Journal of Educational Psychology
2010, Vol. 102, No. 4, 860–871

0022-0663/10/$12.00 DOI: 10.1037/a0019454

Accomplishment in Science, Technology, Engineering, and Mathematics (STEM) and Its Relation to STEM Educational Dose: A 25-Year Longitudinal Study

Jonathan Wai
Duke University

David Lubinski, Camilla P. Benbow, and James H. Steiger
Vanderbilt University

Two studies examined the relationship between precollegiate advanced/enriched educational experiences and adult accomplishments in science, technology, engineering, and mathematics (STEM). In Study 1, 1,467 13-year-olds were identified as mathematically talented on the basis of scores ≥ 500 (top 0.5%) on the math section of the Scholastic Assessment Test; subsequently, their developmental trajectories were studied over 25 years. Particular attention was paid to high-level STEM accomplishments with low base rates in the general population (STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations). Study 2 retrospectively profiled the adolescent advanced/enriched educational experiences of 714 top STEM graduate students (mean age = 25), and related these experiences to their STEM accomplishments up to age 35. In both longitudinal studies, those with notable STEM accomplishments manifested past histories involving a richer density of advanced precollegiate educational opportunities in STEM (a higher "STEM dose") than less highly achieving members of their respective cohorts. While both studies are quasi-experimental, they suggest that for mathematically talented and academically motivated young adolescents, STEM accomplishments are facilitated by a rich mix of precollegiate STEM educational opportunities that are designed to be intellectually challenging, even for students at precocious developmental levels. These opportunities appear to be uniformly important for both sexes.

Keywords: educational acceleration, gifted, longitudinal study, STEM, talent searches

Supplemental materials: http://dx.doi.org/10.1037/a0019454.supp

Professional educators in gifted education recommend that acceleration combined with enrichment should be considered best professional practice when serving the needs of gifted students (National Mathematics Advisory Panel, 2008; Rogers, 2007). Studies of acceleration for intellectually talented and highly motivated students have covered a wide array of opportunities including advanced subject matter placement, special classes, and taking college courses in high school (Benbow & Stanley, 1996; Bleske-Rechek, Lubinski, & Benbow, 2004; Colangelo, Assouline, & Gross, 2004; Heller, Mönks, Sternberg, & Subotnik, 2000; Kulik & Kulik, 1984). Most studies have compared participants receiving one of these opportunities to their intellectual peers who did not receive it (see Table S1 in the online supplemental material); for example, comparing participants who had an Advanced Placement (AP) course before college (Bleske-Rechek et al., 2004) or a college course when in high school (Brody, Assouline, & Stanley, 1990) to those who did not. Although individual studies of this kind are too numerous to review, a major meta-analysis by Kulik and Kulik (1984) concluded that educational acceleration generally has a positive effect on learning (average *ES* = .88). A summative report of an international summit reached a consensus on the educational efficacy of acceleration for highly motivated and intellectually talented adolescents (Colangelo et al., 2004); and, more recently, the National Mathematics Advisory Panel (2008) concluded on the basis of the best scientific evidence that mathematically gifted students who are motivated to do so should be allowed to accelerate educationally. Support for the use of enrichment by itself, while positive, is less compelling (Rogers, 2007). In combination with acceleration, however, enrichment is more potent, and this makes sense intuitively. Speeding up learning and not going deeper or making it more complex would seem empty.

The current investigation seeks to extend knowledge on practices benefiting gifted students in a number of ways. First, rather than comparing mathematically talented students participating in

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This study was based on a dissertation submitted to Vanderbilt University by Jonathan Wai in partial fulfillment of the doctor of philosophy degree. Support for this study was provided by a research and training grant from the Templeton Foundation and National Institute of Child Health and Development Grant P30 HD 15051 to the Vanderbilt Kennedy Center for Research on Human Development. Earlier versions of this article benefited by comments from Stephen N. Elliott, Gregory Park, Kimberley Ferriman Robertson, Stijn Smeets, Andrew J. Tomarken, and Maya Wai.

Correspondence concerning this article should be addressed to Jonathan Wai, Talent Identification Program, Duke University, 1121 West Main Street, Durham, NC 27701, or to David Lubinski, Camilla P. Benbow, or James H. Steiger, Department of Psychology and Human Development, Vanderbilt University, 0552 GPC, 230 Appleton Place, Nashville, TN 37203. E-mail: jon.wai@duke.edu, david.lubinski@vanderbilt.edu, camilla.benbow@vanderbilt.edu, or james.h.steiger@vanderbilt.edu

