Design Considerations for Education Scholars Interested in Complex Systems Research

GWEN C. MARCHAND
University of Nevada Las Vegas

JONATHAN C. HILPERT
Georgia Southern University

As complex systems approaches to research gain a foothold in educational research, educational researchers may be faced with unique study design challenges. Studies that do not target appropriate levels of analysis or do not capture variable change over time at a fine enough granularity run the risk of missing complex, dynamic, and emergent properties that are the hallmark of complex system behavior. By taking into account context, multiple levels of analysis, and change over time complex systems approaches generate evidence for dynamic processes in education. This paper draws upon three example areas from educational psychology to illustrate important design considerations for conducting complex systems research in education. We discuss how complex systems designs can generate new insight for areas of study such as how psychological constructs influence learning, classroom dynamics, and teacher-student interactions.

Education researchers have recently begun to incorporate complex systems methods into a cogent research paradigm for studying education phenomena (Jacobson, Kapur & Reimann, 2016; Kaplan & Garner, 2017; Koopmans & Stamovlasis, 2016). However, little guidance is offered to scholars for making *a priori* decisions about how to design complex systems educational research. Framing educational research within a complex systems perspective requires scholars to closely re-examine the ontological assumptions underlying their focus of study (Hilpert & Marchand, 2018), expand conceptualizations of educational phenomena to explicitly include characteristics of complex systems (Jacobson et al, 2016), and design studies that are rooted in complexity perspectives (Koopmans & Stamovlasis, 2016). A challenge that researchers face in this process is making decisions about where, and how closely, to look for evidence. Because complex systems in education involve dynamic micro processes that produce emergent, complex system behavior, what to study spans multiple levels of analysis and changes over time and across context. Studies that do not target appropriate levels of analysis or do not capture variable change over time at a fine enough granularity run the risk of missing complex, dynamic, and emergent properties that are the hallmark of complex system behavior. By taking into account context, multiple levels of analysis and change over time, complex systems approaches generate evidence for the dynamics of psychological constructs, classrooms and teacher-student interaction that cannot be unearthed with linear methods that are traditional in education research.

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To address this topic, we first define our view of complex systems research in education. We then draw upon three example areas from educational psychology to illustrate important design considerations for conducting a complex systems study in education. Traditional methods for studying these three example areas have often failed to include contextual affordances or constraints in research design, failed to consider how decisions about timescales influence understanding of dynamic processes, and failed to include data collected and analyzed at multiple levels of analyses (micro and macro constructs). The example areas include psychological constructs that influence learning, classroom dynamics, and teacher/caregiver-student interactions. Our discussion of these examples illustrates conceptually how consideration of context, levels of analysis, and time produces findings not possible using traditional linear methods. We conclude with final remarks about emerging trends in complex systems research that have interesting implications for education researchers.

Complex Systems Educational Research

Defining complex systems research. We align with a definition of complex systems as a collection of interacting components that compete, cooperate, or interfere with each other to give rise to complex behavior (Mitchell, 2009; Strogatz, 1994). A complex systems perspective on education research requires scholars to accept a set of ontological assumptions that are different from those of the dominant research paradigms in education (Wan, 2011). Relationships among systems components change in strength and direction over time, vary from context-to-context, and depend on other components in the system. Complex systems are by definition, then, hierarchical, emergent, and multi-scale across both levels and time (Li, Zhang, Ge, & Liu, 2004; Mitchell, 2009; Sawyer, 2004). For example, broadly speaking education can be conceived of as a hierarchical complex system, composed of students, nested with classrooms, nested within schools, nested with districts, and so forth. Change within each of these levels may occur at different scales. For example learning for a single student may progress faster or slower than the overall class, requiring different time scales of analysis to show change. Furthermore, learning *emerges* from a complex combination of interactions between teachers, students, symbols, and objects, and thus no single level of an educational system can be perfectly reduced to the components of the level below.

Researchers applying complex systems approaches seek to move beyond reductionist models in an attempt to seek out complex patterns. Rather than function as a kind of testable theory, a complex systems ontology drives method by establishing overlapping domain general characteristics, namely complex, dynamic, and emergent qualities, to guide exploration. Because complex systems are by nature constantly evolving, a critical starting point for researchers embarking on a new research project is to describe the system of interest (Davis & Sumara, 2006). Along these lines, education scholars can benefit from investing in deep conceptualizations of their phenomena of interest to more fully describe their phenomena as contextually specific, hierarchical, and multi-scaled across time before engaging in more advanced modeling techniques. System conceptualization should include (a) how phenomena may interact with different systems or contexts that impose affordances or constraints on the focal system (b) how a system manifests at different levels of analyses and (c) which timescales are appropriate to capture complex system characteristics (Koopmans & Stamovlasis, 2016; Overton, 2013).

