspective are a set of broad assumptions about taking a long view of time and examining multiple life domains and multiple levels of analysis. Advances therefore rest on better bringing into view the full range of phenomena that affect or comprise contemporary lives. Even more, advances rest on the exposition of the life course as a multidimensional behavioral process performed and experienced by individual actors and shaped by interdependencies and interactions that cross time, domains, and levels.

We take up this task by devoting core sections of this paper to a model for handling the complexity of the life course. We offer a set of propositions related to studying the life course as individual behavioral process. We also offer a tool for studying lives – the 'life course cube.' The cube is a synthetic representation of the life course, in which the axes represent three dimensions of time, domains, and levels at which developmental, behavioral and societal process occur (e.g. Heinz, Huinink, Swader, & Weyman, 2009; Settersten, 2003a,b; Spini, Bernardi, & Oris, 2017). The crossing of the cube's axes become particularly important in pinpointing crucial nodes of interactions and activity for advancing life course theories and methods. The cube is therefore a systematic yet parsimonious way to qualify the complex structure in which life courses, understood as behavioral processes, take place. Our hope is to provide a theoretical foundation to guide the development of interdisciplinary life course research and help integrate and unify the field. Doing so moves life course scholarship beyond the often-cited four general "paradigmatic principles" first offered by Glen Elder (e.g., 1994), which have been indispensable for christening a field, but do not offer an integrated view of life course processes. Our model incorporates Elder's principles, but more systematically tends to relevant processes.

2. The life course as a multidimensional behavioral process

There are numerous definitions of the life course, some more general and others more specific. A rather parsimonious definition is given by Elder & O'Rand (1995, p. 454): "The life course consists of interlocking trajectories or pathways across the life span that are marked by sequences of events and social transitions." This definition has the advantage of being broad enough to encompass a wide range of interpretations, but the double disadvantage of leaving the interdependencies across domains, levels, and time underspecified and of missing an explicit reference to what is at the core of every life course: the individual actor. Another definition, proposed by Giele and Elder, is more specific in this regard, taking the life course to be "a sequence of socially defined events and roles that the individual enacts over time" (Giele & Elder, 1998, p. 22). We also propose to explicitly account for the centrality of an individual's behavior in making their life trajectory, and we assume that individuals, efficiently or not, react to their experiences in their environments. They perceive their environments, estimate their resources and abilities, and tend to their well-being by following what they believe are good reasons to act as they do. As we address experiences and behavior, we want to underscore the fact that this process is not only the result of decisions that are consciously made, but it also the result of routinized or spontaneous behaviors in response to external events.

The life course therefore can be defined as a *multifaceted process of individual behavior*; that is, it evolves from the steady flow of individuals' actions and experiences, which modify their biographical states. We define the biographical state of an individual i at age x and time t – $\mathbf{bs_i(x)}$ – as a vector of (ideally) all attributes that are part of or given to an individual, describing the individual's states in various life domains at age x. We call these attributes biographical state variables (for more comprehensive formal definitions, see the appendix). These variables change as the individual grows older and are simultaneously affected by historical and environmental conditions. The purpose of a theory of the life course is then 'simply' to explain the transitions of individual actors from one biographical state $\mathbf{bs}_i(x)$ to the next $\mathbf{bs}_i(x^+)$ in time. In this sense, a theory of the life course should account for 'nonlinear' dynamics of individual behavior over time (that is, be multidirectional) and simultaneously differentiate action across domains (that is, be multidimensional).

Perhaps most challenging, a theory of the life course must also explicitly differentiate levels of analysis (that is, be multilevel). We distinguish three major levels of biographical state variables: inner-individual, individual, and supra-individual. First, the inner-individual level comprises state variables like genetic, biological, physiological and psychological attributes (e.g., dispositions, values, attitudes, subjective wellbeing). One could characterize them as the inner-individual conditions, resources and, in a dynamic perspective, outcomes of individual behavior in different domains over the life course.

Second, the individual level comprises biographical state variables assigning overt behavioral outcomes of the individual's action over the life course, which occur in different domains. These are socio-structural achievements and characteristics (e.g., education, social status, living arrangement, place of living), as well as the type and amount of resources an individual can invest (inputs) and any special legal rights or social privileges they have to act (e.g., citizenship, gender).

Third, the supra-individual level of state variables includes attributes of the socio-cultural environments in which the individual's behavior in life domain d takes place and which potentially affect individual behavior. These socio-cultural environments extend across a variety of sublevels, ranging from the immediate environment (e.g., made up of personal and professional relationships and networks, organizations and associations) to larger social institutions (e.g., made up of legal, cultural, and economic frames and collective actors). These socio-cultural environments also span a continuum ranging from informal to formal, and from particularistic to universalistic. It is this supra-individual level that defines the 'external' societal opportunity structure for individual experiences, behaviors, and actions.

The investigation of life courses conceptualized as complex behavioral processes must rest on a dynamic theory of individual behavior and decision-making – that is, what we might call a theory of agency. Although an acknowledgment that human agency is central to understanding the life course has long been a basic paradigmatic principle of a life course perspective (Elder, 1994), a concise and comprehensive *dynamic* theory of agency over the life course has yet to be formulated. One of the major challenges is that such a theory must be interdisciplinary and, as such, brings obstacles related to the fragmentation created by isolated disciplinary concepts, language, and approaches. One way to overcome these obstacles is to begin addressing a few of the 'cornerstones' that would allow such a theory to be shared and unambiguously understood across disciplines.

The axiomatic assumption of a behavioral theory of the life course – according to available theories of action – is that actors try to improve, or at least maintain, aspects of their physical and mental wellbeing over time, all the while avoiding other considerable losses. These efforts often happen spontaneously and unconsciously, but they must nonetheless be understood to be part of a behavioral process in which actors are potentially able to make choices related to the actions they take throughout their lives (Baumeister & Bargh, 2014).

We put forward three central propositions for understanding this behavioral process. First, in anticipating consequences of their behavior or observing changes in their environments, individual actors try to achieve as much certainty as possible on what to do or look for next. A weak rationale guiding the actor's decisions might be that they follow their subjective beliefs ('good reasons') about what will best serve their wellbeing (Boudon, 2003). If, as individuals pursue various situation-dependent goals, they have strong reasons to believe that achieving those goals will significantly contribute to relevant dimensions of their wellbeing, they will make a decision to act accordingly (Bandura, 2006).

Second, individual action is embedded in a process of decisions and behaviors that occurs over time. What actors perceive as 'good reasons' to take particular actions are, first and foremost, shaped by their prior biographical experiences (e.g., prior knowledge, expertise, values, and attitudes) – what we might call 'shadows of the past.' At the same time, the current social environments in which persons are located influence their choices and perceptions (e.g., opportunity structure, social embeddedness, developmental state – conditions on the supra-individual level and inner-individual level we described earlier). But these, too, are influenced by the past, including the pre-birth genetic make-up guiding biological and psychological processes.

Finally, actors are influenced in their choices by the more or less uncertain expectations about the consequences of a given action – both for the future generally and as a specific condition for other future actions (e.g., anticipation processes). This uncertainty we might call 'shadows of the future.' An actor's many biographical statuses, as well as aspects of her environments, are affected by such foreseen consequences (Birg, 1991). Individuals try to find a subjectively satisfactory balance between investments in and gains from their actions, and they try to organize their lives in order to obtain a satisfying level of subjective wellbeing with respect to different dimensions of needs (e.g., physical, social) and to their aspirations.

