Abstract Title Page
Not included in page count.

Title: Review of the non-experimental evidence from developmental and cognitive psychological, education science and neuroscience that provided the impetus for the development of the intervention

Authors and Affiliation:

David Grissmer[1], Kevin J. Grimm[2]

[1]University of Virginia
[2]University of California, Davis

Abstract Body

Limit 4 pages single-spaced.

Background / Context:

Description of prior research and its intellectual context.

Duncan et al. (2007) presented a new methodology for identifying kindergarten readiness factors and quantifying their importance by determining which of children's developing skills measured around kindergarten entrance would predict later reading and math achievement. This article extends Duncan et al.'s work to identify kindergarten readiness factors with 6 longitudinal data sets. Their results identified kindergarten math and reading readiness and attention as the primary long-term predictors but found no effects from social skills or internalizing and externalizing behavior. We incorporated motor skills measures from 3 of the data sets and found that fine motor skills are an additional strong predictor of later achievement.

Perhaps the strongest evidence for the linkage between motor and cognitive skills comes from neuroscience and a strand of developmental research on motor skills. Diamond (2000) summarized the neuroscience evidence for the motor-cognitive linkage for the developmental community. Diamond's neuroimaging evidence suggests that some of the primary regions of the brain previously thought to be involved only in motor activities (cerebellum and basal ganglia) or cognitive activities (prefrontal cortex) are co-activated when doing certain motor or cognitive tasks. Neuroanatomy also provides evidence for two-way neural communication linkages between these motor and cognitive areas. Diamond (2000) also provides evidence for a prevalent co-occurrence of both motor and cognitive deficits in many developmental disorders, movement disorders, and in brain damaged patients. Diamond (2000) also proposed that executive function, primarily located in the prefrontal areas, coordinates complex activities requiring several parts of the brain regardless of whether the task is motor or cognitive. The conclusions drawn by Diamond have only been strengthened by neuroscience and developmental evidence since 2000.

This evidence has converged to suggest that (1) a surprising complex prefrontal cognitive capacity is developed during motor development that is partially used later during cognitive development, and (2) specialized functions developed during motor development in the cerebellum and basal ganglia- areas traditionally thought to be dedicated to motor functions and not to be involved in cognitive functioning- are used in many types of cognitive processing. Adolph (2005;2006;2008) suggests that motor development involves "learning to learn", that is, a "neural learning infrastructure" is developed when learning motor skills that is later used when learning cognitive skills. Neuroscience evidence suggests that this "neural learning infrastructure" may include simultaneous and coordinated functions performed in the prefrontal areas and the cerebellum and basal ganglia and include the neural communication pathways between these prefrontal and motor areas (Haber, 2003,;Middleton and Strick,2003). Theories suggest that these functions and pathways constitute an adaptive control system that guides a trial and error, reinforcement/reward driven process that guides learning whether learning motor or cognitive skills (Ito, 2005; Cohen & Frank, 2008; Doya, 1999). The prefrontal areas contributes executive function and representational capacity, while the cerebellum and basal ganglia contribute capacities such as sequencing, categorization, time estimation and reward generation (Ashby & Spiering, 2004; Graybiel, 2005; Nicolson et al, 2001; Saint-Cyr, 2003; Shohamy et al, 2008; Topak et al, 2006).

A potential implication of this evidence and these theories is that cognitive development may partially depend on an "inheritance" of neural capacity from motor development, i.e., the quality and developmental timing of the neural learning infrastructure built during motor learning might impact the quality and developmental timing of cognitive learning. While the evidence and theories arising from neuroscience are continually and rapidly evolving, there is a virtual consensus about a fundamental linkage between motor and cognitive development.

