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A Complexity Approach Toward Mind–Brain–Education (MBE); Challenges and Opportunities in Educational Intervention and Research

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ABSTRACT— In the context of an educational or clinical intervention, we often ask questions such as "How does this intervention influence the task behavior of autistic children?" or "How does working memory influence inhibition of immediate responses?" What do we mean by the word *influence* here? In this article, we introduce the framework of complex dynamic systems (CDS) to disentangle the meaning of words such as *influence*, and to discuss the issue of education and intervention as something that takes place in the form of complex, real-time, situated processes. What are the applied implications of such a CDS framework? Can we use it to improve education? Five general principles—process laws—are introduced, which can be used to guide the way we formulate research questions and methods, and the way we use the results of such research. In addition, we briefly discuss a project in progress, in which we ourselves attempt to apply the process laws that govern educational activities. Finally, we report about a discussion about the usability of the process laws, both in educational research and in the classroom, as was held during our workshop at the Mind, Brain, and Education Conference, November 2014.

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INVESTIGATING EFFECTS AND INFLUENCES: THE VIEWPOINT OF COMPLEX DYNAMIC SYSTEMS

In the context of mind, brain, and education (MBE), researchers and educators often ask questions such as: "How does executive functioning influence school results?" "What is the effect of a particular training program on math performance?" "How does maturation of the frontal lobes influence children's decision making?" It is often taken for granted that such questions have an obvious, "natural" meaning. After all, executive functioning is an important cognitive function, and it is highly likely that it influences—that it has an effect on—school results, the question only being to what extent it actually does so. In addition, it is also taken for granted that such questions can be answered by doing research in accordance with the standards of good research practice, such as experimental studies with control groups, or randomized controlled trials with big representative samples.

In contrast with the often tacit assumptions that the nature of the questions and the way of answering such questions by means of scientific research are relatively obvious, we contend there is no one-size-fits-all answer to how to formulate researchable questions in MBE, and how to apply the results of research in educational practice. The answers to the preceding questions—those on the effects of one property on another as well as those on how to answer these questions scientifically—depend on what we believe about "the way the world is." Much prevailing research believes that we can understand issues at the intersection of mind, brain, and education by understanding how properties, which are conceived of as variables, are related to other properties, that is, to other variables. Much prevailing research also believes that we can treat some properties as independent and others as dependent variables. It is commonly assumed that the relationship between an independent and a dependent variable is represented by a statistical association between those variables across the population, for instance, a correlation between the levels of executive functioning and school performance in a representative sample of 5-year-olds. These assumptions have proven to be useful in contexts where the target of the research question is the population, or differences between populations (e.g., a population being subjected to a particular educational intervention in comparison to a population having been given "teaching-as-usual").

However, it is also widely—and often tacitly—believed that once you found such relationships in the form of group-based correlations, you can apply them to the individuals in your group (for instance, the group effect of an intervention applies to every individual in that group plus or minus basically random variation). This is a very important belief because it connects research results to educational activities that take place in individual contexts, for example, ongoing teacher–student interactions.

The bad news is that there is a growing body of statistical, theoretical, and empirical research showing that this latter assumption is wrong. Take for instance an educator who is teaching a class of 5-year-olds. This teacher is immersed in a concrete, real-time, and ongoing process of asking questions and reacting on answers given by the children, organizing and guiding activities, monitoring and maintaining the order in the class and so forth. Our point is that questions, methods, and answers based on a look from "above," that is the population level, and the big samples that represent particular populations, are of a different kind than questions, methods, and answers originating from the look from "within," that is to say from the level of individual, concrete processes (Molenaar & Campbell, 2009; Rose, Rouhani, & Fischer, 2013). The answers from one perspective cannot be simply plugged into the questions from the other perspective, which is the perspective of real educational processes. This point of view specifically implies that new approaches to research are necessary: if research is aiming at making statements about processes—that is, events evolving over real time in concrete contexts—it must begin by looking at the world from the perspective of such real-time, concrete processes that occur with individual teachers, students, or classes.