These points reinforce the significance of agency as a concept in life course research. Elder's general definition of the principle of agency establishes that "individuals construct their own life course through the choices and actions they take within the opportunities and constraints of history and social circumstances" (Elder, Johnson, & Crosnoe, 2003) – what Settersten and Gannon (2006) called having "agency *within* structure," or what Evans (2007) called "bounded agency." That is, the agency of an individual (or of a group, for that matter) is not unlimited or unbridled; it is situational, bound to the 'objective' or perceived circumstances of a place, time, and developmental state and assessed with respect to the past and to anticipated futures.

Hitlin and Elder (2007) distinguish between four types of agency, depending on the time horizon for action and the nature of choices to be made. Life course agency is related to the future, while identity agency is related to an individual's present roles. Pragmatic agency is situationally defined, while existential agency is a more universal ability to choose. Agency should matter for individuals' future aspirations, both in terms of their perceived ability to affect the future and their perceived life chances (Hitlin & Johnson, 2015). Simply put, individuals have to 'know' what to do next in life, given that there is more or less uncertainty about the consequences of their particular actions and developments in the future.

3. The life course as a complex set of interdependencies

3.1. First-order interdependencies

As depicted in Fig. 1, our 'life course cube' identifies a system of complex interdependencies that are central to understanding contemporary life courses. At the most basic level are three 'first-order' interdependencies related to time, domains, and levels. These represent the core axes of the cube. Continuing with our formal definitions, these are:

a) The *time-related interdependence of the life course* between the history of a life course (accumulated experiences and resources reflected in biographical states before x_1), current life circumstances, and the future life course (short and long term effects of current behaviors on the future life course). In Fig. 1, these are displayed on the *time axis* of the cube at times T1, T2, T3, … Tx.
b) The *interdependence between life domains*, meaning that individuals' goals, resources, and behaviors in one domain (such as work, family, education, or leisure) are interrelated with goals, resources, and behaviors in other domains. This means that domain-specific sub-processes are correlated with each other both at once and over time. In Fig. 1, these are displayed as the *life domain axis* of the cube between domains D1, D2, D3, … Dx.
c) The *multilevel interdependence of the life course*, which connects individual action and behavior over the life course ('individual action level') with the life courses of other people, social networks, and the 'external' societal opportunity structure ('supra-individual levels') and the 'internal' dispositions and psycho-physiological functioning ('inner-individual levels'). This means that level-specific sub-processes are correlated with each other both at once and over time. In Fig. 1, these are displayed as the *level axis* of the cube across levels L1, L2, L3, … Lx).

Below, we provide an in-depth discussion of each of these interdependencies in turn.

3.1.1. Time-related interdependence

Of all the interdependencies we will discuss, those related to time have most often been the subject of investigation in life course research. We draw attention to three important issues: path dependency, anticipation, and turning points.

Path dependency

The first aspect is the relevance of the past, not just the recent past but also the far-away past, in determining the present. Path dependency processes are those in which the probability of an occurrence and the direction of a change in a biographical state variable at age x_1 depend on the longer life history, not only on the biographical state at age x_1-1. The sequential contingency implied in path dependency mechanisms means that the Markov property – the conditional independence of past states prior to x_1-1 – does not hold. The distribution of biographical states at age x_1+1 and future pathways depends on the biographical history up to age x_1, and the universe of possible future pathways is restricted due to the causal impact of the previous biography and decisions (Liebowitz & Margolis, 1995). Stagnation – in the sense of pathways that are blocked or 'locked in' – can be perceived as a consequence of path dependency. The degrees of freedom with respect to planning and goal pursuit in the future are determined by previous experiences and decisions.

To date, path-dependency has mostly been used in studying macro-level processes in economics and social sciences (e.g., Mahoney, 2000; Pierson, 2000). In life course research it has been mainly, but often only indirectly, addressed to show that life course outcomes can be the result of the *accumulation of disadvantage or advantage* (Dannefer, 2003; DiPrete & Eirich, 2006) – for example, common appeals to the fact that early life privileges or hardships can pile up and be compounded over time. This conceptualization of path dependency is similar to that of *causal pathways* or risk chain models, as long as one can assume that early states set into motion a chain of direct effects on subsequent states (Kuh, Ben-Shlomo, Lynch, Hallqvist, & Power, 2003) and therefore channel the life course. An alternative and complementary way in which one can think of path dependency in life course terms is to consider it alongside the concept of a turning point (2001, Abbott, 1997), which we discuss below, or a bifurcation point (Grossetti, Bessin, & Bidart, 2009). Here, for example, Ebbinghaus (2009) uses the metaphor of path dependency as a "road juncture" at which the individual person takes one or the other of multiple available routes in order to proceed, after which it may be difficult or impossible to backtrack.

Path dependency and risk chain models, while clearly relating the present to the past, do not solve major challenges related to identifying

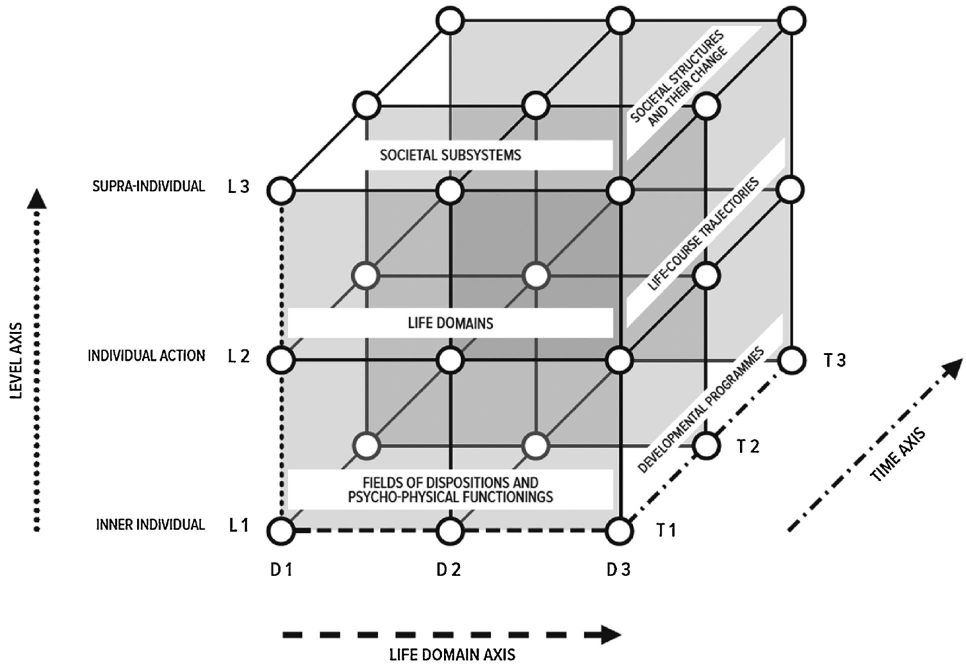

Fig. 1. The Life Course Cube: Time, Domain, and Level Interdependencies.

the time window in the past that is relevant to an investigation. Nor do they solve associated issues of endogeneity and causality. When our view extends back over many decades, the life course becomes an endogenous causal system that seeks to explain the present with the past. The risk is that more proximate social effects overrun correlated earlier events, thus giving way to spurious interpretations. The increased use of the term 'life course' in research that predicts later outcomes by measuring social-causal factors at only a single prior observation period is misleading, for it fails to consider the explanatory potentials of similar (and possibly correlated) social-causal factors appearing later in the life course – or the other way around. The longer lives are studied, the more difficult it becomes to trace connections, and the possible connections seem endless and tenuous. It is hard to know which variables are important, when they are important, how they might be arrayed in sequence, and what processes and mechanisms drive these connections. Variables are also likely to be multiply confounded, not only at single time points but especially across multiple time points.

