Fine Motor Skills and Early Comprehension of the World: Two New School Readiness Indicators

David Grissmer
University of Virginia

Sophie M. Aiyer and William M. Murrah
University of Virginia

Kevin J. Grimm
University of California, Davis

Joel S. Steele
University of California, Davis

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. Using one of the data sets, we also predicted later science scores and incorporated an additional early test of general knowledge of the social and physical world as a predictor. We found that the test of general knowledge was by far the strongest predictor of science and reading and also contributed significantly to predicting later math, making the content of this test another important kindergarten readiness indicator. Together, attention, fine motor skills, and general knowledge are much stronger overall predictors of later math, reading, and science scores than early math and reading scores alone.

Keywords: school readiness, fine motor skills, general knowledge, achievement

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Duncan et al. (2007) presented a new methodology for identifying school readiness factors and quantifying their importance by determining which of children’s developing skills measured around kindergarten entrance would predict much later reading and math achievement. This research utilized six international longitudinal data sets that collected data between birth and kindergarten entry and followed children at least through third grade. School readiness factors tested in Duncan et al.’s analysis included measures of early reading and math, attention, internalizing and externalizing behavior, and social skills. Their regressions included as controls a large set of diverse family and child characteristics measured from birth to kindergarten entry. A meta-analysis of their results suggested that measures of early math and reading and attention were significant predictors of later math and reading achievement and that internalizing and externalizing behavior and social skills were not significant predictors. Earlier math measures predicted both later math and reading scores, but early reading measures predicted only later reading scores. Early math scores predicted later reading as strongly as early reading scores.

The results suggest that early math skills should receive more attention in research and curriculum because they predict both later math and reading scores. The results also suggest that not all socioemotional skills may be equal in boosting later achievement. Attention measures appear to be consistently linked to later scores, but social skills and internalizing and externalizing behavior were not. Duncan et al. (2007) provided several caveats for these findings. First, the results measured only the association with later achievement, and including a broader range of long-term developmental outcomes could show different results. Second, socioemotional behavior may affect other students’ achievement more than one’s own achievement. Third, problem behaviors may emerge more strongly after school entry, so later measures may show different results. For instance, class sizes are smaller in kindergarten compared with later grades, and problem behavior may be more frequent when children enter larger classes where teachers have less control.
The main objectives of this article 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 and neuroscience literature to assess and suggest mechanisms for a link between early motor skills and later achievement. For the first objective, we used three longitudinal data sets that measured fine motor skills and were also used in Duncan et al. We added these measures to similarly specified and estimated equations to test whether fine motor skills were predictive of later achievement and, if so, its relative strength compared with attention. For the second objective, we utilized the Early Childhood Longitudinal Survey—Kindergarten Cohort (ECLS-K) to (a) test whether the null effects of social skills, internalizing behavior, and externalizing behavior are sensitive to different specifications, (b) test whether the relative strengths of kindergarten math and reading scores in predicting later math and reading scores are sensitive to inclusion of the general knowledge score, (c) explore the relative strength of the motor and attention measures in predicting fifth-grade scores without kindergarten math and reading measures, (d) add results for later science scores and compare with math and reading results, and (e) interpret the changing predictive effect of child’s age on scores from kindergarten to fifth grade to suggest that the key developmental skills linked to school readiness may be captured by this analysis.

The link between attention and cognitive development is not conceptually difficult because of research on executive function as well as personal experience in maintaining attention when doing cognitive tasks. However, the link between motor skills and cognitive skills is less apparent. For the third objective, we review the neuroscience and developmental literature that has linked motor and cognitive development to provide additional empirical and theoretical support for the linkage and make this linkage easier to grasp.

**Empirical Evidence From Three Longitudinal Data Sets With Motor Measures**

The ECLS-K, the British Birth Cohort Study (BCS), and the National Longitudinal Survey of Youth (NLSY) included measures of motor skills that were not included in Duncan et al. (2007). These data sets were described in Duncan et al. and the associated supplemental materials. We describe only the motor measures used in each of these 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; Puget, 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 assessment 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, & Whittemore, 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).