Why does education need complex systems research? Valisner (2008) defines education as the process of setting up conditions for a developing person to be open to innovation or change. This definition can be interpreted such that education includes the study of the developing person in a developing context (Turner & Patrick, 2008). In educational research, regardless of the unit of analysis (e.g., district, school, classroom, person) data by which to make ultimate judgments about the effectiveness of educational endeavors typically originates with the learner, most often students. And, this is often where analyses end, with analyses of group differences in student outcomes (see Koopmans, 2014 for discussion). However, as others have argued, this approach to educational research has limited utility for understanding the conditions that facilitate learner development (Kaplan & Garner, 2017; Koopmans & Stamovlasis, 2016; Langer, 2009) or in other words, how changing contexts and changing individuals interact to manifest some kind of new outcome for the context, the individual, or both.

The field of psychology has paved the way for rich and varied approaches to investigating intra-individual development, particularly through developmental systems theory (see Molenaar, Lerner, & Newell, 2014 for a history), which posits that human development is the product of context sensitive and contingent interacting influences (Molenaar & Nesselroade, 2014). Studies grounded in this theory and its derivatives have yielded innovative methods for testing assumptions about dynamic processes, determining systems limits provided by contextual influences, and identifying conditions leading to sudden shifts in behavior, to name just a few (Molenaar & Newell, 2010). However, despite considerable crossover in areas of interest and focal outcomes, few of these theoretical or methodological approaches have found their way into educational research (but see Hilpert and Marchand 2018; Jacobson et al. 2016; Kaplan and Garner 2017; Koopmans and Stamovlasis, 2016). In our experience, this limited translation between fields is likely less to do with educators lacking a view that education and human learning is complex or multiply influenced, but more to do with graduate training rooted in linear research design and analytic approaches coupled with the dominant value of a single educational practice or intervention that will work in similar ways for large groups of students or teachers (Berliner, 2002; Harris, 2018).

Certain fields in education research, such as educational psychology, have developed primacy of particular research paradigms, such as carefully controlled experimental approaches focused on between-subject factors with the individual as the sole unit of analyses. As these methods gained dominance, the factors that emerged as important for design considerations excluded context, multilevel phenomena, or dynamic interactions that led to the state of the system at the point of entry of study and give rise to emergence. The research design process from a complex systems perspective depends on explicit considerations about the point in time to begin a study, the spacing of measurement points, the rates of change in an educational process of interest, and so forth. Commonly, in educational research, starting points for beginning data collection, or initial conditions for the focal system, may be arbitrarily defined depending on a variety of factors that are only tangentially related to the constructs of interest, including convenience, school schedules, and school district policies about research, and may not reflect a meaningful starting point for research for the focal system. In fields where complex systems approaches to research have gained a foothold, it has become routine for empirical researchers to establish the unique mechanisms for emergence and change within each level of the system, determine stability conditions for complex systems, and identify how phenomena are correlated across levels and temporal scales (Li et al., 2004). Much education research has not yet adequately identified variables at different levels of a system or the granularity of time at which change in systems behavior may be determined for many important areas of study.

What is typical research practice in educational psychology? To illustrate the promise of complex systems research approaches we focus on the subfield of educational psychology. We consider three common areas of research: psychological constructs that influence learning, classroom dynamics, and teacher/caregiver-student interactions. Research on learning includes a wide range of constructs including *a variety of motivational factors*, such as students' self-beliefs, values, and goals (Graham & Weiner, 2012; Pintrich, 2003), as well as student engagement, the manifestation of motivational states (Skinner, Furrer, Marchand, & Kindermann, 2008). For decades, research on student motivation was dominated by cross-sectional studies, or at best, studies spanning two time points. Motivation has often been measured by global self-report scales in naturalistic settings or following a carefully controlled lab-based intervention. These studies often reveal small effects using variable-centered analyses (Hilpert & Husman, 2017), leading scholars to voice concern that the research results rarely reflect what is believed to be a rich source of influence on student learning (Marchand & Gutierrez, 2017). Recently, scholars in the field have begun to develop design-based studies and have advocated for alternative research paradigms that might more accurately reflect motivational processes and dynamics, particularly as they are bound by contextual conditions and how they vary over different timescales (e.g., Kaplan, Katz & Flum, 2012).