This literature suggests that substantial cognitive capacity including development of visuo-spatial skills are built to meet the increasing demands of motor development, and that this capacity involves neural networks linking the pre-frontal and motor areas that are used in many types of later learning and cognitive performance. Visuo-spatial skills involve understanding visual representations and their spatial relationships, and are used in distance and depth perception, perceiving rotated objects, reproducing drawings or replicating objects, and navigating in our environment (Newcombe & Frick, 2010). Early measures of visuo-spatial skills also predict later math achievement, and EF and visuo-spatial measures have similar predictive strength when both measures are included (Cameron et al., 2012; Grissmer et al., 2010; LeFevre et al., 2010; Murrah, 2010; Son & Meisels, 2006). Developmental research suggests that substantial cognitive capacity, including complex visuo-spatial skills, is built while learning motor skills (K. E. Adolph & Robinson, In Press; K. E. Adolph & Berger, 2006; Diamond, 2000; Newcombe & Frick, 2010). Neuroscience literature suggests that neural networks built during motor development for sequencing, categorization, and time estimation are also likely used when needed in math tasks (Cohen & Frank, 2009; Doya, 2000; Grissmer et al., 2010; Ito, 2005). Neuroimaging evidence shows that the brain areas used in visuo-spatial tasks are also used in math tasks (S. Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; S. Dehaene, Molko, Cohen, & Wilson, 2004; Eslinger et al., 2009). Finally, neuroimaging evidence suggests that building visuo-spatial skills utilizes EF resources especially in earlier learning stages (Eslinger et al., 2009).

Purpose / Objective / Research Question / Focus of Study:
Description of the focus of the research.

The main objectives of this paper are threefold: (a) provide new empirical evidence that fine motor skills, a developmental skill measured at school entry but not included in Duncan's et al.'s (2007) analysis, is strongly predictive of later scores, (b) present several sensitivity analyses that extend Duncan et al.'s findings, including assessing the predictive power of a child's knowledge of the world, and (c) review the developmental, cognitive, and neuroscience literature to assess and suggest mechanisms for a link between early motor skills and later achievement.

Population / Participants / Subjects:
Description of the participants in the study: who, how many, key features, or characteristics.

Three large scale longitudinal data sets are used in this study. They are the Early Childhood Longitudinal Survey– Kindergarten Cohort (ECLS-K), the British Birth Cohort Study (BCS), and the National Longitudinal Survey of Youth (NLSY).

Research Design:
Description of the research design.

In all three data sets, estimation was done with weighted ordinary least squares. Missing data were handled in the ECLS-K with multiple imputation (20 imputations) and in the NLSY through full information maximum likelihood. Results reported here for the BCS are taken from the supplemental materials in Duncan et al. (2007) because the motor variables were included in the original analysis. Missing data were handled in the BCS through inclusion of missing value dummies. Because the motor measures are of key interest in this study, they are described for each of the three longitudinal data sets.

Motor Measures in the ECLS-K

Two measures of psychomotor assessment were obtained in the ECLS-K: gross and fine motor skills. The ECLS-K uses motor items adapted from the Early Screening Inventory–Revised (Meisels, Marsden, Wiske, & Henderson, 1997). This inventory is a well-standardized multidomain screening test widely used to identify preschool and kindergarten children at risk for school failure (Kimmel, 2001; Paget, 2001). For the assessment of fine motor skills, participants used building blocks to replicate a model, copied five figures on paper, and drew a person. For the assess ment of gross motor skills, participants skipped, hopped on one foot, walked backward, and stood on one foot. Interitem reliability (alpha coefficient) was .57 for the fine motor scale and .51 for the gross motor scale. The low reliabilities are partially a function of the binary scoring system for the items that comprised the scales and the small number of items.

Motor Measures in the NLSY

The motor skills measure for the NLSY was developed at the National Center for Health Statistics and comprised items based on standard and reliable measures of child motor and social development (including the Bayley, Gesell, and Denver methods). Age appropriate sets of dichotomous items were determined on the basis of previous analyses of 2,714 U.S. children (Peterson & Moore, 1987). On the basis of the determined age ranges, the instrument completed by the child's mother contained eight components designed to assess children from ages 22 to 47 months. Standard scores were created that are comparable for children of different ages. More detailed information regarding the reliability and validity of these measures is available in the discussion of motor skills development in the *NLSY79 Child Handbook* (Baker, Keck, Mott, & Quinlan, 1993) and the *NLSY Children, 1992* (Mott, Baker, Ball, Keck, & Lenhart, 1995).