**Estimation**

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. The full estimation results are provided in the supplemental materials.

**Results**

Table 1 summarizes the results in format similar to that used by Duncan et al. (2007). The patterns of results for early math and reading, attention, social skills, internalizing problems, and externalizing problems were very similar to those found by Duncan et
Table 1
Summary of Results Predicting Later Achievement With Earlier Math and Reading Readiness and Socioemotional and Motor Skills With Three Longitudinal Data Sets

<table>
<thead>
<tr>
<th>Measure</th>
<th>Reading ECLS-K</th>
<th>Reading NLSY</th>
<th>Reading BCS</th>
<th>Math ECLS-K</th>
<th>Math NLSY</th>
<th>Math BCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier cognitive</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reading</td>
<td>.08***</td>
<td>.10****</td>
<td>.13***</td>
<td></td>
<td>ns</td>
<td>.11*****</td>
</tr>
<tr>
<td>Math</td>
<td>.20***</td>
<td>.10****</td>
<td>.13***</td>
<td>.33*****</td>
<td>.14*****</td>
<td>.09***</td>
</tr>
<tr>
<td>Socioemotional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attention*</td>
<td>.16****</td>
<td>-.05**</td>
<td>-.08**</td>
<td>.21*****</td>
<td>-.05**</td>
<td>-.09***</td>
</tr>
<tr>
<td>Externalizing-I</td>
<td>ns</td>
<td>-.04*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Externalizing-II</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Internalizing</td>
<td>.03*</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Social skillsb</td>
<td>ns</td>
<td>.06****</td>
<td>-.04</td>
<td>.04**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross motor</td>
<td>-.02*</td>
<td>ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine motor</td>
<td>.07****</td>
<td>.14****</td>
<td>.05**</td>
<td></td>
<td></td>
<td>.36***</td>
</tr>
<tr>
<td>Motor/social</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copy 8 designs</td>
<td>-.26**</td>
<td></td>
<td></td>
<td>.36***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human drawing</td>
<td>.09*</td>
<td></td>
<td></td>
<td>.09*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Profile of head</td>
<td>ns</td>
<td></td>
<td></td>
<td>ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family/home controls</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Early measures</td>
<td>X</td>
<td>X</td>
<td>.45</td>
<td>.55</td>
<td>.30</td>
<td>.45</td>
</tr>
<tr>
<td>Adjusted R²</td>
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<td>.31</td>
<td>.45</td>
<td>.55</td>
<td>.30</td>
<td>.45</td>
</tr>
<tr>
<td>Observations</td>
<td>7,814</td>
<td>5,462</td>
<td>1,778</td>
<td>7,830</td>
<td>5,462</td>
<td>1,753</td>
</tr>
</tbody>
</table>

Note. Blank cells indicate that the measures were not available on a specific data set. X indicates that family/home controls or early measures were included in the regression. All coefficients are standardized. ECLS-K = Early Childhood Longitudinal Survey–Kindergarten Cohort; NLSY = National Longitudinal Survey of Youth; BCS = British Birth Cohort Study.

*The attention measures on the ECLS-K were teacher-rated attention where higher values indicate more attention. For the NLSY and BCS, the attention measures were of attention problems, and higher values indicate poorer attention. In the NLSY, the social skills measure of sociability, which was a rating by the test administrator given at 42 months, was not included in Duncan et al. (2007) as a social skills measure.

*p < .05. **p < .01. ***p < .001. ****p < .0001. *****p < .00001.

al. For the ECLS-K, early math scores appeared to be the best predictors of both later math and reading scores, whereas reading scores also added significant predictive accuracy for later reading scores but not for later math scores. The ECLS-K, however, suggested a stronger role for reading in the prediction of later reading and mathematics achievement than the ECLS-K did. The attention coefficients for the three data sets showed the same sign as in Duncan et al., and all were statistically significant at an alpha level of .01 or better. The coefficients of social skills, internalizing problems, and externalizing problems also showed patterns similar to those of Duncan et al., who found mostly nonsignificant results or significance far less than that for attention or early reading and math. The exception is for the measure of social skills in the NLSY, which showed strong significance for both reading and math. However, the measure of social skills used a rating by the test administrator when participants were between ages 54 and 78 months. This measure was not included in Duncan et al., perhaps because of its possible unreliability.