In order to understand the processes that occur in real educational interactions, the world of MBE should be conceived of as a complex dynamic system (CDS), which must be understood and investigated as such. A CDS is a system of processes that operate on various scales of organization, from policy/political levels to the organization of a concrete student–teacher interaction, and back (van Geert & Steenbeek, 2014). These processes occur on various intertwining timescales ranging from the short-term time scale of real-time, educational activities to the long-term time scale of learning and development. A CDS consists of many components (e.g., mind, brain, and education components), many of which interact, that is, influence one another over time. These interactions lead to self-organization, that is to say, they lead to the spontaneous emergence of attractors. An attractor can be defined as a specific self-sustaining state to which the system spontaneously moves as a consequence of the interactions among components.

Understanding CDS (e.g., a particular teacher–group of students; Steenbeek & van Geert, 2013; van Geert & Steenbeek, 2008) implies that we start from the idea that systems are characterized by their processes, that is, by how they change, fluctuate, or remain the same over time. Processes are mostly nonlinear, characterized by typical fluctuations, eventual temporary regressions and discontinuities and by the fact that effects are very often not proportional to the strength of their causes (think about the effect of an educational intervention). Processes are mostly idiosyncratic, that is, they show typical individual differences implying that most processes differ quite dramatically from the "average" trajectory obtained by aggregating over many individual ones. In order to understand CDS in education, we can use a number of general principles, process laws, which we can use to guide the way we formulate research questions and methods, and the way we use the results of such research. Below five process laws are described which we are articulating here based on our own work and that of others in the field (Steenbeek & van Geert, 2013; van Geert, 2009).

PROCESS LAWS

The first process law is that components in a process influence each other, and, in doing so, form the process. A concrete teaching–learning process, for instance, emerges from the interactions in the entire educational context, but in particular they result from the reciprocal interactions between the student and his or her teacher. For instance, the student's help-seeking behavior has an influence on the teacher's help-giving behavior, which on its turn influences the student's help-seeking behavior. Also on the level of the participating individuals—for example, the student—we may distinguish a system of mutually influencing components: a student's cognition, motivation, and emotions for instance, mutually influence each other in shaping the behavior and emotions that this student will show. The same applies to the teacher.

The second process law is the law of iterativity. Iterativity means that what happens in the next step in the process depends on the preceding step. For instance, the actions (and emotions) of the student on the present moment are

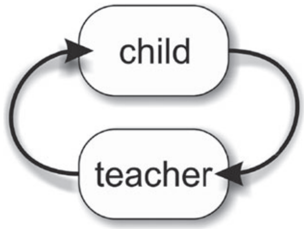

Fig. 1. The interaction between a teacher and a student is an example of an iterative, dynamic loop.

influenced by the actions (and emotions) from the previous moment. Iteration is an important mechanism of change. The fact that learning takes place in the form of iterative steps can be modeled as a series of computational operations, in which the output of the preceding operation is the input of the next one (e.g., van Geert, 2014).

With regard to external influences, iterativity implies that the nature and strength of this external influence depends on the current state of the process (note the definition of nonlinearity, implying that effects are not always proportional to their causes). For instance, the effects of a particular step in an intervention to enhance children's executive functioning depend on the child's current activity and how this activity assimilates this intervention step. Figure 1 shows the iterative character of the interaction dynamics between a student and his teacher during an instruction session: each previous action of the student has an influence on the subsequent (re-)action of the teacher, and vice versa (e.g., Guanglu, 2012). Over time, each instruction session has an influence on the subsequent instruction session of this student–teacher pair.