A second example area takes a more explicit conceptual focus on a different level of the educational system: *the classroom*. Scholarship on classroom dynamics grown to broadly include research on classroom-level properties, such as classroom goal structures or collective self-efficacy (Meece, Anderman & Anderman, 2006), and studies of peer groups or collaborative learning (Laninga-Wijnen, Ryan, Harakeh, Shin & Vollebergh, 2018). However, despite conceptual descriptions that tend toward a systems conceptualization (e.g., bioecological theories/Bronfennbrenner & Morris, 1998), much research has exported individual-variable centered approaches to the study of classroom behaviors. Studies may include individual perceptions of a classroom characteristic, perceptions of personal characteristics aggregated to the group level, perceptions of supportive others in the classroom, or observed characteristics of group interactions often aggregated to a single indicator. Scholars have just recently begun to include designs that would allow for the investigation of simultaneous characteristics of the individual and the group or interactions amongst levels within the group (e.g., Ryu & Lombardi, 2015). The nature of self-organization within classrooms and the emergence of macro properties from group dynamics that might be ontologically distinct from individual characteristics is a nascent topic in this field (Stamovlasis, 2016).

Finally, *teacher-student interaction* is a growing area of study in educational psychology. One way that teacher-student interactions are operationalized within educational psychology is as teacher-student relational quality (Hughes & Kwok, 2007). Researchers have consistently found effects of positive teacher-student relationships on student socio-emotional outcomes (Stroet, Opdenakker, & Minnaert, 2013) and teachers are posited to have a strong influence on student academic experiences and learning outcomes of diverse student populations (e.g., Gray, Hope & Matthews, 2018). However, despite the acknowledgement that the quality of teacher-student relationships likely emerges from a history of many moment-to-moment transactions that are constrained by individual and contextual characteristics and that these transactions in turn contribute to a relatively stable relational quality that is emergent and jointly held (Pennings, van Tartwijk, Wubbels, Claessens, van der Want & Brekelmans, 2014; Pianta, Hamre & Stuhlman, 2003) research designs rarely allow for questions of relational development and dynamics to be asked. Teacher student interactions are often assessed globally in terms of relational quality or self-reported in terms of instructional or motivational support (Hagenauer, Hascher & Volet, 2015).

Design Choices

When making decisions about research design, education scholars are frequently guided by practical research goals and outcomes. Often the goal of research is to better an outcome, such as to improve learning or create more equitable learning environments. Further, researchers are often faced with finite resources and must necessarily impose feasibility limits on the study of naturalistic systems. The number of variables that can be observed, and the granularity at which they can be collected, is limited by technology, resources, and time. However, there are many levels of analysis and time scales at which phenomena unfold (Koopmans, 2016), and contexts or environments within which educational phenomena interact. Thus, what to target for research is often use-inspired (Sloane & Gorard, 2003). By that, we mean that what matters for any given project is what is intended for its use by stakeholders, whether they be other researchers, practitioners, policymakers or someone else. Those intentions must fall within the feasibility limits of any given study. From a use inspired perspective (i.e. Stokes, 1997), researchers need to make informed choices about variables that span levels of analysis, time, and context in order to meet research goals and feasibility requirements.

Context. The environment or context is deemed important in education research for defining the circumstances under which systematic observations will occur. Chan (2001) argues that the distinction between a system and context is artificial. She suggests that systems do not adapt to different environments, rather systems co-evolve with other systems in a larger ecosystem. In this way, the extent to which a researcher can expand outward or drill down conceptually is limitless. Thus, when defining context the researcher is faced with an arbitrary decision about where to establish contextual boundaries for a given study. The boundaries must be defined within the context of the research objectives. For example, if the objective is to improve student collaborative learning, the context may be defined as a collaborative group in a classroom. If the goal is make the classroom more equitable, the context may be defined as many classrooms within a school. From here, researchers must consider the appropriate affordances and feasibility limitations of a given context. An affordance is the resources or support offered from a given environment, including the ability to perceive and use them. Consideration of affordances offers the researcher the opportunity to examine the micro level system critical variables that contain important information about system dynamics, as well as to examine the feasibility limitations of observing and measuring those variables. For example, if improving collaborative learning is the goal, then student conversation in their collaborative groups may contain system critical information about collaborative dynamics. Garner and Russell (2016) note that context or environmental influence can often lead systems behavior to reorganize in response to environmental perturbations. These contextual conditions can act as control parameters for system behavior (Kaplan & Garner, 2017), which are likened to boundary conditions for the system. In education, the limits to intra- or inter-personal systems behavior in response to control parameters has not been well defined or explored, particularly when multiple control parameters may interact in ways that radically alter behavior (Kaplan & Garner, 2017).