Measures of fine motor skills showed highly significant results for both math and reading in all three data sets. However, the gross motor measure in the ECLS-K was not a significant predictor. The profile drawing test in the BCS was not significant for either reading or math, but all other fine motor measures showed statistical significance at the .01 alpha level or better. Comparisons of statistical significance between fine motor skills and attention measures showed that fine motor skills were almost always as significant or more statistically significant than attention. The comparison of the coefficients for effect sizes showed that attention was much stronger than motor skills for predicting reading in the ECLS-K but was of similar strength in the NLSY and BCS. For math, the coefficients for attention were somewhat greater or approximately similar to those for fine motor skills for the ECLS-K and NLSY, but the BCS showed stronger effects for fine motor skills. This evidence suggests that both attention and fine motor skills were important developmental predictors of later achievement, controlling for family and child characteristics and earlier math and reading.

Results From Sensitivity Analyses With the ECLS-K

We used the ECLS-K for analysis of five additional issues. The first issue was whether the socioemotional variables that were generally not significant would show stronger effects in the absence of the attention measure. The attention measure used in the ECLS-K, a measure of approaches to learning, is a composite measure that includes attention-related measures (attention, persistence, and concentration) but also measures linked to eagerness to learn, interest, curiosity, creativity, and responsibility. Such a broad measure could mask the effects of other socioemotional measures. Table 2 contrasts the results when the approaches to learning measure was included and excluded in the analysis. The results showed that social skills for math and reading became significant, although still much less significant than attention and
fine motor skills. Internalizing and externalizing behavior remained insignificant.

In addition to the early math and reading test, the ECLS-K had a test measuring knowledge of the world or early science and social science knowledge. The science items assessed factual and conceptual understanding as well as the ability to formulate and answer questions related to the natural world. Social studies questions assessed children’s knowledge about their environment across a broad range of categories, including history, economics, and culture. Duncan et al.’s (2007) results and the results reported in Table 1 included the test of general knowledge as a control variable, but its coefficients were not included in the summary table.

Table 3 shows the effects of including and excluding the test of general knowledge. The results show that the general knowledge test was a very strong predictor of later reading, far stronger than the early reading test, and was also a strong predictor of later math scores, although early math remained the strongest predictor. General knowledge was a much stronger predictor of both reading and math than early reading. The pattern of results for the socioemotional, attention, and motor skills was generally unaffected by the inclusion of general knowledge.

One possible explanation for the strength of the general knowledge test is that it captured comprehension and ability to integrate knowledge of the external world—skills that may be needed at fifth grade in both reading and math. Children make a key transition in reading skills between kindergarten and fifth grade from learning to read to reading to learn. The general knowledge test may better track this transition than the early reading test.

Another issue was the sensitivity of the attention, motor, and socioemotional measures to the removal of the early math and reading tests. The fifth-grade estimates that included the earlier readiness tests can underestimate the potential effects of the motor, attention, and socioemotional measures if these measures and early readiness scores are correlated. In fact, attention and motor measures are also strong predictors of early math and reading, so the effect of attention, motor, and possibly the other socioemotional measures on fifth-grade achievement may be underestimated (e.g., indirect effects through early math and reading).