According to the third process law, this cyclical pattern takes place on various interdependent time scales. In a CDS, all levels of the developing system interact and consist of nested processes that unfold over many time scales, from milliseconds to years (Lewis, 2002; Thelen & Smith, 1994; for an application to brain development in an educational context, see Westermann et al., 2007; for an application to a learning–teaching process, see Steenbeek, Jansen, & van Geert, 2012). This process law says that it is important to study the mutual relationship between real-time characteristics of short-term processes and those in long-term development, which indicates that causality must be conceived of as having a cyclical (or reciprocal) character.

The fourth law is that processes show intrinsic variability, that is, intra-individual variability which can be defined as: "differences in the behavior within the same individuals, at different points in time" (van Geert & van Dijk, 2002, p. 341). While intra-individual variability is traditionally treated as measurement error, which is extrinsic, that is, independent of the observed phenomena, a CDS approach treats it as a source of information about the underlying developmental process (e.g., Meindertsma, van Dijk, Steenbeek, & van Geert, 2014). Frequent sampling is necessary because "sampling at wide intervals makes change appear more abrupt than when sampling is more frequent, because it often misses short-term regressions and periods of high variability" (Flynn & Siegler, 2007, p. 107).[1]

The fifth law says that in processes characterized by the phenomena described in the preceding laws, self-organization and attractors emerge spontaneously. An attractor is a state in which the components are such and interact in such a way that their properties and interactions become self-sustaining. Attractor states result from the developments in the system which self-organizes, and are not determined by an external force. The educationally ideal attractor state is that of continuous change toward a finally self-sustaining educational goal level, established by a smooth coupling between the teacher's guidance and instruction and the students' learning and performance. In reality, educational attractor states are often far from ideal, and sometimes even undesirable. For instance, it is possible that a particular system of teacher and student components and interactions self-organizes into an attractor state in which the participants lock each other up in self-sustaining suboptimal performance levels, consisting of poor learning performance in the student and poor guidance and teaching performance in the teacher (e.g., Steenbeek & van Geert, 2013). Particular student(s)–teacher systems—or MBE systems—can have more than one attractor state, and they may switch from one attractor to another as a consequence of the way the system reacts to an external cause (a perturbation, in the jargon), or as a consequence of the intrinsic dynamics of the system—for example, cycles of high-level and low-level cognitive performance during instruction sessions (e.g., van der Steen, Steenbeek, van Dijk, & van Geert, 2014).

Important questions for education are: can educators create conditions for "ideal" educational attractor state? or: how can we change unwanted attractors into more desirable, educationally more effective states, given that we must, by necessity, act in accordance with the process laws described above? In the next section, we will briefly discuss a "project in progress," in which we ourselves struggle with these questions and the laws that govern our educational activities.

STUDY OF A STUDENT WITH AUTISM AND HIS TASK ORIENTATION AND COMMUNICATION: AN EXAMPLE OF "WORK IN PROGRESS"

The aim of this study, which is currently in the pilot phase, is to intervene in such a way that a child with an autism spectrum disorder (ASD) can learn task-related behavior and communication skills in interaction with an adult (e.g., teacher), in order to improve self-guidance in school learning and performance. That is, his current task-related behavior and communication is an attractor we consider undesirable and that we wish to replace by a new one that is more beneficial for learning and satisfying for all participants involved.

Over the course of a year, every 2 weeks, 1-hr sessions take place in our play and learn lab. A session consists of six phases simulating different activities during a school day. The focus of the intervention is on specific learning–teaching goals as defined by the adult. The final goal is to reach a self-sustaining attractor state in which the child shows a significant reduction in his adult-dependent activity, and a significant increase in his independent activity, such that the child can be admitted in special education (a goal that is very important for the child's parents). This final goal is reached by subsequently working with specific subgoals per session, which are formulated for both the child and the adult (the mother in this case). For instance, Phase 2 in the session is a "play" phase, in which the child's goal with regard to playing is that he takes at least two initiatives during play. The mother's goal is to stimulate the child in his communication and taking initiatives, for example, by using prompts (Koegel & Koegel, 2006). The mother received information in a preceding instruction session, such as about the use of prompts, and about the importance of using scaffolding techniques in guiding the child's actions. In addition, at the end of each session the coach gave the mother tips, using a video feedback coaching procedure.