Levels of analysis. Levels of analysis are most often referred to when scholars are interested in describing the nested nature of complex systems (Simon, 1962). Like cells within organs within bodies, educational phenomena can be captured at multiple levels of analysis to address varying intra and inter personal characteristics. Students have competing cognitive and affective processes that shape how they interact within interpersonal groups, which in turn influence overall classroom level characteristics, which make up schools, and school districts, and so forth. For example, researchers interested in self-regulated learning may target physiological stress experiences that may occur during learning; moment-to-moment subjective experiences of motivation or emotion during learning tasks; metacognitive strategies used to monitor learning at a more macro level; group interactions related to problem solving; class supports or climate related to facilitation of self-regulated learning; family dialogue related to study skills; and more. For feasibility reasons, empirical researchers typically target at most two or three levels at which to collect data. Because the mechanism between levels is emergent (Sawyer, 2004), unique levels represents ontologically distinct components, i.e. a higher level cannot be reduced to the sum of its parts (Bunge, 2000). Yet, the dynamic processes within each level are constrained by interactions with other levels. And, the macro level behavior that emerges from interactions within a system serves as a component within the higher-order systems (Marion & Schreiber, 2016). When using a complex systems framework, the researcher may consider the multiple environments in which the system operates within a single level *and* if the emergent behavior is repeatable, or would "hold" in each permutation of the environment. For example, individuals may be a part of multiple dyads or groups within a single learning environment, or individuals may swap in and out of these situations. Or, as in the case of discipline-based research, individuals may move between parallel structures with different topical domains, or those domains may be populated by different groups of students. For instance, a middle school student may attend six different classes through the course of a day, each with a distinct domain and social structure, but which are conceptually at the same level of analysis (the class). Researchers may ask themselves if the macro characteristic can be measured the same way across contexts at parallel levels. Or, they may consider how parallel contexts may afford different demand characteristics, influencing the dominance of the variables interacting at the micro-level (i.e., multiply realized).

Time. Change over time within different levels of a system may occur at different time scales. For example, individual change may be faster than social change, so different time scales may be required at different levels to understand complex system behavior (Ram et al., 2014). Timescales have two fundamental properties: they differentiate the temporal continuum into units of different sizes that can be used to determine observation and aggregation intervals; and they have either a socially constructed or objectively determined nature (Zaheer et al., 1999). Timescales relevant to change in human learning and psychological development have been described in numerous ways, ranging from evolutionary time to individual timescales for the development of specific psychological processes (Lewis, 2000; Lewis & Liu, 2011). However, complex systems education researchers have noted the absence of the deep consideration of time and timescales in education research (Koopmans, 2016), particularly when education researchers attempt to extrapolate findings from cross-sectional between-subject designs to within-person views of development and change in learning (Steenbeek, van Vondel, & van Geert, 2017). However, social scientists in other fields have explicitly incorporated multiple conceptualizations of time and associated timescales to apply in research design. Molenaar and colleagues' work on ergodic theory (2008, 2014) in psychology states the ergodic assumption is that cross-sectional research findings from groups generalize to the within-person behavior of individuals. Koopmans and others (e.g., Hamaker, 2012; van Geert, 1997) ask readers to consider what can be learned about patterns of behavior and change in education from analyzing how time contributes to behavioral variation for individuals. Across the levels of the education system, in many cases for change to occur, actors exist in a state of disequilibrium, the extent of which can be indicative of adaptive system functioning, though change can also be linear (Hilpert & Marchand, 2018; Koopmans, 2016; Valsiner, 2008). If researchers conceptualize time as invariant, they assume it is irrelevant. However, arguments against this proposition are strong (Molenaar & Nesselroade, 2014). Contributions from dynamical systems research remind scholars that phenomena often only appear stable while internal processes that are not being measured work to move the system towards change events, which may be dramatic in fashion (Koopmans, 2016; Molenaar & Nesselroade, 2014). Timescales and methods to capture periods of transformation must be carefully designed, as the memory of the system may exist on long or short time scales, thus making it difficult to predict future behavior from past behavior if the behavior is variable over different time scales (van Geert & Steenbeek, 2005). To begin to address these shortcomings, researchers must give deeper consideration to time when developing their research studies. At times, in education, investigation of change processes are rooted in convenience or structural boundaries (e.g., the beginning and end of a semester). Education scholars can forefront time as a critical element in creating boundaries around the system. They can do this by drawing upon pilot data, theoretical formulations about development and change, previous empirical research that includes time as a design element and yields findings that could act as a platform for understanding change processes of the phenomena, simulation studies, or even cross-sectional studies with diverse age populations that could indicate differential change processes at different stages of development.