Motor Skills in the BCS

In the BCS, motor skills at age 5 were measured with three drawing tasks: design copying, human figure drawing, and profile drawing. The copying task required children to copy eight basic designs. Children were allowed two attempts with no assessor assistance. This test was used in previous studies to assess fine motor and visual control (Davie, Butler, & Goldstein, 1972; Rutter, Tizard, & Whitemore, 1970). In the human figure drawing task, children were asked to create a full body drawing of a person. Children received no instructor help during drawing, but clarification of aspects of the drawing was allowed after completion. In the profile drawing test, children completed the profile of a basic head shape from a test booklet with no assessor help. These tests have a reported reliability of .94 and good discrimination properties (Harris, 1963; Koppitz, 1968).

Findings / Results:
Description of the main findings with specific details.

The results indicated that gross motor skills were not a significant predictor of later achievement but that fine motor skills were a very strong and consistent predictor of later achievement. The relative strength of fine motor skills, compared with attention, varied across tests and data sets. In the ECLS-K, attention was a stronger predictor of reading and math than motor skills were, whereas the NLSY fine motor skills and attention showed approximately equal strength in their prediction of later achievement. In the BCS, fine motor measures were stronger predictors than attention. Incorporating motor skills into the analysis did not change the pattern of significant effects for early math and reading or the insignificant or weak effects for internalizing and externalizing behavior and social skills. These results suggest that both attention and fine motor skills measured at kindergarten are important developmental skills that predict later achievement.

Conclusions:
Description of conclusions, recommendations, and limitations based on findings.

The potential discovery of two new school readiness indicators in addition to attention, which was found by Duncan et al. (2007), may be important for at least three reasons. The first reason is that it might provide a new direction for intervention and experimentation that can test whether the relationships are casual and actually result in higher math and reading achievement. For instance, one possibility for the motor relationship is an inverse one that stronger innate cognitive skills build better fine motor skills. The second reason, provided these results are causal, is the potential impact on educational policies and practices and broader social policies. The third reason is to spur new developmental and neuroscience research that links these early skills through causative mechanisms to later cognitive development.

Appendices

Not included in page count.

Appendix A. References

References are to be in APA version 6 format.

References

Adolph, K. E., & Robinson, S. R. (In Press). The road to walking: What learning to walk tells us about development. In P. D. Zelazo (Ed.), *Oxford handbook of developmental psychology*. New York: Oxford University Press.

Adolph, K. E., & Berger, S. E. (2006). Motor development. *Handbook of child psychology: Vol 2, cognition, perception, and language (6th ed.).* (pp. 161-213) Hoboken, NJ, US: John Wiley & Sons Inc.

Ashby, F. G., & Spiering, B. J. (2004). The neurobiology of category learning. *Behavioral and Cognitive Neuroscience Reviews, 3*(2), 101-113.

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development, 83*(4), 1229-1244. doi: 1.1111/j.1467-8624.2012.01768.x

Cohen, M. X., & Frank, M. J. (2009). Neurocomputational models of basal ganglia function in learning, memory and choice. *Behavioural Brain Research, 199*(1), 141-156. doi: 10.1016/j.bbr.2008.09.029

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science, 284*(5416), 970-974. doi: 10.1126/science.284.5416.970

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology, 14*(2), 218-224. doi: 10.1016/j.conb.2004.03.008

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*(1), 44-56. doi: 10.1111/1467-8624.00117

Doya, K. (2000). Complementary roles of basal ganglia and cerebellum in learning and motor control. *Current Opinion in Neurobiology, 10*(6), 732-739. doi: 10.1016/S0959-4388(00)00153-7

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., . . . Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428-1446. doi: 10.1037/0012-1649.44.1.217

Eslinger, P. J., Blair, C., Wang, J., Lipovsky, B., Realmuto, J., Baker, D., . . . Yang, Q. X. (2009). Developmental shifts in fMRI activations during visuospatial relational reasoning. *Brain and Cognition, 69*(1), 1-10.

Graybiel, A. M. (2005). The basal ganglia: Learning new tricks and loving it. *Current Opinion in Neurobiology, 15*(6), 638-644.

Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology, 46*(5), 1008-1017. doi: 10.1037/a0020104

Haber, S. N. (2003). Integrating cognition and motivation into the basal ganglia PAthways of action. In M. Bedard, A. Yves, S. Chouinard, S. Fahn, A. Korczyn & P. Lesperance (Eds.), *Mental and behavioral dysfunction in movement disorders* (pp. 35-50). Totowa, NJ: Humana Press.