Table 4 shows the results including and excluding the early measures of math, reading, and general knowledge. The results that excluded early reading and math scores may better predict possible effects of early interventions to improve attention and fine motor skills. The results showed that the pattern of results for the

Table 3
Sensitivity Test to Inclusion of General Knowledge

<table>
<thead>
<tr>
<th>Measure</th>
<th>Math</th>
<th>Reading</th>
<th>Math</th>
<th>Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef</td>
<td>t</td>
<td>Coef</td>
<td>t</td>
</tr>
<tr>
<td>Attention</td>
<td>.21</td>
<td>15.15</td>
<td>.18</td>
<td>12.09</td>
</tr>
<tr>
<td>Social skills</td>
<td>−.00</td>
<td>−0.07</td>
<td>−.01</td>
<td>−0.84</td>
</tr>
<tr>
<td>Externalizing</td>
<td>−.00</td>
<td>0.09</td>
<td>.01</td>
<td>0.91</td>
</tr>
<tr>
<td>Internalizing</td>
<td>.02</td>
<td>1.69</td>
<td>.02</td>
<td>2.47</td>
</tr>
<tr>
<td>Self-control</td>
<td>−.05</td>
<td>−2.74</td>
<td>−.02</td>
<td>−1.07</td>
</tr>
<tr>
<td>Gross motor</td>
<td>.01</td>
<td>1.15</td>
<td>.00</td>
<td>−0.05</td>
</tr>
<tr>
<td>Fine motor</td>
<td>.15</td>
<td>14.25</td>
<td>.09</td>
<td>8.03</td>
</tr>
<tr>
<td>Math</td>
<td>.37</td>
<td>25.27</td>
<td>.28</td>
<td>18.60</td>
</tr>
<tr>
<td>Reading</td>
<td>.02</td>
<td>1.76</td>
<td>.11</td>
<td>7.72</td>
</tr>
<tr>
<td>General knowledge</td>
<td>.55</td>
<td>.51</td>
<td>.56</td>
<td>.55</td>
</tr>
</tbody>
</table>

Note. Coef = coefficient.
other socioemotional measures remained similar, mostly insignificant or of far lower significance than the attention and motor measures. However, the coefficients of attention and fine motor skills increased markedly with greater statistical significance. The attention coefficients were larger in both reading and math compared with the fine motor coefficients. The estimated effect sizes for attention and fine motor skills were around .3 and .2, respectively. Perhaps more important is that interventions that combine attention and fine motor skills might predict effect sizes of around .5.

We also studied the sensitivity of early and later math and reading scores to the child’s age. Children in the United States start kindergarten with a range of ages that can span 18 months. The large age range arises from the normal 1-year entry window for kindergarten combined with differences between states in the lowest kindergarten entry age. Table 5 contains regression coefficients controlled for family characteristics and for age of child at kindergarten entrance and in the spring of first, third, and fifth grade. Table 5 also contrasts the age coefficients when socioemotional, attention, and motor variables are included and excluded. With socioemotional, attention, and motor skills excluded, the results suggest that differences in age when children were tested were very significant predictors of kindergarten entry and spring first-, third-, and fifth-grade scores, but their significance declined markedly by grade. However, when socioemotional, attention, and motor skills were included, the effect of age completely faded by third grade.

Sensitivity of scores to age can indicate that a developmental variable dependent on age was missing from the analysis. That is, age itself is not a causative mechanism, but rather the significance of age indicates that developmental differences were present at different ages that need to be specified in the equations. For instance, Table 5 illustrates that the absence of attention, motor, and socioemotional variables at any given grade causes declines in the strength and statistical significance of the age variable. Thus, the inclusion of developmental measures reduces the significance of the age variable. When age becomes insignificant at third grade, it might suggest that developmental variables measured at kindergarten have been accounted for.

Another issue was whether fifth-grade science scores showed patterns similar to those for math and reading. Table 6 shows that later science scores were much more strongly predicted by the general knowledge test, with some contribution from math and little from reading. The effect of fine motor skills on later science scores to age can indicate that a developmental variable dependent on age was missing from the analysis. That is, age itself is not a causative mechanism, but rather the significance of age indicates that developmental differences were present at different ages that need to be specified in the equations. For instance, Table 5 illustrates that the absence of attention, motor, and socioemotional variables at any given grade causes declines in the strength and statistical significance of the age variable. Thus, the inclusion of developmental measures reduces the significance of the age variable. When age becomes insignificant at third grade, it might suggest that developmental variables measured at kindergarten have been accounted for.
was stronger than the effect for reading but weaker than the effect for math. Attention was a somewhat weaker predictor of science than either later reading or math. However, the general knowledge test had effect sizes of .2, .3, and .4, respectively, for math, reading, and science. General knowledge was a much stronger combined predictor of all three tests than either early math or reading. Similar to later reading and math, none of the other socioemotional variables showed statistical significance or they showed much weaker significance than attention and fine motor skills.

