***Research Summary***

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My research program is multi-disciplinary, incorporating cognitive science with various educational disciplines, i.e., science and mathematics, using a systematic approach. First, controlled laboratory studies produce data documenting developmental constraints of learning disciplinary and non-disciplinary materials. Second, those data inspire the development or advancement of theoretical accounts of learning both within and across academic domains. Third, classroom interventions evaluate whether these theoretical accounts can be applied effectively to classroom instruction. Fourth, the results of these interventions are used to evaluate the effectiveness of the developmental theory, which in turn inspire more classroom interventions, continuing an iterative process of laboratory and classroom based studies. Within the domain of arithmetic, I have been investigating the interaction between the development of executive functions and the acquisition of arithmetic knowledge. Within the domain of science, I focused on how the development of causal understanding and causal reasoning interact with learning scientific phenomena.

***How does task switching improve educational performance and executive functions?***

Recent studies have suggested that students with better executive functioning abilities have higher academic achievement. There is not one single definition for executive functions, but generally it is a comprehensive term that refers to the processes involved in goal-directed behaviors across a variety of cognitively challenging situations. Executive functions undergo various developmental changes throughout the lifespan and appear to be related to the development of the frontal lobes, suggesting that academic performance is biologically constrained by the development of executive functioning abilities. However, it is very likely that educational achievement tests used to establish these claims necessitate executive functioning abilities that are not routinely required by educational practice. In other words, links between educational achievement and executive functions might be constrained by educational materials. Furthermore, it is possible that educational materials that incorporate regular use of executive functions improve executive functioning, classroom performance, and performance on state standards tests. I have been investigating this question by exploring intersections between cognitive development, neurological development, and knowledge acquisition of arithmetic skills and achievement.

Initially, I investigated executive functions in children's abilities to switch between arithmetic tasks and compared this performance to switching in non-arithmetic tasks more similar to those reported in previous developmental studies of switching (Ellefson & Chater, in preparation; Ellefson, Shapiro, & Chater, 2006). One effective paradigm for studying this phenomenon is called task switching. By using the task switching paradigm, I could evaluate the impact of switching on individual trials and on groups of trials that required switching versus groups of trials that did not require switching. These first studies indicated that the developmental trajectories of switching are different for arithmetic compared to the typical executive function task, i.e. matching figures by shape and color. However, regardless of these domain differences, I have found that the development of executive functions is linked with performance in an arithmetic switch task (Ellefson & Chater, 2005). Furthermore, I have found that the development of inhibitory skills influences the development of accuracy on these tasks and the development of switching skills influences the speed of accurate responses (Ellefson, Johnstone, Blagrove, & Chater, 2006; Ellefson, Chater, & Blagrove, in preparation). Based on these results, I predicted that if children were given an opportunity to practice switching, then their overall accuracy would improve.

In contrast to the predictions of the results from my developmental studies of task switching, the typical instructional design of early arithmetic instruction engages children in only one type of computational skill over multiple weeks, with little or no practice of other computations. For example, children might spend weeks learning simple subtraction equations with very little time, if any, spent practicing the addition equations they may have learned previously. This blocked learning strategy has short-term gains because children can focus on one type of task. However, proficiency with other tasks decreases because children do not receive regular practice with those tasks. Most, importantly, children rarely practice switching between different computations. Evidence from developmental studies of executive functions, indicates that young children have great difficulty switching between tasks and practice with specific executive function skills improves general executive functioning abilities. If both switching and inhibition are important for performance during an arithmetic switch task, if switching is necessary for arithmetic achievement tests, and if practice with executive function tasks improves executive functions like switching and inhibition, then I expected that educational interventions using interleaved learning might have a positive impact on arithmetic performance.

Interleaved learning involves learning new information alongside previously learned information. For example, children who learn arithmetic using interleaved learning would have regular practice switching between various types of computations, e.g., addition, subtraction, etc. One advantage of learning using this method is that students continually practice new information alongside familiar information. A second advantage of interleaved learning is that students will have regular practice switching between various types of items. I have investigated the role of practice with interleaved sums on performance in task switching for both arithmetic and non-arithmetic domains. In this study, 7-year-old children continued their normal arithmetic lessons, but were randomly assigned to either a switch practice or a non-switch practice group (Ellefson, Clinch, Crean, Carroll, & Chater, in preparation). Practice occurred during the first 15 minutes of the school day for eight weeks. Pre- and post-test assessments indicated that the generally robust finding for switch costs, even in adults, was eliminated for the switch group. The switch group demonstrated improvements for both switch and non-switch conditions, whereas the non-switch group demonstrated improvements only for non-switch conditions. Furthermore, practice switching in arithmetic transferred to non-arithmetic settings with children in the switch group attending more carefully to the switch information than children in the non-switch conditions. These very early results are incredibly promising. Subsequent studies are planned to study the impact of these practice sessions over the entire year and the impact of regular switching as part of the everyday arithmetic curriculum.

The results of this educational intervention have inspired additional laboratory studies. The first set of task switching studies included only addition and subtraction. Currently, I am investigating whether these same developmental trajectories hold for other computations like multiplication and division. Additionally, the results of both the educational intervention and the developmental studies have suggested that the developmental trajectories of performance in task switching may be influenced by a complex interaction of both neurocognitive development and the nature of knowledge acquisition in the classroom. Furthermore, performance on these tasks appears dependent on current knowledge of the domain (Ellefson, Blagrove, & Chater, in preparation). Additional studies are underway to investigate developmental trajectories in other academic domains like reading and science. The first set of task switching studies in reading have explored developmental patterns of switching between non-words and words with regular and irregular grapheme-phoneme correspondences, i.e., regular and irregular spelling to sound correspondences in words. Initial analyses indicate that the developmental trajectories for switching between word types are not identical to our other developmental trajectories (Ellefson, Blagrove, Johnstone & Chater, 2006).