How did we incorporate the process laws in this study? First of all, in this research we focus on a real-time, concrete process, namely an individual child's learning process in interaction with his mother. We could of course have chosen for a research design based on comparing average scores in a big sample of children with ASD, and a big sample of children forming a control group. However, this approach would not have allowed us to understand the process in accordance with the laws specified above. Instead, we followed the interaction process over time (several subsequent sessions) while incorporating both micro- and macro-measures (taken on different timescales). This approach is driven by the idea that it will reveal a sequence of changes in the process over time, and that these changes give us important information about the underlying developmental processes that we can carry over to succeeding interventions with other ASD children. The first process law (mutual influence of components in the process) is visible in that we use data of both partners in the dyad as interacting, mutually dependent components of the process, and that we do so in an iterative manner. In addition, the research question is formulated with regard to changes in the dyad's dynamic change process over time, that is, "how does this dyad change over time, with regard to the interaction process, i.e., the child's independent task behaviors and communication and the mother's guiding the child's task behavior and communication?" The second process law, iterativity, is also demonstrated in the method of data analysis, that is, by analyzing action–reaction chains: e.g., "prompt mother" → "reaction child" → "reaction mother" → "reaction child" → "prompt mother" → .... It can also be seen in that we ask the participants to formulate successive micro- and macro learning goals. That is, the mother formulates her learning goals as a function of what she has accomplished the previous time, in a successive, history-dependent manner.

The third process law concerning time scales, more precisely the mutual relationship between short-term processes and long-term development can be seen in the design of the study in that a longitudinal design is combined with microgenetic measures, that is to say measures focusing on short-term change, for instance change in communication behaviors during a particular play session of the mother and the child.

The fourth process law, "variability as a naturally occurring expression of nonlinearity," is used by explicitly examining fluctuation in the variables, for example, rapid fluctuations in the mother's "amount of prompts" that can precede a change in the nature of the interaction pattern.

The fifth process law (self-organization and attractors) is expressed in the formulation of hypotheses about three types of attractors that potentially occur: (1) interaction patterns without the child's initiatives; (2) interaction patterns based on the child's initiatives that require prompts; and (3) interaction patterns based on the child's initiatives that do not require prompts (virtual attractor; final goal). In our analysis of the data, we try to demonstrate which of these attractor states—qua self-sustaining, typical patterns of interactive behavior—are present and how they succeed one another.

CONCLUSION AND DISCUSSION

We believe that this approach provides tools for applying a new perspective to research and practice, a perspective that is consistent with the very nature of education, which is to understand and (help) manage educational processes.

In the second part of the workshop, the audience came with questions and suggestions all pertaining to the issue of the usability of the process laws. One question focused on *what could a teacher get out of seeing these data (data from the examples we discussed during the workshop)?* Most of the existing, group-based research tends to provide recipes, but virtually never provides a picture of how these recipes work out over time, that is, constitute a real-time process, which is in fact a crucial thing. We are giving teachers examples of how things evolve over time, based on studies with one or a few individual subjects or classes with teachers. One can learn from these studies in the way people in general learn from examples. An example is a demonstration of how some abstract principle works out in reality. The reality of education is a reality of complex processes, and the examples must demonstrate these complicated dynamics. For instance, in one of our researches we show how a teacher in interaction with a particular student unconsciously fell into a self-sustaining pattern, which is not beneficial to long-term learning (Steenbeek et al., 2012). We did not pretend that all such cases follow the steps we found in the case we studied. However, by giving a demonstration of how general dynamic principles can lead to such undesirable self-sustaining educational processes, we hope to make it easier for the practitioner to recognize and interfere with processes that are most likely very different in the details but similar in the general principles.