Neuroscience and Developmental Evidence for a Motor–Cognitive Link

One possibility that might partially account for a motor–cognitive causal link is that most activities that build or display cognitive skills also involve the use of fine motor skills. Writing requires fine motor skills with the hands as well as hand–eye coordination. Speaking requires fine motor skills that control the production of sound. Reading requires the use of fine motor skills controlling eye movement for word tracking. Poor fine motor skills can make cognitive learning and performance more difficult because of the simultaneous need for fine motor skills in cognitive activities. However, evidence from neuroscience and recent child development research presents a much more complex relation between early motor and later cognitive development. Evidence suggests that even if cognitive development required no simultaneous usage of motor and cognitive skills, earlier motor skill development could have a significant impact on later cognitive development. In this section, we summarize some of this evidence. This review is not comprehensive but summarizes some of the evidence and current thinking about how early motor skills might be linked to later cognitive development.

Diamond (2000) summarized the links between motor and cognitive skills, using evidence from neuroimaging and neuroanatomy, from co-occurrence of effects from brain damage or brain abnormalities, and from correlations between deficits in motor and cognitive skills in developmental disorders. Diamond found significant evidence for a motor–cognition association in each of these areas. Historically, cognitive and motor activities were assigned to separate brain areas. Diamond’s neuroimaging evidence suggests that some of the primary brain regions previously thought to be involved only in motor activities (cerebellum and basal ganglia) or cognitive activities (prefrontal cortex) are coactivated when doing certain motor or cognitive tasks. Neuroanatomy also provides evidence for two-way neural communication linkages between these motor and cognitive areas. Diamond also proposed that executive function, primarily located in the prefrontal areas, may coordinate complex activities requiring several parts of the brain regardless of whether the task is motor, emotional, or cognitive.

Diamond (2000) also provided evidence for a prevalent co-occurrence of both motor and cognitive deficits in many developmental disorders, in movement disorders, and in brain damaged persons. Individuals with brain damage to either the primary motor or primary cognitive areas often show impairment in both skill areas. Also, ADHD and dyslexia, both traditionally classified as childhood cognitive disorders, are often characterized by poor motor coordination. Individuals with Parkinson’s disease, which is primarily thought of as a movement disorder, often show areas of significant cognitive impairment. Although these linkages involve primarily disorders outside the normal variation of motor and cognitive skills in the general population, the evidence provided from the longitudinal surveys suggests a motor–cognitive linkage due to variations found within populations without significant disorders.

Since Diamond’s (2000) study, multidisciplinary research has substantially strengthened the evidence for the motor–cognitive link and has elucidated the nature of the linkage. This research suggests that motor and cognitive development are inextricably linked. Literature suggests that the linkage occurs primarily for two reasons: (a) many types of cognitive activities utilize specialized control and modulation functions located in the cerebellum and basal ganglia that develop during motor acquisition, and (b) some of the neural infrastructure linking the prefrontal and motor areas built to adaptively control the learning process during motor development is also used to control learning in cognitive development. The evidence to support this view comes from neuroimaging, neuroanatomy, studies of motor/cognitive disorders, psychological testing, and recent child development research on motor skills.
Doya (1999) suggested that the prefrontal cortex, basal ganglia, and cerebellum are all specialized to different types of learning, with the prefrontal areas more specialized to unsupervised learning, the basal ganglia more specialized to reinforcement learning, and the cerebellum more specialized to supervised learning. Seger (2006) suggested that two important common functions utilizing the basal ganglia and shared by some motor and cognitive tasks are performing a sequential, coordinated series of events over time and complex categorization. The sequential events could be performing a coordinated motor movement, organizing grammatical elements in language, or sequencing subgoals in complex reasoning.