***Why don't science students reason like intuitive scientists?***

In addition to my work in arithmetic and executive functions, I have been investigating how the development of causal reasoning might interact with learning scientific phenomena and whether these results can lead to similar educational interventions. Grasping scientific phenomena includes more than the mere memorization of scientific facts. It requires the creation of an appropriate model of the important aspects of the phenomena and how these aspects are related. Many, but not all, of these relations are causal. A growing number of studies have suggested that children (and adults) have remarkable causal reasoning and learning abilities in laboratory settings, claiming that they can reason like intuitive scientists. Unfortunately, abilities demonstrated in laboratory studies do not seem to transfer to achievement in the science classroom. I have been investigating how causal learning and reasoning influences learning and understanding in the science classroom.

One major difference between the laboratory and the classroom is the complexity of the causal structures. Causal structures in the science classroom contain many more potential causes that interact with each other in complex ways. Young children seem particularly sensitive to the frequency of the occurrence of the causal events associated with more than one potential cause (Ellefson, Johnstone, & Chater, 2005). This frequency can bias their ability to create accurate causal structures of events, especially when this bias is accompanied by inconsistent outcomes. There are many examples of inconsistency of results in the science classroom and inappropriate use of the frequency of events that may hinder scientific reasoning in educational settings. The nature and complexity of the scientific materials themselves may hinder scientific understanding. In collaboration with Prof. Nick Chater and Dr. Anne Schlottmann, I have developed a series of studies to investigate how children's naïve views of physical and biological sciences constrain their understanding of causal structures in those domains. Furthermore, in work with Dr. Kelly Goedert, I am investigating using studies of expertise in these areas to document a trajectory of causal reasoning across levels of scientific knowledge to inform better practice in science education.

How complex are the causal structures that students learn in the classroom? I have been investigating the nature of students' causal models in high school science with Dr. Christian Schunn (Ellefson, Brinker, & Schunn, 2007). The results indicate that the complexity of student models of scientific phenomena is related to their knowledge of the domain. Students who have more knowledge of the domain produce causal structures that are more complex, include multiple potential causes, and multiple effects. However, the causal relations that they describe are simple and rarely include interactions. A separate study indicates that students use reasoning structures that are too simple to effectively understand these interactions, especially under uncertain conditions (Ellefson & Young, 2006). Science experiences that require students to think about and investigate complex interactions may provide opportunities for students learn science more effectively. I have been developing and implementing such experiences for high school chemistry and biology classrooms. For example, through the process of genetic engineering and manipulating the environment to turn genes on or off, biology students are learning about the complex interactions between the genes and environments while learning about the process of how DNA becomes a trait.

### ***Why should we iterate between laboratory and classroom settings?***

Up to this point, I have described my two research foci and the strategies that I use to move between laboratory and classroom settings. Grounding myself in both settings strengthens the quality of the educational interventions and developmental studies I create. In addition, this strategy affords investigations of the very complex interaction between developmental phenomena and educational practice. I have begun to explore whether what has been assumed to be standard developmental trends are actually a result of educational instruction and to what extent instruction mediates cognitive development (e.g., Ellefson, Treiman, & Kessler, in press). It is my intention that my work informs theories of cognitive development and theories of good educational practice. I focus these investigations in the general sphere of how children process and learn complex information. This complexity can be constrained by the inherent structural complexity of the to-be-learned information (e.g., Ellefson, Young, Christiansen, & Espy, 2006), educational practice (Ellefson, Treiman, & Kessler, in press), or the process of development itself (e.g., Ellefson, Shapiro & Chater, 2006; Ellefson, Johnstone, Blagrove, & Chater, 2006; Ellefson & Chater, 2006).

My academic and professional training have allowed me to incorporate a wealth of cognitive scientific and educational techniques into my research program. For example, in collaboration with Drs. Janet Vousden and Nick Chater, I have been using computational modeling to investigate developmental learning phenomena inside and outside of the classroom. I have conducted studies investigating the interaction between curriculum and cognitive development in international settings (e.g., Ellefson, Treiman, & Kessler, in preparation) and I plan to conduct more international studies using my task switching and causality frameworks. I routinely administer standardized assessments of school achievement, IQ, and developmental phenomena. As necessary, I have modified existing or created new assessments of developmental phenomena that can be used in the classroom. For example, Dr. Kimberly Andrews Espy and I have been extending her preschool executive function assessment for use with older children, adolescents, and adults. I have developed high school science curricula in chemistry and biology using design-based learning (Ellefson, Brinker, Vernacchio, & Schunn, in press; Apedoe, Reynolds, Ellefson & Schunn, submitted). This educational approach incorporates fundamental principles of engineering design to the science classroom. The practice of engaging in an engineering design process allows students to investigate scientific phenomena more meaningfully than traditional classroom practice. I plan to enhance my current research program by utilizing electrophysiological measures to understand further how educational instruction and cognitive development influence the learning of complex information. I plan to revisit some of my previous work and complete a few studies that explore electrophysiological correlates of various issues students face while learning to read, compute various mathematical procedures, or while acquire scientific knowledge and experience using event-related potentials (ERPs) and/or eye tracking methodologies.

My experience with curriculum development and implementation, have inspired both my theoretical curiosity and my commitment to educational reform through evidence based interventions that are theoretically appropriate and relevant to cognitive development and educational practice. My experience with urban and non-urban education at the primary and secondary school levels with students of all academic, social, language, and ethnic backgrounds from international locations is evidence of my commitment to investigating the cognitive development and improving the educational experiences of all children throughout their school years.