Examples for Educational Psychologists: Cases of Complex Systems Research

In the following sections, we illustrate how studies that approach educational phenomena from a complex systems perspective explicitly investigate contextual constraints on system behavior, account for micro and macro behavior of the system, and include systems-defined timescales for analyses. We use these examples with the intent of illustrating how these design decisions yield distinct information from that which could be garnered from traditional approaches to the study of psychological constructs, classroom characteristics, and teacher/caregiver-student interaction. For each example, we focus on context, levels of analysis, and time, and conclude with some comments about the uniqueness of the findings.

Psychological constructs that influence learning. Delignieres, Fortes, and Ninot (2004) utilized fractal analysis methods, a form of nonlinear time series analysis, to examine the dynamics of self-esteem and perceptions of physical self. The purpose of the study was to examine the stability of self-esteem and other related self-perceptions, widely considered as static personality traits by psychologists uses cross sectional and other non-intensive methods. The *context* of the study was the daily morning and evening routines of four adult subjects who agreed to participate. The participants were asked to complete a personality inventory (i.e. Likert scale ratings) twice a day for 512 consecutive days. The *levels of analysis* in the study were the underlying cognitive system at the micro level, and the emergence of personality traits at the macro level. The system critical variable was the dynamical behavior of the time series measure, which was treated as emergent evidence of the underlying push and pull of the unobserved cognitive system at the micro level. Making inferences about the nature of the underlying system using the nonlinear behavior of intensive data taken from the system is a common technique in nonlinear time series analysis. The *time scale* for the study was in days, where measures were taken twice a day for a year and a half, a very fine granularity for personality studies. Result indicated long range fractal correlations in the self-esteem and physical self-data. Because fractal behavior at the macro level can be regarded as the outcome of a complex system in a critical self-organized state, the authors conclude that self-esteem and perceptions of physical self may be better characterized as emergent outcomes as opposed to stable personality traits.

Classroom dynamics. Shin (2018) uses RSIENA, a form of longitudinal network analysis, to examine helping seeking among friends as a form of self-regulation in the classroom. The goal of the research is to examine how classroom climate and student propensities shape the formation of help seeking ties between friends. The *context* of the study was 26 fifth and sixth grade classrooms in four elementary schools in South Korea. Using a survey technique, students were asked to nominate their friends in the class, and then rated the quality of their help seeking and the classroom climate on Likert scale indicators. The *levels of analysis* in the study were student characteristics (i.e. race, gender, achievement, help seeking, etc.) at the micro level and the ties between students, or the friendship networks, at the macro level. Classroom climate was a contextual affordance modeled in the analysis. The *time scale* for the study was an entire semester, where micro level data was collected pre and post and the macro level data represented change in friends' ties over the semester. The change in friendship help seeking over the semester revealed an emergent pattern of influence and selection effects, where students were both more likely to seek and receive adaptive help if they were adaptive in their own habits as well as if the classroom climate supported adaptive behavior. The findings highlight the importance of both endogenous (friendships) and exogenous (classroom climate) effects on adaptive self-regulatory behavior.