Anticipation

The matters of path dependency we have just described relate to 'shadows of the past.' But time interdependencies also relates to 'shadows of the future' (after Axelrod & Hamilton, 1981). That is, what individuals anticipate in the future affects their present decisions and actions. Knowing that (decisions about) today's activities may have consequences for our wellbeing and freedom to act in the future – whether in the next minute or decades from now – is an important and unique aspect of human life (Birg, 1991). Here, we address the concept of *anticipation*, meaning that the probability of an occurrence and the direction of a change in a biographical state variable at age x_1 depends on the expectation of wellbeing -related effects in the future. From a life course perspective, and in light of possible long-lasting path dependencies, actors in principle try to estimate these effects in both the short and long term. This means that they prefer current activities that bring highly certain (positive) consequences (Friedman, Hechter, & Kanazawa, 1994) and act in order to make individual aspirations meet individual expectations about the future (Hitlin & Johnson, 2015). The shadow of the future not only affects choices because of expected repeated interactions among actors, but also because it affects one's subjective agency – that is, "people's internal sense that they can influence their lives" (Hitlin & Kwon, 2016, p. 432).

Turning points

Time-related interdependence includes the concept of a 'turning point,' which reflects a radical deviation or disruption in the trajectory an individual has been on or from one that was personally or socially expected in the future. It is, in technical terms, a circumstance in which the probability of the transition from a biographical state at age x or time t to the next at age x + 1 or time t + 1 is highly unlikely. Therefore, the concept of a turning point is strongly connected to the concepts of path dependency and anticipation because it represents a discontinuity in anticipation and cumulative processes – a space for contingency to play a crucial role in directing the life course. Turning points cannot be understood without reference to the history or the anticipated future of the life course. Turning points have the effect of changing the direction of a pathway (2001, Abbott, 1997) – a point at which a life trajectory makes a distinct turn upward or downward, at the same time altering opportunities and experiences immediately thereafter, if not also in the long term. But this is not to say it is irreversible.

There can be many reasons for the occurrence of a turning point. It can be the result of a conscious decision and action taken at time t in order to alter the pathway's direction because it does not promise a sufficiently appreciable future (in the extreme case, averting suicide). It can be due to an external shock that completely changes the conditions of gaining or maintaining individual wellbeing in the future. It can occur when the life course approaches a critical juncture characterized by unstable equilibrium in a nonlinear process of interdependent biographical state variables, leaving the future pathway highly uncertain. Small changes in the conditions of the process, and small fluctuations in biographical state variables, can result in very different future trajectories. At such a point, the alternative is to follow the pathway (perceived as being) associated with more stabilizing conditions or to leave the path altogether, undergoing drastic changes until a new stable state is reached. In the latter case, path-dependency is 'switched' at a 'bifurcation point,' only to start working again immediately afterward (Grossetti et al., 2009).

From a subjective standpoint, a turning point generally suggests that the individual, and probably also intimate others in the person's social world, are conscious of the change and even understand life in starkly different terms after the turning point has occurred. The turning point is likely to alter perceptions of (in)stability and (un)certainty, given that it signals marked discontinuity in the life course.

3.1.2. Interdependence of life domains

The interdependence of life domains is created through various kinds of interconnections between activities A and B, situated in domains d_A and d_B, which modify biographical state variables on the inner-individual or individual level (e.g., Diewald, 2003; Lutz, 2014). This involves some treatment of resources and the outcomes of those activities.

First, consider resources. Individuals use resources to perform activity A in domain d_A (such as work) and activity B in d_B (such as leisure). Activities A and B can compete for the resources needed to perform them (such as time), and A and B may be more or less reconcilable – or, to put it differently, they may bring different opportunity costs for each other. This means there are resource-related issues to reconcile regarding activities in d_A and d_B. At the same time, resources may be generated by A and B (money in the case of work, or mental or physical health in the case of leisure) such that they mutually support each other (following our example, work may provide the financial resources required for leisure activity, which may improve competencies and performance at work). One can assume that actors seek constellations of activities that are reciprocally supportive across domains or for which a single resource simultaneously serves multiple life domains. An example of such 'joint production' or 'co-production' of resources and activities might be an individual who is residentially mobile and conducting a job search in a particular location so that they improve wages as well as opportunities to be engaged in their favorite leisure activity.

Second, consider the outcomes of activities A and B, such as the wellbeing objectives for which individuals are striving. Following our example, subjective wellbeing or psychological functioning are not just resources but also outcomes (in a dynamic perspective). On one hand, gaining or lacking enjoyment at work can be supportive or detrimental for the enjoyment of leisure activity (that is, it can spillover in positive or negative ways). On the other hand, gaining enjoyment at work can substitute for enjoyment that might have been derived from leisure activities, or compensate for it if there are limited opportunities to perform leisure activities (Diewald, 2003). Similar interdependent wellbeing dynamics have been shown for other domain-specific combinations (Bernardi, Bollmann, Potârcâ, & Rossier, 2017).

Thus, life course theories need to address questions related to how much individuals should invest in various life goals and activities – a topic that intersects nicely with established theories in economics, anthropology, and psychology. In economics, the "second law" of the German economist Gossen, a pioneer of marginal utility theory, is that individuals must distribute their time into different fields of production, or at least maintain wellbeing in such a way that the investments in those fields should result in the same gain in wellbeing. If one substitutes time with other resources, like money (which is most often examined in research), the individual's income should be "allocated among the various goods such that the marginal utility of the last atom of money spent on any good is the same" (Jolink & van Daal, 1998, p. 45). Optimally, the marginal utility is equal to the marginal cost (effort) in all fields of wellbeing production. This only makes sense, however, if one assumes that the costs and outcomes in each field of wellbeing production are substitutable (that is, it disregards the possible incommensurability of various fields of wellbeing production).

Moving well beyond Gossen's law, life history theory in anthropology (Kaplan, Hill, Lancaster, & Hurtado, 2001; Lawson, 2011; Mace, 2000) addresses the multidimensionality of human life courses from an evolutionary perspective. It focuses on the long-term outcomes of human investments alongside current ones and observing the whole life course rather than a single time point. This approach assumes that an individual's resource allocation strategies reflect the pursuit of fundamental goals of reproduction, growth, and survival. In addition, "observed life histories are constrained by a combination of finite resource budgets and the 'Principle of Allocation,' that is, resources – like time and effort – allocated to one function cannot be allocated to another" (Lawson, 2011, p. 183).

3.1.3. Interdependence across levels

Classic sociological research has pointed to the need to identify dual mechanisms through which social structures affect individual behavior, on one hand, and those through which individual behaviors create patterns of social stability or change, on the other. These principles are also embodied in a life course perspective, which has at its center a concern for cross-level interactions. The social patterning of lives is explicitly modeled in terms of supra-individual forces that exert their influence differentially on the life course patterns of individuals and groups. At the same time, a life course perspective acknowledges that inner-individual phenomena to some extent control the life course by influencing actions at the individual level. In other words, just as phenomena occurring at the supra-individual level are taken into account by individuals when they act, phenomena at the inner-individual level also regulate action from the inside, for instance differentiated by risk-taking attitudes.

Life course scholars from the social sciences have emphasized interdependencies between 'micro' and 'meso' levels, and between 'micro' and 'macro' levels. In our terms, the individual (micro) level and a hierarchy of supra-individual (meso, macro) levels are addressed here. Typically, the inner-individual level is not considered in this scholarship, although we will provide some examples below. The interplay between the micro and meso levels reveals how individual trajectories are shaped by support, shared meaning, and normative influences. For example, research has examined the extent to which individuals' resources (e.g., health, social, and financial resources), and the uses that can be made of them (e.g., the reciprocal competition, substitution or compensation effects of available resources), are affected by immediate social environments, such as nuclear or extended family networks, communities, peer groups, school and working climates (e.g., the role of peer groups in shaping family or health trajectories; Bernardi & Klärner, 2014; Thrash & Warner, 2016).