Subsequently, cognitive tasks attributed primarily to motor areas include tracking and estimation of time durations, sequential learning tasks, nondeclarative and categorical learning, learning based on implicit or explicit rewards, and the acquisition of new skills (Ashby & Spiering, 2004; Graybiel, 2005; Nicolson, Fawcett, & Dean, 2001; Saint-Cyr, 2003; Shohamy, Myers, Grossman, et al., 2004; Shohamy, Myers, Kahanthi, & Gluck, 2008; Shohamy, Myers, Onloao, & Gluck, 2004; Toplak, Dockstader, & Tannock, 2006). For instance, Ashby and Spiering (2004) suggested three different types of category learning that utilize specialized coordinated subsystems that draw from prefrontal and motor areas (basal ganglia). These studies provide evidence of a highly developed specialization of brain areas linked by distinct and specialized bidirectional loop circuitry to carry out different types of learning. Haber (2003), Middleton (2003), and Middleton and Strick (2000, 2002) reported anatomical evidence that the necessary communication pathways are present between the cerebellum, basal ganglia, and prefrontal areas. Paquier and Marien (2005), Middleton (2003), and Middleton and Strick (2000, 2002) suggested that the cerebellum modulates cognitive functions through the cortico–ponto–cerebellar system and the cerebellum–thalamo–cortical pathways.

Evidence of motor–cognitive linkages from developmental disorders, brain abnormalities, and brain damage has also grown much stronger. Theories about the causal mechanisms in both ADHD and dyslexia now involve malfunctions in the cerebellum and/or basal ganglia (Banachewski et al., 2005; Casey, Nigg, & Durston, 2007; Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Castellanos & Tannock, 2002; Durston & Casey, 2006; Durston & Konrad, 2007; Krai & Castellanos, 2006; Nigg & Casey, 2005; Schmahmann, 2003, 2004; Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003; Smith, Taylor, Warner, Newman, & Riba, 2002; Sonuga-Barke, 2003; Sonuga-Barke, Auerbach, Campbell, Daley, & Thompson, 2005; Sonuga-Barke, Dalen, & Remington, 2003; Sonuga-Barke, Sergeant, Nigg, & Willcutt, 2008; Toplak, Dockstader, & Tannock, 2006). For instance, deficits in timing associated with the basal ganglia have been linked to children with reading problems like dyslexia and language deficits and ADHD (Nicolson et al., 2001; Smith et al., 2002). Evidence also suggests that damage to the cerebellum can produce cognitive deficits, specifically called cerebellar cognitive affective syndrome, that include impairment in executive function, spatial cognition, linguistic processing, and verbal working memory (Ravizza et al., 2006; Schmahmann, 2003).

This research provides a compelling case for significant utilization during cognitive development of highly specialized neural infrastructure built during motor development in the cerebellum and basal ganglia. The literature also suggests that motor development contributes a second type of neural infrastructure, involving both the motor and prefrontal areas, that adaptively controls the learning process itself whether motor or cognitive skills are being learned. Surprisingly, motor development appears to require and develop a quite sophisticated cognitive control capacity, later used when learning cognitive skills.

Adolph (2005, 2008; Adolph & Berger, 2006) suggested that researchers’ views of motor development have been naïve because they have not recognized the quite complex cognitive tasks demanded of infants. Adolph proposed that infants are learning to learn as they master locomotion and subsequent gross and fine motor skills. Infants continually have to solve complex problems in adapting and changing each movement in response to their perception of the current but ever changing environment, their changing constraints on physical movement because of physical growth of arms, limbs, and other body parts, and their current levels of neural maturation and motor capability. In essence, no two motor movements are ever the same but require continual adaptation.

New theories of motor development to help explain such child development research have addressed how children adapt to and solve these continuing motor challenges. These theories required the postulation and testing of interplay between cognitive and motor functions. The underlying conceptual model common in theoretical models of motor and some cognitive tasks is the adaptive control system that sequentially uses a trial-and-error, reward sensitive, or reinforcement feedback process that iterates and hones initial representations of cognitive or motor actions to desired objectives (Cohen & Frank, 2008; Doya, 1999, 2000; Ito, 2005).