The examples we discussed pertain to processes occurring over the relatively long periods, for instance two school years, and one of the questions focused on *how would one implement these process laws in a limited time scale*? In fact, the time scale does not matter: an educator can use these process laws to analyze processes that last no longer than a couple of minutes, for instance a videotaped discussion between the teacher and a student about how to solve a particular math or physics problem (see, for instance, van der Steen et al., 2014). What matters is that we look at processes from a time-serial perspective, as a sequence of events connected in time, be it the short-term time scale of activities or the long-term time scale of learning and development.

A third question concerned intervention, *how does this approach help us to follow a student who is a particular on an intervention plan?* Often, teachers focus on one variable and if they do not see a straight line of progress, they view the intervention as failing. How do we change this view of the importance of the straight line? In fact, the belief in the reality of the straight line of progress—associated with a straight line of intervention activities—is a beautiful illustration of how a wrong picture of the world, namely that of linear progress, is what you get from averaging over individuals and then thinking that this general picture applies to all individuals, plus or minus random variation that you should control for by means of averaging over repeated measurements. We tell teachers that this is the wrong view of the world. It might be an adequate view for the policy makers, as they deal with aggregated effects over many individuals. Teachers and educators, however, should have a concrete understanding of nonlinearity, for instance the occurrence of fluctuations, temporary regressions, or periods of stagnation (see also Note 1 about technical methods for distinguishing types of meaningful variability). These fluctuations are highly meaningful and informative about the ongoing dynamics of a concrete intervention process and should not be treated as measurement error, which, again is an interpretation stemming from doing research by averaging over individuals (or by calculating correlations over individuals).

One participant asked: "What do you caution teachers against?" In the preceding sections, we already cautioned against seeing the world in ways that are deeply inadequate, such as focusing on linear change. In addition, we also caution against using labels—such as ADHD and ASD—too easily, and to see these labels as explanations of what goes on with a particular student. Instead, we recommend that teachers should become their own process researchers. One way to achieve this aim is that teachers participate in process-based video feedback coaching programs (vfc-t) (an example is the vfc-t program for primary school teachers, aimed at improving the quality of science, technology, engineering, and mathematics (STEM) education developed by Wetzels, Steenbeek, and van Geert (submitted). Looking at their own video data, with a coach who understands the principles of dynamic process laws, can help teachers make abstract notions such as iterativeness or dynamic scaffolding concrete in the context of their own actions with individual students. This in turn can help them understand the actual process of interaction between themselves and their students and help them find out what kind of process works best with a particular student.

The final question is *whether this approach can be scaled up to the entire classroom*. In fact, it is not so much a matter of scaling up as a matter of applying the same process laws to components of a different nature, for example, either individuals or entire classrooms. For a teacher, the classroom is an entity in its own right, and what the teacher is doing is in a sense interacting with the classroom and not just with isolated individual students. Principles such as iterativeness or self-organization apply to individual students as well as to classrooms.

We started with questions such as how does "this" influences "that." We hope to have demonstrated that the word *influence* does not refer to a simple relationship, but refers to something that takes place in the form of complex, iterative, time-scaled, situated processes. Applying process laws (i.e., starting from properties that belong to CDS) helps to take "influence" into account in a proper manner, that is, by doing right to the idea that the world is a CDS, which must be understood, investigated, and treated as such.

NOTES

1 There is a growing body of research on methods for distinguishing variability in the form of classic random noise from variability that can inform the researcher

about underlying processes of the system; some of these methods are highly technical (e.g., detrended fractal analysis; for an example see de Ruiter, den Hartigh, Cox, van Geert, & Kunnen, in press), others are fairly simple and consist of studying whether the distribution of the fluctuations is asymmetrical (e.g., Van Geert & Van Dijk, 2002) or whether the magnitude of the fluctuations temporarily increases or decreases (e.g., Bassano & Van Geert, 2007).

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