The interplay between the micro and macro levels reveals how individual trajectories are shaped by population composition and dynamics, economic institutions and labor markets, welfare policies, and culture (e.g., Hagestad & Dykstra, 2016; Leisering, 2003; Mayer & Müller, 1986; Mayer & Huinink, 1990). For instance, declining fertility, combined with increases in life expectancy, have created longer and more interdependent family relationships in individual trajectories (Hagestad & Dykstra, 2016). As labor market opportunities and requirements change, so does the redistribution of resources by the welfare system (e.g., increases in health expenditures and retirement ages) and the expectations and demands of care in families and communities. Similarly, increases in divorce and family complexity within a population change marriage markets and gender roles (e.g., shared custody arrangements may bring opportunities for fathers to devote more time to care, and for mothers to devote more time to work or activities outside the household).

Like demographic change, legal and policy changes have the power to structure interdependence among individuals depending on their characteristics (e.g., citizenship, age, gender, marital status). Social norms and culture, which often go hand in hand with formal legal regulations, contribute to such interdependence. For instance, a gender regime in which women's social integration is primarily ensured through the family, and men's social integration primarily through the labor market, will differentially weight the childcare and career responsibilities of mothers and fathers (Le Goff & Levy, 2016; Townsend, 2004).

On the inner-individual level, physiological and psychological developmental change might prompt individuals at particular ages to pursue, heighten, or relinquish certain goals (Baltes, Lindenberger, & Staudinger, 2006; Elder & Shanahan, 2006; Luhmann, Orth, Specht, Kandler, & Lucas, 2014). What we called 'developmental programs' in the life course cube is mainly addressed by life span psychology. Baltes et al. (2006) emphasize the two crucial assumptions here: first, development extends across the whole life course and is not just a matter of the early years; and second and most important, individual development is greatly driven by adaptive processes and does not exactly follow a given biological program. Therefore, "adaptive changes across life can be more open and multidirectional than the traditional concept of development with its strong focus on development as growth in the sense of maturation and advancement may suggest" (Baltes et al., 2006, p. 569). Following this premise, the authors develop their "systemic and overall theory of life span development," Selective Optimization with Compensation. The theory of developmental control has been developed with similar aims (e.g., Heckhausen, Wrosch, & Schulz, 2010). Both approaches reveal that inner-individual processes allow for much plasticity and context-sensitivity, underscoring highly relevant interdependencies between the inner-individual development and supra-individual living conditions and societal structure.

Epigenetics is another field of study that points to crucially important crossovers between the inner-individual and supra-individual levels. Major progress has been made with respect to analyzing interactions between genes and environment over time. This research has repeatedly shown that experiences and social environments may not only change genetic responses, but may actually affect the genetic makeup of an individual through epigenetic processes (e.g., Kim, Evans, Chen, Miller, & Seeman, 2017; Taylor-Baer & Herman, 2017). Discoveries in molecular genetics in the past decade have increasingly demonstrated that gene expression is conditional on social environments, giving rise to environmental epigenetics and social genomics studies (Landecker & Panofsky, 2013). These developments are particularly relevant since the processes regulating gene expression are dynamic, partially regulated by the social environment and throughout the whole life course (Dannefer, Kelley-Moore, & Huang, 2016).

The axes of the life course cube are the three types of first-order interdependencies across time, domains, and levels. To advance theories and research, however, it is imperative to realize that, although these axes are useful analytical distinctions, they are themselves interdependent. That is, the cube helps us see even more complex second- and third-order interdependencies that must be probed in order to achieve more comprehensive and rigorous understandings of contemporary life courses.

3.2. Second-order interdependencies

As can be seen in Fig. 1, the first-order interdependencies outlined above themselves interact, creating three second-order interdependencies (Buhr & Huinink, 2014). These are:

1 The connection between time-related interdependence and the multilevel structure (first order 1*2).
2 The connection between the multilevel structure and multiple domains (first order 1*3).
3 The connection between time-related interdependence and multiple domains (first order 2*3).

We discuss each of these in turn.

3.2.1. The connection between time-related interdependence and the multilevel structure

This connection infuses time into each of the levels. At the supra-individual level, it reveals changes in the institutional programs and age-specific socio-structural patterns in which individuals live (e.g., forms of social grouping and organization, living arrangements, linked lives). Forces like economies and labor markets, policies, legal regulations, or a "hidden curriculum" in schools or workplaces (Leisering, 2003) influence time-related interdependencies in the life course (Kohli, 1985; Levy & Bühlmann, 2016; Mayer, 2004; Mayer & Müller, 1986). For example, socially expected (normative) life scripts give direction to individual trajectories, and can be sharply different for men and women (Hagestad & Settersten, 2017; Krüger & Levy, 2001). These supra-individual level institutions, norms, and social structures not only specify timetables for life course events and transitions, but also define broader time horizons (Heinz et al., 2009; Settersten & Hagestad, 1996b, 1996b). This means that they establish expectations that require and permit an appropriate anticipation of future developments and their time- and/or age-related patterns. Although these supra-individual forces channel individuals onto certain tracks or restrict their movement, they also provide a sense of what lies ahead, which is recognized to be a fundamental human desire (Friedman et al., 1994)

An important substantive issue to be addressed here is *socialization* and its effects on later achievements. An example is Heckman and Mosso's (2014) economic model of human development, skill formation and social mobility. Parents transmit abilities, traits, behaviors and outcomes to their children and grandchildren in a variety of life domains through heritable dispositions or mechanisms of socialization (e.g., for education, Behrman & Rosenzweigm, 2002; for health, Coneus & Spiess, 2012; for fertility norms, Bernardi, 2016). In this case, the supra-individual level is conceivable only through the time needed for at least two generations to exist and possibly interact. Open and popular questions for analyzing these interdependencies concern the relative importance of inherited and social components (nature versus nurture), the conditions under which one or the other is stronger or effective, the disentangling of selection and causation in observed transmission, and the most appropriate data for identifying transmission mechanisms.

At the individual level, there are the observed trajectories of individual action and behavior, with the past affecting future behavioral options and opportunities, as we discussed earlier. And at the inner-individual level, developmental programs guide and impact the life course as individuals age across life stages (Pulkkinen & Caspi, 2002). We have already referred to the close independence between inner-individual dispositions and behavioral processes. There is extensive psychological research, for example, on developmental control and modes of goal management and adaptation (e.g., Brandtstädter & Rothermund, 2002; Heckhausen, 1999; Heckhausen et al., 2010). Dispositional, physiological, and culturally-defined age-specific deadlines to perform certain activities play major roles in these phenomena (Heckhausen, Wrosch, & Fleeson, 2001; Settersten, 2003a,b).

3.2.2. The connection between the multilevel structure and multiple domains

This connection refers to the relationship between separate segments (fields) of welfare production in the life course and the functional differentiation of a society. A major issue to be addressed here is how the subsystems of modern functionally-differentiated welfare societies (supra-individual level) correspond with the organization of the life course in different domains of activity (individual action level) (Levy & Bühlmann, 2016; Mayer, 2004; Weymann, 2004). At the individual level, multidimensionality refers to the various life domains D in which individuals are engaged. At the supra-individual level, these domains largely correspond with different subsystems of societies. These subsystems follow different, and even incompatible, goal logic, pursuit, and timetables. These differences can create contradictions in the life planning efforts of individuals, affecting whether and how activities in different domains can be harmonized. At the inner-individual level, multidimensionality refers to different fields of dispositions and dimensions of psycho-physiological functioning that must again, in turn, be understood in relation to the various domains of individual action.