Ito (2005) suggested that a common function shared by certain motor and cognitive-learning tasks is needed for control and manipulation of internal neural representations. In motor development, this representation involves a model of the body in the external environment that predicts, iteratively in a trial-and-error process, how to control physical movement in a way to achieve the desired motor action. For some cognitive tasks, the representation is often of abstract symbols for similar trial and error and adaptive manipulation toward a solution.

Adolph’s (2005, 2008; Adolph & Berger, 2006) learning to learn analogy suggests that the neural infrastructure built to control and guide the adaptive control process for motor skills is also used when solving cognitive problems. This control process appears to be orchestrated from the prefrontal areas but also involves the cerebellum and basal ganglia. This research suggests that virtually no new motor development or action can occur without an increasingly sophisticated cognitive capacity that adaptively controls and habituates motor actions. By the time children reach preschool age, they have developed, during motor development, quite a sophisticated cognitive capacity to initiate learning actions and use executive function skills in pursuit of motor learning. They have also developed a significant capacity to orchestrate activities among prefrontal, cerebellum, and basal ganglia that manipulates increasingly complex representational models to achieve desired motor adaptations.

The sophistication of this cognitive capacity built during motor development may depend on the challenges encountered during motor development. An important part of motor development is a spiraling process whereby newly developed motor skills provide expanding opportunity for children to experience more diverse and
ever more challenging environments that, in turn, require more complex cognitive maps. If diverse and more challenging motor environments vary for children, the cognitive capacity brought to kindergarten may also vary.

Discussion

Summary of Results

Duncan et al. (2007) used six longitudinal data sets that tracked children from before school entry through later grades to identify school readiness indicators—those skills known before school entry that strongly and consistently predicted later achievement in reading and math. The research identified early mathematical skills and attention as strong predictors of both later math and reading, whereas early reading was an important predictor of later reading. The research also found that internalizing and externalizing behaviors and social skills were not strong predictors of later math and reading.

This article utilized three of the six longitudinal data sets that measured motor skills and added these measures to similarly estimated models. 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.

Using the ECLS-K, we also tested whether a third test in addition to the math and reading given at kindergarten entrance predicted later achievement. A general knowledge test measured the child’s early comprehension of physical and social science facts. Whereas the early math and reading tests focused mainly on procedural knowledge, the general knowledge test focused mainly on declarative knowledge (i.e., elementary knowledge or comprehension of the external world). General knowledge was the strongest predictor of later reading and science and, along with earlier math, was a strong predictor of later math. General knowledge measured at kindergarten entrance may reflect early comprehension skills that are necessary when reading changes from a more procedural task in early grades (learning to read) to incorporating more comprehension around third through fifth grades (reading to learn).

Later science scores were predicted very strongly by the general knowledge test, with smaller contributions from early math—but no contribution from early reading. Attention and motor skills also predicted science scores with about equal predictive strength but were weaker than their contribution to the prediction of later math. Skills linked to early observation and comprehension of the social and physical world appear to be as important as early math and reading skills and likely should be included as an important kindergarten readiness indicator.

Eliminating kindergarten math and reading measures in predicting fifth-grade scores considerably increased the strength and statistical significance of attention and fine motor skills but left the remaining socioemotional variables as mainly insignificant or considerably less significant. Predicted effect sizes at fifth grade from improving attention and fine motor skills were around .3 and .2, respectively. In addition, effect sizes for general knowledge were .2, .3, and .4, respectively, for math, reading, and science.

Kindergarten-entrance reading and math scores’ sensitivity to a child’s age is quite strong, but this effect is reduced if developmental skills are present in the estimated equations. One interpretation is that age is not a causative mechanism but rather that age is a proxy for developmental differences that need to be specified in the equations. The significance of age as a predictor of scores declines from kindergarten entrance to fifth grade and disappears completely when developmental skills are incorporated into the equations. The complete elimination of age effects at fifth grade when developmental skills were incorporated may indicate that no other developmental skills at kindergarten entrance were missing when predicting later achievement.