Ito, M. (2005). Bases and implications of learning in the cerebellum — adaptive control and internal model mechanism. *Progress in brain research* (pp. 95-109). Japan: Elsevier. doi: 10.1016/S0079-6123(04)48009-1

Korkman, M., Kirk, U., & Kemp, S. (1998). *NEPSY: A developmental neuropsychological assessment*. San Antonio, TX: The Psychological Corporation.

Kroeger, L. A., Brown, R. D., & O'Brien, B. A. (2012). Connecting neuroscience, cognitive, and educational theories and research to practice: A review of mathematics intervention programs. *Early Education and Development, 23*(1), 37-58.

Middleton, F. A. (2003). Fundamental and clinical evidence for basal ganglia influence on cognition. In M. Bedard, A. Yves, S. Chouinard, S. Fahn, A. Korczyn & P. Lesperance (Eds.), *Mental and behavioral dysfunction in movement disorders* (pp. 13-34). Totowa, NJ: Humana Press.

Murrah, W. M., III. (2010). *Comparing self-regulatory and early academic skills as predictors of later math, reading, and science elementary school achievement.* US: ProQuest Information & Learning). *Dissertation Abstracts International Section A: Humanities and Social Sciences, 72*(1-), 76.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain and Education, 4*(3), 102-111. doi: 10.1111/j.1751-228X.2010.01089.x

Nicolson, R. I., Fawcett, A. J., & Dean, P. (2001). Developmental dyslexia: The cerebellar deficit hypothesis. *Trends in Neurosciences, 24*(9), 508-511.

Paquier, P., & MArien, P. (2005). A synthesis of the role of the cerebellum in cognition. *Aphasiology, 19*, 3-19.

Shohamy, D., Myers, C. E., Kalanithi, J., & Gluck, M. A. (2008). Basal ganglia and dopamine contributions to probabilistic category learning. *Neuroscience & Biobehavioral Reviews, 32*(2), 219-236.

Son, S., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*(4), 755-778. doi: 10.1353/mpq.2006.0033

Saint- Cyr, J. A. (2003). Frontal-striatal circuit functions: Context, sequence, and consequence. *Journal of the International Neuropsychological Society, 9*(01), 103-128.

Toplak, M. E., Dockstader, C., & Tannock, R. (2006). Temporal information processing in ADHD: Findings to date and new methods. *Journal of Neuroscience Methods, 151*(1), 15-29.

Appendix B. Tables and Figures
Not included in page count.

Table 1

Summary of Results for Three Longitudinal Data Sets Comparing Effects of Attention and Fine Motor Skills on Later Achievement After Controlling for Extensive Family/Home/Child Characteristics

	Reading			Math		
	ECLS-K	NLSY	BCS	ECLS-K	NLSY	BCS
Earlier cognitive						
Reading	.09*****	.10*****	.13***	NS	.11*****	.09***
Math	.20*****	.10*****		.35*****	.14*****	
Socio-emotional						
Attention	.15*****	-.046 **	-.08**	.17*****	-.047**	-.09**
Externalizing –I	NS	-.038*	NS	NS	NS	NS
Externalizing-II	NS	NS		NS	NS	
Internalizing	NS	NS	NS	NS	NS	NS
Social skills [2]	NS	.056 *****		NS	.039**	
Motor						
Gross motor	NS			NS		
Fine motor	.08*****			.15*****		
Motor/social		.045 ***			.046***	
Copy 8 designs			.26***			.36***
Human drawing			.09 **			.09 **
Profile of head			NS			NS
Controls						
Family/home	X	X	X	X	X	X
Early measures			X			X
Adj R-Squared	.51	.31	.45	.53	.30	.45
Observations	8130	5462	1778	8130	5462	1753

Note. Early Childhood Longitudinal Study of Kindergarten (ECLS-K) outcome time point is fifth grade; National Longitudinal Study of Youth (NLSY) outcome time point is age 13-14; British Cohort Study (BCS) time point is age 10.
NS = non-significant, * $p < .05$, ** $p < .01$, *** $p < .001$, **** $p < .00001$, ***** $p < .000001$.