Such interactions are the basis of approaches in life course epidemiology, which consider the dynamic interplay between genetic and contextual factors over time, and their influence on observed behavior and outcomes (Kuh et al., 2003). For example, this is reflected in studies that examine how genes affect individuals' reactions to social structures, as well as how individuals' biographical experiences in multiple social contexts affect their genetic expression (Shanahan & Boardman, 2009). Similarly, Kuh and colleagues' discussion of "embodiment" addresses how socially-patterned exposures during childhood influence disease risk and socioeconomic position in adulthood, which may account for social inequalities in adult health and mortality (Kuh et al., 2003). The process of embodiment is one in which the extrinsic factors experienced in different life stages are inscribed into an individual's body functions or into social structures. This may occur through developmental processes like habituation, learning, damage, and repair (see also Keating & Hertzman, 1999).

Anthropological perspectives as well emphasize that the human life course is based on a set of "interconnected, time-dependent processes and the co-evolution of physiology, psychology, and behavior" (Kaplan et al., 2000, p. 182; Mace, 2014). For instance, Lancaster, Kaplan, Hill, and Hurtado (2000) suggest that typical human life courses must have evolved from a flexible gathering and hunting life style, which allowed humans to exploit the environment but at the same time to specialize in acquiring skills and knowledge in order to maximize productivity in later life stages. They conclude that there are strong links between the ordering of psychological milestones (like language development, self-regulation) and the timing of brain growth, physical growth rates in childhood and adolescence, rates of survivorship, and rates of senescence and ageing (Lancaster et al., 2000).

3.2.3. The connection between time-related interdependence and multiple domains

This connection refers to the fact that activities in one life domain (dimensions of the state space) are influenced by *earlier* activities in another domain, and vice versa. At the same time, they affect *future* actions in any life domain. As we have already shown, these cross-domain effects can be supportive or competing in regard to resources that may be needed in the future. With respect to outcomes, one may observe lagged complementary or spillover effects, as well as future options for substitution or compensation wellbeing effects, across domains (e.g., Diewald, 2012; Lutz, 2014). With respect to how resource investments in one life domain might hinder or support investments in another, consider how the timing of fertility might be related to the occupational career: Occupational success might be a substitute for the benefits of family life, but gainful employment might be perceived as a prerequisite for starting a family (Huinink & Kohli, 2014).

As another example, life domains have and also impose different calendars for transitions. Some calendars may be strongly normatively regulated, legally or via informal social norms, while others may be more flexible. For instance, social clocks regulating education and labor market entry seem to be stricter than those for family formation in Western countries. While professional trajectories are only slightly postponed because of the increasing time spent in the educational system, family formation is delayed considerably (Huinink & Kohli, 2014). Inconsistencies between different institutional time clocks can pose significant conflict for individuals and families as they try to manage and integrate different domains.

Another example again comes from evolutionary life history research, which analyzes the tradeoffs of investing in fundamental goals (e.g., reproduction and the survival of oneself and one's offspring) in both the short and long term under various environmental conditions (e.g., Kaplan et al., 2001; Strassmann & Gillespie, 2002). As Lawson (2011, p. 184) puts it, "[l]ife history studies are thus principally concerned with deriving and testing predictions about the particular optimal populations and individuals can be expected to evolve under natural selection of various alternative strategies."

3.3. Third-order interdependencies

The three second-order interdependencies just described are already highly complex. However, life course theories and research should also strive for an understanding of third-order interdependencies that connect time-related interdependence, the interdependence between life domains, and the multilevel structure (first order 1*2*3). This means understanding how such interdependencies work in combination. For example, we must consider aspects of pre-determination by the past (such as level- and domain-specific memories) and possible outcomes of individual activities, economic or political processes, or institutional regulations in the future. The latter addresses the level- and domain-specific 'shadows of the future' – which can open but also close life options. Here, terms like "planfulness" and "planful competence" come into play (Clausen, 1991) – that is, the capacity of human beings (and the institutions created by human beings) to anticipate the possible consequences of action.

A consideration of third order interdependencies implies, for example, that patterns of combining activities in different life domains (like work and family) over time (first order 2) cannot be understood without acknowledging the relevance of actors' expectations for the future (first order 1), given their past experiences (first order 1), and the opportunities, constraints, and composition of particular socio-structural and institutional environments (e.g., living arrangements, the gender system, the structure of the labor market, or social norms) (first order 3). It is well known that the same behavior (e.g., having a child) has very different consequences for the work trajectories of women depending on whether they are in traditional versus gender-egalitarian institutional settings and partnerships, and depending on their age at birth (Gornick & Meyers, 2003). The consequences of becoming a mother are moderated by the level and type of social and economic resources to which a mother has access. Being in a market with strong child care options, and having the ability to afford good child care, make it possible for women to combine motherhood and work and have occupational success. The mother profits from the cumulative advantages of her occupational trajectory as long as certain conditions are met. One could propose that a more generous family policy that favors the reconciliation of motherhood and work by weakening path-dependent trajectories and opening options for the future possibility of having a more satisfying balance of work and family. In this case, such a policy could generate greater diversity in life courses. While some women would continue to work full time, others would opt for a more balanced time spent in family and work roles.

Life course heterogeneity should generally grow (1) if the interdependencies between supra-individual level and the individual level, and between the inner-individual level and the individual level, become less strict, (2) if improvements in technologies and practices facilitate engagement in multiple life domains and multiple spaces, and (3) if biographical states become more reversible or path dependencies weaken. Again, the three first-order interdependencies have strong effects on one another. Fewer restrictions on individual action and weaker path-dependent processes will make modeling third-order interdependencies, and predicting individual life courses and societal developments, increasingly challenging endeavors. These are important frontiers for theory development.

4. Discussion and Conclusion

We argued that the purpose of a theory of the life course is to explain transitions of individual actors from one biographical state to the next as a result of the 'non-linear' dynamics of individual behavior with its numerous, multifaceted and interdependent dimensions. We take the life course to be a steady flow of an individual's actions and experiences, which modify domain-specific biographical states and affect individual wellbeing over time.

With the life course cube, we provided a parsimonious heuristic tool to identify interdependencies of time, domains, and levels that create complex life course processes. The life course cube, along with our conceptualization of the life course as a complex behavioral process, can guide the development of theory and research across and beyond disciplinary boundaries. It provides a systemic framework for a dynamic theory of individual behavior as the basis for explaining individual decision-making in the multidimensional and multilevel context of the life course. It fosters the integration and unification of a plentitude of theoretical and empirical strands of life course science. And although theories and empirical research often focus on particular parts of the cube, the cube forces us to be mindful and humble that what we are investigating is only part of a highly complex and nonlinear process that is driven by the three axes of interdependence and their interaction.

What do these considerations mean for whether or how a theory of the life course might be envisioned? In the scientific literature, the life course approach is often described as a 'perspective,' a 'framework,' a 'paradigm,' or even sometimes as a 'theory.' As we see it, it is not yet *a* scientific theory in the "conventional sense of linked hypotheses deduced from postulates tested by empirical evidence" (Brynner, 2016, p. 27). There is no all-encompassing theory of the life course in the sense of a system of statements following the deductive-nomological approach of Hempel and Oppenheim (1948). No single theory or model is likely to satisfy all requirements necessary to test the third-level interdependencies. Yet, there are guiding principles that some scholars might argue *approximate* theory, without it being a theory in a strict sense, and certainly contribute to the development of life course theories. Following Merton (1949), such approximations can be classified on a continuum moving from more general to more specific theories. The specific theories might, in the best case, complement each other and be connected by a general foundational theory that indicates how the dimensions and variables can be combined or joined in empirical work. Such a theoretical foundation needs to explicate basic mechanisms that link all of the variables or processes. The life course cube provides a parsimonious set of basic mechanisms, or building blocks, by addressing the three fundamental interdependencies in the life course.