Finally, the developmental and neuroscience literatures provide theories and evidence to support the use of the neural infrastructure built during motor development during cognitive development. This neural infrastructure includes highly specialized capacities in the basal ganglia and cerebellum that are used in specific types of learning and sophisticated adaptive control capacity that may be essential to both motor and cognitive learning. Adolph (2008) suggested that we learn how to learn during motor development.

Concluding Remarks

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.

There are few interventions directly testing whether strengthening early attention, fine motor skills, or knowledge of the world would improve later math and reading achievement. Schellenberg (2004) provided experimental evidence that an 8-month intervention that provided first graders with musical keyboard and voice training in small groups twice a week boosted Wechsler Intelligence Scale for Children cognitive scores (effect size = .35), but providing similar structured drama training did not improve cognitive scores. One main difference between the interventions was the increased use of fine motor skills in the musical interventions but not the drama intervention. Diamond, Barnett, Thomas, and Munro (2007) reported an experiment with a curriculum directed
toward strengthening executive function skills with promising results on cognitive skills.

Current experimental interventions mainly focus on changing the child’s instructional environment without understanding how that change will influence the neural development underlying later cognitive performance. Almost all of these interventions involve changing the way that math and reading are taught: earlier instructional (prekindergarten), different curriculum, better classroom climate and teaching, and additional time on task. The results of our research would certainly support improved early math and reading because these early skills are strongly predictive of later math and reading. As in Duncan et al. (2007), our results suggest that early math should receive additional emphasis because reading has already been receiving additional emphasis and math is more predictive of later math and reading than is early reading. However, an important question is whether significant marginal gains can be obtained in early math and reading from instructional interventions, given the overwhelming focus of past interventions.

Our results suggest that the focus of interventions should shift from a primary emphasis on changing the direct math and reading instructional environment to interventions that build better foundational skills of attention and fine motor skills and a better understanding of the world outside schools. The results suggest that current direct math and reading instruction is insufficient to build attention and fine motor skills. Building these skills may rely more on subjects and curricula that have been de-emphasized to provide more math and reading instruction: the arts, music, dance, physical education, and free play. Each of these subjects and curricula may need to be redesigned to focus on building foundational skills in the same way that math and reading have been redesigned in recent years. Building stronger knowledge of the external world also suggests that improving early science and social studies curricula are important. Paradoxically, higher long-term achievement in math and reading may require reduced direct emphasis on math and reading and more time and stronger curricula outside math and reading.

However, it is also likely that building improved attention, fine motor skills, and knowledge of the world will require family, parental, and societal emphasis before the start of school and outside of school once children start school. Disadvantaged children from all racial/ethnic groups likely have fewer opportunities to build these skills than more advantaged children. For instance, Grissmer and Eiseman (2008) reported that achievements gaps found later in schooling between racial/ethnic groups are largely present before school entry, suggesting that differences in earlier environments and differential access to quality preschools primarily cause score gaps. Grissmer and Eiseman also reported that substantial gaps are present in attention and fine motor skills between Black and White students at kindergarten entrance and may account for up to 40% of the Black–White achievement gap. The Black–White achievement gaps in reading and math have not been closed in a sustained way over the past 25 years despite substantial increases in school spending and the implementation in virtually all states of standards-based accountability systems that emphasize math and reading performance (Magnuson & Waldfoelge, 2008). Closing these gaps may be less about better math and reading instruction than about building better attention and fine motor skills and better awareness and knowledge of the external world. It is likely that much of this work needs to be done before kindergarten in extended preschools and in families and perhaps in after-school programs.

In addition to suggesting new priorities for intervention, experimentation, and educational and social policies, these results should spur new developmental and neuroscience research that links these early skills through causative mechanisms to later achievement. This literature over the past 10 years has provided substantial support for significant contributions of executive function and motor development to later cognitive development. Building stronger theories and knowledge about the interrelationships among attention, fine motor skills, knowledge of the world, and the potential causative mechanisms that might link them to later achievement can result only in better design and increased power and efficiency of interventions.

References


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.