Teacher-student interactions. Pennings and colleagues (2014) utilize state space grid analysis, a form of nonlinear dynamical modeling, to examine teacher-student relationships in the classroom. The *context* of the study was eight secondary education classrooms, across a range of subjects. The authors code thirty minute video recordings of classroom behaviors exchanges during a typical lesson on a moment to moment basis. The codes are based on a continuum of agency (i.e. dominant behavior) and communion (i.e. supportive behavior) to describe the behavioral exchanges. The coded data produce a time series of hundreds of observations for each teacher over the half hour lesson. To establish *levels of analysis*, the authors operationalize the observed real-time interpersonal dynamics between students and teachers as the micro level system critical variable. They operationalize stable patterns (i.e. attractor states) in these dynamics on a state space grid of agency and communion as the emergent, macro level system critical variable. At the micro level the *time scale* of observation was in seconds and at the macro level it was in half hours. Although the micro level interactions among subjects were unique across classrooms, they observed repeatable instances of emergent patterns in interpersonal dynamics at the macro-level that could be classified as teacher profiles at a higher time scale/ level of analysis. Findings indicate that the interpersonal teacher student dynamics can be understood as the process of development for emergent teacher interpersonal characteristics. Implications are discussed for preparing teachers to create positive classroom climates by establishing good teacher-student relationships.

Concluding Thoughts

In the discussion of design characteristics and examples of studies in typical areas of educational psychology, findings emerge that distinctly diverge from findings generated by traditional methods used in educational research. Psychological constructs that influence learning vary moment-to-moment as opposed to being stable personality characteristics, as they appear in studies that apply global measures and widely spaced time points for data collection (Deligniéres et al., 2004). Classroom dynamics surrounding peer networks and help seeking self-organize around personal characteristics and contextual conditions and student group interaction is not driven only by personal interests or only by contextual input, in contrast to much of the research on classroom dynamics (Shin, 2018). Interpersonal relational styles or patterns teachers leverage in the classroom emerge from many different patterns of micro-level interactions between teachers and students; teacher supports are not unidirectionally provided and determined by teacher characteristics (Pennings et al., 2014). These examples clearly illustrate the rich potential for complex systems approaches to educational research to provide information that is distinct from traditional studies, and this begins with asking different questions (Hilpert & Marchand, 2018).

As we develop a landscape of complex systems research, we look to other fields with richer histories in complex systems applications for guidance in conceptualizing and framing research (e.g. Urban, Osgood, Okamato, Mabry & Lich, 2014). In education, we also have characteristics in terms of the wide range of informal and formal contexts where learning occurs, the multiple structural and human systems that interact, and the range of different timescales for systems to unfold that could be leveraged to prospectively contribute to the development of theory and method that may be of interest to other fields and disciplines working within complex systems frameworks. We urge interested education scholars to attend to emerging work across disciplines and consider how education theory and research may be informed by this work and also how educational research may contribute to emerging ideas. As researchers work to define their system, they might consider if knowledge or learning systems have different "lifespans" or how social constructions of educational structures create timescales and how these timescales interact with individual learning at different points in development; or what the gain and loss processes and timescales for different learning and interpersonal relational systems within the educational system may be and whether these gain and loss processes change with age and development. Would we understand learning within the socially bound system of formal education differently if we developed theory and research to consider different timescales and interacting time scales?

Complex systems scholars have written many excellent texts about theory, approach, and analyses in complex systems science (e.g., Bar-Yam, 2003; Mitchell, 2009). It is clear that complex systems approaches to research generates findings that can generate insight into how learning processes unfold over time and within contexts. The research community of complex systems researchers in education, though small, have contributed excellent studies that can help educators think differently about their topics of concern. Yet, why haven't these considerations gained greater momentum to date in the empirical research generated by educational researchers? As noted by Wood (2014), systems approaches tend toward the multidisciplinary, which requires translational language and collaborative team science to gain momentum. Wood communicates an anecdote of a colleague who asked the question of where to begin when thinking about embarking into complex systems research. He mistook her question to mean, how do I start the research? But what she meant by the question was, how do I start thinking about the complexity of the system I want to study? Considering context, levels of analysis, and time as key design characteristics can facilitate this process.

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About the Authors

Gwen C. Marchand is an Associate Professor in Educational Psychology at the University of Nevada Las Vegas and the Director of the UNLV Center for Research, Evaluation, and Assessment. Her current research interests include the study of student engagement and classroom systems from a complex systems perspective and the development of teacher competencies to support student motivation in middle school science. Correspondence: gwen.marchand@unlv.edu

Dr. Jonathan C. Hilpert is an Associate Professor of Educational Psychology in the College of Education (COE) at Georgia Southern University. His research interests include student motivation, engagement, and interactive learning; complex, emergent, and dynamic properties of educational systems; and knowledge construction of complex scientific phenomena. Correspondence: jhilpert@georgiasouthern.edu