Viewing the life course as a dynamic system, one can use the term 'mechanism' in Bunge's (1997, p. 414) sense that a "mechanism is a process in a concrete system that is capable of bringing about or preventing some change in the system or in some of its subsystems." When we study and explain the outcomes of particular life course dynamics, which are necessarily entangled in the interdependencies of the cube, we need to employ additional, specific theories from different disciplines to address those phenomena. These theories, for example, might address particular mechanisms, such as the theory of dissonance reduction by Festinger (1957), which posits a mechanism pertinent to inner-individual opinion-building and decision-making. Other lower-order theories might genuinely be life course theories – for example, as we discussed earlier, the tendency to reduce possible resource competition between domains by adopting a 'connected production' strategy that simultaneously serves wellbeing in multiple domains. This theory incorporates both agency and the interdependence of life domains.

It is seemingly impossible to develop a single and complete life course theory, strictly speaking, that explains what causes human lives to develop as they do (Mayer, 2009). Here, one can draw an analogy to the study of social change, which also deals with highly complex (including several dimensions), non-linear processes (proceeding in multidirectional ways, following path-dependent processes and experiencing critical junctures). Boudon (1983) similarly entertained whether a theory of social change is possible, proposing to use "general and formal models, frameworks, and systems of concepts which, as such, can be applied to no specific social process, but can do so, once properly specified and qualified" (p. 15). It is our position that the life course cube, as a set of theoretically well-defined mechanisms, is much more than a 'framework.' This is why we propose it together with and based on a theory of individual behavior, as a *theoretical* foundation of life course research. It serves as an ordering structure into which all specific mechanisms relevant to study life course dynamics can be integrated.

We see this is a first necessary step to transition from a rather superficial or generic paradigm (or perspective, or ideograph) to a more comprehensive but nonetheless specific testable theory of the life course. This does not mean that all interdependencies can be tested simultaneously. That is unrealistic. But as life course researchers test middle range and partial theories, for example, those theories can be assembled into our more integrative model. Over time, this would also bring at least three clear benefits: First, it will allow us to identify and bring together redundant middle range theories and concepts (e.g., due to disciplinary divides) because it will be clear that they target the same parts of the cube and the same set of interdependencies and behavioral processes. Second, it will generate greater awareness of which parts of the cube, and which interdependencies and processes, are not being addressed. This knowledge will help researchers be more sensitive in the interpretation of data and more realistic about the merits and limitations of research. Largely vacant spaces in the cube will also be indispensable in generating innovative directions for future theories and methods. Third, it will provide a common language for describing life course interdependencies and processes, thus making it easier to facilitate interdisciplinary collaborations and integrate cumulative knowledge.

What do the life course cube and our conceptualization of the life course as a complex behavioral process mean for the conduct of research across disciplines? Life course research is a genuinely interdisciplinary endeavor. A careful inspection of dominant theories in disciplines like anthropology, psychology, or sociology gives us reason to be optimistic. The life course cube offers a central tool for moving forward. Researchers can take an inventory of theories across disciplines that have been brought to bear on phenomena in distinct sections of the cube. How often it is that we are surprised to find that researchers in other disciplines are addressing similar topics and asking similar research questions – but working in isolation or as if they are unique. A good start for fostering interdisciplinary cooperation is to improve the exchange between disciplines by intensifying communication about theories, methods, and mechanisms in different parts of the cube.

Finally, do we have the methods and data to tackle the challenges of modeling the complexity of contemporary life courses? The task of examining and explaining dynamics over many decades of life, and across multiple domains and levels, not only makes demanding requests of theories, but also of methods and data. With regard to the methods, we suggest, as do the methods articles in this issue, that the basic tools for advancing the field are already in place. Event history methods allow us to conduct multilevel, multidimensional longitudinal analysis and to combine the advantages of cohort analysis to model complex individual life courses in societal context. Techniques such as latent growth-curve modeling and sequence analysis have also matured as tools for analyzing multidimensional life course trajectories by including multichannel and multistate variants. Finally, refined methods for analyzing biographical data and narrative approaches help us identify possible mechanisms, and particularly those that connect the inner-individual level and the level of overt individual behavior. In the best possible world, theory guides better data collection and, in turn, better data allow us to reduce the number of assumptions we must make in statistical models.

With the life course cube, we defined and illustrated three axes of interdependencies (time, domains and levels) and their interactions, which characterize the dynamics of individual life courses. Together with its emphasis on action, the cube provides a theoretical foundation to guide the development of life course research and its integration across disciplines. We offer it as a promising step towards mastering the significant complexity of contemporary life courses.

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Appendix

A Formal Representation of the Life Course: Interdependencies across Time, Domains, and Levels

In this Appendix, we offer a formal representation of the life course as a behavioral process, as well as interdependencies across time, domains, and levels, as described in our paper (Bernardi et al., under review). Along the way, we also offer as illustrations a formal representation of two concepts – path dependency and anticipation –that are central to our paper and important challenges in life course research. It is our hope that these formal representations will provide a language that can be extended to other issues and readily adopted across disciplines and foster integration in life course research.

The Life Course as an Individual Behavioral Process[1]

We start with a definition of the *life course* as a (stochastic) process in continuous time x (*age)* and a multidimensional state space, i.e. a process (**BS**(x), x > 0), where **BS** denotes the vector of **b**iographical **s**tate variables and

$\mathbf{BS(x)} = (Z_k(l,d;x)\text{: } l = 1,\ldots,L;\ d = 1,\ldots D;\ k = 1,\ldots, K_{l,d})$

and $Z_k(l,d)$ is the k^{th} state variable in the d^{th} life domain on process level *l*; L denotes the number of different process levels; D is the number of different domains; $K_{l,d}$ is the number of state variables on process level l in domain d.

(**BS**(x); $0 \le x < x^*$) is called the history of the life course until age x*. (**BS**(x); $x > x^*$) is called the future of the life course after x*.

The state variables $Z_k(l,d)$ with their values span the multidimensional state space **Σ** of **BS**(x) at age x. A subset of **Σ** forms a sub-dimension of **BS**(x). For example, all state variables belonging to a certain domain d form the domain specific sub-dimension of **BS**(x), which might be denoted by **BS**(d,x). State variables related to a certain process level l form the sub-dimension of **BS**(l,x). **BS**($l_{(inner)}$,x) stands for the sub-dimension of the life course encompassing all inner-individual state variables.

The age x corresponds one-to-one to a time point t in calendar time and with c being the exact calendar time of birth it holds; x = t - c. The year C contains the date c, i.e. the year of birth defines the 'birth cohort' C. The calendar year in which the life course is observed at age x is called the 'period' P (Mayer & Huinink, 1990). We always have to take into account three time related references when we observe a certain biographical state, namely age x, time point in t in period P and the year of birth C.

The *biographical state* of individual i at age x is represented by one particular data point in state space **Σ**:

$\mathbf{bs}_i(x) = (z_{k,i}(l,d;x)\text{: } d = 1,\ldots,D,\ k = 1,\ldots, K_{l,d})$

where $z_{k,i}(l,d;x)$ are observed values in state variables $Z_k(l,d)$ at age x. The (complete) observed *trajectory* of the i's life course is given by

$(\mathbf{bs}_i(x),\ x > 0) = (z_{k,i}(l,d;x)\text{: } d = 1,\ldots,D_l,\ k = 1,\ldots, K_{l,d};\ x > 0).$

($\mathbf{bs}_i(x)$; $x_1 \ge x > x_2$) is called the observed sub-trajectory of i's life course between age x_1 and age x_2. ($z_{k,i}(l,d;x)$; $x_1 \ge x > x_2$) may be called the observed sub-trajectory of state variable $Z_k(l,d)$ in domain d on process level l between age x_1 and age x_2. ($\mathbf{bs}_i(d,x)$; $x_1 \ge x > x_2$) is the observed sub-trajectory in domain d. ($\mathbf{bs}_i(l_{(inner)},x)$; $x_1 \ge x > x_2$) is the observed sub-trajectory is the observed sub-trajectory of the inner-individual state variables of individual i. Similarly we can define sub-trajectories of other sub-dimensions of the life course. The sub-trajectory ($\mathbf{bs}_i(x)$; $0 \le x < x_1$) is called the observed history of individual i's life course until x_1 and the sub-trajectory ($\mathbf{bs}_i(x)$; $x > x_1$) is called for the realized future of i's life course after x_1.

A *life event* ev($Z_k(l,d)$,x) is defined as a shift or change in a discrete state variable $Z_k(l,d)$ on level l and related to domain d. An *episode* of the state variable $Z_k(l,d)$ is defined by the time interval between two events ev($Z_k(l,d)$, x_1) and ev($Z_k(l,d)$, x_2). The length of the episode – that is, the difference between x_2 and x_1 – is the *duration* of this episode. These definitions are generalizable to a multidimensional case including more than just one discrete state variable (sub-dimension). Then, we observe multidimensional (sub-)trajectories. Let us assume we observe two state variables Z^1 and Z^2 (for the sake of simplicity, we will skip all of the other indices). In this case, life events in Z^1 and Z^2 can be observed at different ages or at exactly at the same age. In the latter case, x_1 is equal to x_2 because Z^1 and Z^2 are synchronous events. The definition of episodes can now be related to both state variables – that is, it is defined by the time interval between two events in Z^1 or Z^2. This can be generalized to the case with more than two state variables, i.e. a sub-dimension **Z** of **BS**.

The definition of life events can be generalized to continuous state variables, say Z^1. Because an event is defined for a certain discrete point in time, one has to define for instance which change in Z^1 between two ages x_1 and x_2, $\Delta Z^1(x_1,x_2)$ is perceived as an event. For example, an event could be defined by the fact that $\Delta Z^1(x_1,x_2)$ becomes bigger than a certain threshold.

The complete trajectory or a sub-trajectory ($\mathbf{bs}_i(x)$; $x_1 \ge x > x_2$) of i's life course now can be defined as a continual sequence of episodes in the life course of an individual. From a substantive point of view, episodes are not only time intervals. We need to qualify them, and understand their nature, in order to get to a meaningful trajectory rather than just a series of neutral time intervals.

Next, we present formal representations of interdependencies related to time, domains, and levels, respectively. We provide detailed explications of some first-order interdependencies, and some examples of how second and third order interdependencies can be addressed formulaically.

[1] In this and the following sections, we indicate multidimensional vectors with bold characters.

Formal Representation of First-Order Interdependencies Related to Time, Domains, and Levels

Time-related interdependence

The history (**BS**(x); $0 \leq x < x^*$) of a life course until age x*, the present biographical status **BS**(x*) at age x*, and the future of a life course (**BS (x)**; $x > x^*$) of life course after x* are not independent of each other.

In a weak sense, time related interdependence means that there are sub-dimensions of **BS,** let us call them $\mathbf{Z}^1$, $\mathbf{Z}^2$, and $\mathbf{Z}^3$, including the same attributes or not, which hold for least two ages $x_1 < x^*$ and $x_2 > x^*$:

$$\text{cov}\ (\mathbf{Z}^1(x_1), \mathbf{Z}^2(x^*)) \neq 0 \text{ and cov } (\mathbf{Z}^2(x^*), \mathbf{Z}^3(x_2)) \neq 0,$$

for each x* with $0 \leq x_1 < x^* < x_2$. This includes the case that cov $(\mathbf{Z}^1(x_1), \mathbf{Z}^3(x_2)) \neq 0$.

In a strong sense, time-related interdependence means that there are sub-dimensions of **BS,** let us call them $\mathbf{Z}^1$, $\mathbf{Z}^2$, and $\mathbf{Z}^3$, including the same attributes or not, a function f_p on (part of) the history of the sub-dimension $\mathbf{Z}^1$ of the life course, $(\mathbf{Z}^1(x)$: $x_1 \leq x < x^*)$, and a function f_f on (part of) the future of the sub-dimension $\mathbf{Z}^3$ of the life course, $(\mathbf{Z}^3(x)$: $x^* < x \leq x_2)$, and it holds:

$$\text{cov}\ (f_p(\mathbf{Z}^1(x)\text{: } x_1 \leq x < x^*), \mathbf{Z}^2(x^*)) \neq 0 \text{ and cov } (\mathbf{Z}^2(x^*), f_f(\mathbf{Z}^3(x)\text{: } x^* < x \leq x_2)) \neq 0,$$

for each x* with $0 \leq x_1 < x^* < x_2$. Again this means that cov $(f_p(\mathbf{Z}^1(x)\text{: } x_1 \leq x < x^*), f_f(\mathbf{Z}^3(x_5)\text{: } x^* < x \leq x_2)) \neq 0$.

Simple examples of time-related interdependence are phenomena of auto-regression in one state variable Z over time, which might be due to different kinds of mechanisms (e.g., the power law in the case of cumulative processes). Besides methods of time series analysis, time-related interdependence can be formalized further and studied using mathematical tools for analyzing multidimensional non-linear dynamics (e.g., Bask & Bask, 2015; Box, Jenkins, Reinsel, & Ljung, 2015; Gilbert, 2008; Heath, 2000).

The issue of causality cannot be discussed here in detail. The interdependence between biographical states or state components may be causally explained in different ways. We speak of *state dependency* between a past and a present or future biographical state **BS** or sub-dimension **Z**, if there is a mechanism by which the present or future biographical state **BS**(x*) or (**BS**(x), $x > x^*$) is causally affected by stable states at least in a sub-dimension **Z** in the past ($x \leq x^*$). We speak of an *event- or trigger-effect* when there is a mechanism by which a life event regarding a status variable Z^1, i.e. ev(Z^1, x) at $x \leq x^*$, causally affects the probability of the short term occurrence of a life event of another status variable Z^2 (see also Blossfeld & Rohwer, 2002).

Interdependence between life domains

Weak interdependence between the domains d_1 and d_2 means that the following condition holds for a sub-dimension $\mathbf{Z}^1(d_1)$ of the domain-specific sub-dimension **BS**(d_1) and a sub-dimension $\mathbf{Z}^2(d_2)$ of the domain-specific sub-dimension **BS**(d_2) and for ages x_1 and $x_2 > 0$:

$$\text{cov}\ (\mathbf{Z}^1(d_1;x_1), \mathbf{Z}^2(d_2;x_2) \neq 0 \text{ for } d_1, d_2 = 1,\ldots,D.$$

In contrast, strong interdependence between the domains d_1 and d_2 means that the following condition holds for sub-dimension $\mathbf{Z}^1(d_1)$ of **BS**(d_1) and $\mathbf{Z}^2(d_2)$ of **BS**(d_2), functions f_1 and f_2, ages $x_{11} < x_{21}$ and ages $x_{12} < x_{22}$:

$$\text{cov}\ (f_1(\mathbf{Z}^1(d_1,x), x_{11} \leq x \leq x_{12}), f_2(\mathbf{Z}^2(d_2,x),), x_{21} \leq x \leq x_{22})) \neq 0 \text{ for } d_1, d_2 = 1,\ldots,D.$$

This means that sub-trajectories in domains d_1 and d_2 are correlated, whereas the age intervals for which the state variables are observed do not have to be equal. Again, the issue of causality is not part of the definitions. However, in connection with time-dependency and how processes in different domains affect each other, one can think of mechanisms based on event dependency or state dependency. Given that $x_{11} = x_{21} = x_1$ and $x_{12} = x_{22} = x_2$ (that is, we observe the same age interval), the covariance between the domain-specific sub-trajectories between x_1 and x_2 can be due to what in time series analysis is called 'co-integration' – meaning that states in different domains evolve in mutual equilibrium, except when there are temporary disturbances (Engle & Granger, 1987).

Interdependence across process levels

Weak interdependence between the processes on process levels l_1 and l_2 means that the following condition holds for a sub-dimension $\mathbf{Z}^1(l_1)$ of the level-specific sub-dimension **BS**(l_1) and a sub-dimension $\mathbf{Z}^2(l_2)$ of the domain-specific sub-dimension **BS**(l_2) and for ages x_1 and $x_2 > 0$:

$$\text{cov}\ (\mathbf{Z}^1(l_1;x_1), \mathbf{Z}^2(l_2;x_2) \neq 0 \text{ for } l_1, l_2 = 1,\ldots,L.$$

In contrast, strong interdependence between the processes on process levels l_1 and l_2 means that the following condition holds for sub-dimension $\mathbf{Z}^1(l_1)$ of **BS**(l_1) and $\mathbf{Z}^2(l_2)$ of **BS**(l_2), functions f_1 and f_2, ages $x_{11} < x_{21}$ and ages $x_{12} < x_{22}$:

$$\text{cov}\ (f_1(\mathbf{Z}^1(l_1,x), x_{11} \leq x \leq x_{12}), f_2(\mathbf{Z}^2(l_2,x),), x_{21} \leq x \leq x_{22})) \neq 0 \text{ for } l_1, l_2 = 1,\ldots,l.$$

As a result, sub-trajectories on levels l_1 and l_2 are correlated, but again the age intervals at which the state variables are observed do not have to be equal. The issue of causality is again not part of these definitions, and one can think of mechanisms based on event or state dependency.

Formal Representation of Second- and Third-Order Interdependencies Related to Time, Domains, and Levels

A second-order interdependency means that a non-random interrelation exists between two first-order interdependencies. These can be formalized as conditional covariances, but space limitations prevent us from doing so.

A weak version means that the occurrence and strength of the interdependence of state variables in one dimension of the life course cube (e.g., between domains) differs systematically with one or more relevant state variables in a second dimension (e.g., between different time points or process levels). In the case of time dependence, for instance, the concept of dynamic conditional correlations is important (e.g., Lebo & Box-Steffensmeier, 2008).

A strong version means that the occurrence and strength of the interdependence of sub-trajectories in one dimension of the life course cube (e.g., between domains) differs systematically with the (kind of interdependence between) sub-trajectories in a second dimension (e.g., between different time intervals or process levels).

Third-order interdependencies can be conceptualized in a similar way. That is, we can assume that interdependencies in one dimension of the cube (such as those between domains) are conditional on state variables, sub-trajectories, or even the kind of interdependence between sub-trajectories, in the two other dimensions of the cube (in this case, time and multilevel structure).

Finally, for illustrative purposes, we provide a representation of two central concepts: path dependence and anticipation. Again, this logic can be extended to other concerns in life course research.

Path dependency

A helpful "positive" definition of path dependency is given by Davis (2001, p. 19): "A path dependent stochastic process is one whose asymptotic distribution evolves as a consequence (function of) the process's own history." Davis also provides a "negative" definition referring to the mathematics of stochastic processes: "Processes that are non-ergodic, and thus unable to shake free of their history, are said to yield path dependent outcomes" (p. 19).

Path dependency means that the present state and the future sub-process in a sub-dimension of **BS**, called **Z** after time x*, depends on the history of the life course (**BS**(x); 0 ≥ x > x*) or a sub-dimension of it. Here, one can study the path dependency of the present state and futures states of **Z** or functions f of it. Consider a function f_p on the history of the life course until x*. With ε as a random error term, we assume path dependency if:

$f(\mathbf{Z}(x^*)) = f_p(\mathbf{BS}(x);\ 0 \geq x > x^*) + \varepsilon$ or

$f(\mathbf{Z}(x),\ x > x^*) = f_p(\mathbf{BS}(x);\ 0 \geq x > x^*) + \varepsilon.$

One also could look at the path dependency of the probability of life events in **Z**. We assume path dependency if:

$P(ev(\mathbf{Z},x^*)) = f_p(\mathbf{BS}(x);\ 0 \geq x \geq x^*) + \varepsilon.$

Instead of the probability P of an event, it is usually the transition rate r from Z(x*) to $Z(x^{*+})$ at time x* that is considered. Causally, path dependency can be due to state- and event-dependencies.

Anticipation

Anticipation means an individual i estimates the distribution of different future trajectories ($\mathbf{bs}_i(x)$, x > x*) of the life course, or sub-dimensions or sub-trajectories of it, based on their perceptions of both their past and present situations as well as their available experiences, knowledge, competences, and convictions **Exp**. New information is allocated and learning is updated, which may lead to better estimates of these distributions (Dennett, 2017). The possible impact of the i's behavior or i's planful action on the future and effects of path dependencies is also considered. Then, the (Bayesian) brain continuously guides our unconscious behavior and conscious decision-making. In case of the latter, an algorithm like the subjective utility model 'decides' how to behave or act in the present integrating the expected and discounted and more or less reliably anticipated future outcomes over time (Dehaene, 2014).

To formalize the anticipation process, we think a Bayesian approach is appropriate (e.g., Willekens, Bijak, Klabunde, & Prskawetz, 2017, p. S9). Let (**BS**(x); x > x*), (part of) the future of a life course (or a sub-dimension) simply be denoted by $\mathbf{BS}^{F^*}$ here. Let f_f be a function on $\mathbf{BS}^{F^*}$. **BS**(x*) is the present biographical status (or a sub-dimension). According to the Bayes-Theorem, one can use the following equation (for a special simplified example, see Griffiths & Tenenbaum, 2006):

$p(f_f(\mathbf{BS}^{F^*}) \mid \mathbf{BS}(x^*), \mathbf{Exp}) = (p(\mathbf{BS}(x^*) \mid f_f(\mathbf{BS}^{F^*}), \mathbf{Exp}) \cdot p(f_f(\mathbf{BS}^{F^*}) \mid \mathbf{Exp})) \,/\, p(\mathbf{BS}(x^*) \mid \mathbf{Exp})$

with the estimated posterior probability $p(f_f(\mathbf{BS}^{F^*}) \mid \mathbf{BS}(x^*), \mathbf{Exp})$, an estimated (or believed) conditional probability or likelihood $p(\mathbf{BS}(x^*) \mid f_f(\mathbf{BS}^{F^*}), \mathbf{Exp})$ and the estimated (or believed) prior probability $p(f_f(\mathbf{BS}^{F^*}) \mid \mathbf{Exp})$ given the prior knowledge **Exp**. The more appropriate **Exp** and the perception of **BS**(x*), the better the estimation of future developments because they are not stochastically independent from of **Exp** and **BS**(x*). The perception of **BS**(x*) itself could be modeled using the Bayesian approach of cognition (e.g., Willekens et al., 2017). If **Exp** is distorted by incorrect convictions that lead to biased estimates of the likelihood $p(\mathbf{BS}(x^*) \mid f_f(\mathbf{BS}^{F^*}), \mathbf{Exp})$ or the prior probability $p(f_f(\mathbf{BS}^{F^*}) \mid \mathbf{Exp})$, posterior distributions (anticipation) will also be distorted and decisions based on them might lead to unintended and unanticipated outcomes. However, we cannot go into greater detail here.

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