one advanced learning opportunity to their intellectual peers whom have not experienced it, we introduce the concept of "educational dose" (viz., the density of advanced and enriching precollegiate learning opportunities beyond the norm that students have participated in), which serves as a rough estimate of the amount of intellectual stimulation provided through various interventions or opportunities. The important thing is that needs are met with the appropriate amount and the right mix. Some students differ in their preferences, and some school districts will offer certain opportunities but not others to keep students appropriately challenged and motivated. Because differences in exposure and opportunity vary widely within intellectually talented student populations, we were able, in the two studies that follow, to examine the extent to which individual differences in experiencing these opportunities subsequently factor into differential accomplishments later in life, in particular to ascertain how these experiences relate to real-world accomplishments in science, technology, engineering, and mathematics (STEM). More specifically, we focus on mathematically talented participants, differences in advanced/enriching precollegiate STEM learning experiences (or a STEM educational dose), and STEM outcomes assessed up to 25 years later (viz., STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations). We ask, within this population, what is the relationship between educational dose and accomplishments much later in life? Is there a pay-off for experiencing a higher educational dose?

Participants for this investigation are drawn from the Study of Mathematically Precocious Youth (SMPY; Lubinski & Benbow, 2006). Study 1 tracks 1,467 mathematically talented (top 0.5%) adolescents over 25 years and examines their STEM accomplishments as a function of the density of their advanced precollegiate educational experiences in STEM. Study 2 retrospectively profiles the specific adolescent educational histories of a sample of 714 top STEM graduate students (identified as first- or second-year graduate students in 1992) and assesses their impact on STEM accomplishments up to age 35. Each study consists of two phases; in the first we examine how the constituents of STEM educational dose operate in aggregate, whereas in the second we ascertain how they operate individually. Finally, in Study 2, because this cohort of STEM graduate students is balanced in gender representation, we take a detailed look at their early educational histories to determine whether contrasting opportunities factor into differential accomplishments in STEM as a function of sex.

The Concept of Educational Dose

We decided that our conceptualization of educational dose should encompass accelerating and enriching opportunities. Figure 1 contains examples of some components of educational dose. Figure 2 contains a more circumscribed dose refinement involving only STEM, which we utilize in this study, as well as the outcome criteria we seek to predict as a function of STEM educational dose. Technical clarification of the dose components found in Figures 1 and 2 is given in Table 1. In Study 1, we hypothesized that mathematically talented adolescents with a higher dose of STEM educational opportunities would achieve more STEM accomplishments later in life in comparison to their intellectual peers with relatively fewer of these opportunities. In Study 2, we hypothesized the same for top STEM graduate students (but here the learning experiences are assessed from retrospective reports).

The idea behind educational dose is similar to formulations of interchanging interventions and measures in other contexts. For example, what matters most when one works to improve his or her physical health is not that one must eat one particular type of food or exercise in a particular way but that an individual has a good mix of healthy foods and appropriate exercise. No one opportunity or thing is required. We suspect the same would be true for developing academic expertise and knowledge. Just as powerful psychological constructs can be measured in commensurate ways through distinct assessment vehicles (Campbell & Fiske, 1959; Lubinski, 2004), powerful educational interventions can be delivered in multiple ways through contrasting educational opportunities that engender commensurate stimulation for intellectually talented youth.

Study 1

Method

Participants. Participants were taken from the first three of SMPY's (Lubinski & Benbow, 2006) talent search cohorts (i.e., Cohort 1: 1972–1974, Cohort 2: 1976–1978, and Cohort 3: 1980–1983). Cohort 1 includes 2,188 participants who scored ≥ 390 on the math section of the Scholastic Assessment Test (SAT-M) or ≥ 370 on the verbal section of the Scholastic Assessment Test (SAT-V) before age 13. Cohort 2 includes 778 participants who scored SAT-M ≥ 500 or SAT-V ≥ 430 before age 13. Cohort 3

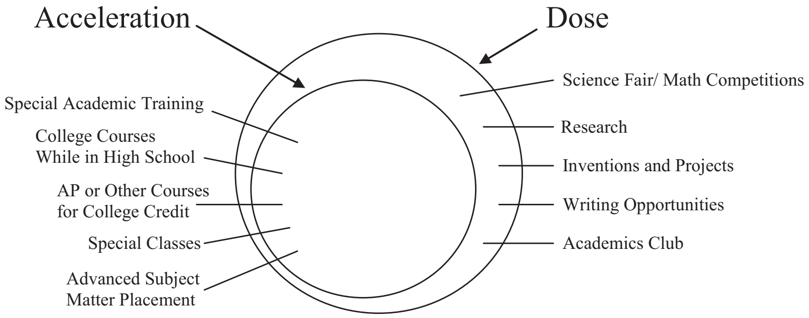

Figure 1. Illustration of how educational dose encompasses more than acceleration. Technical clarification of each of the components can be found in Table 1.

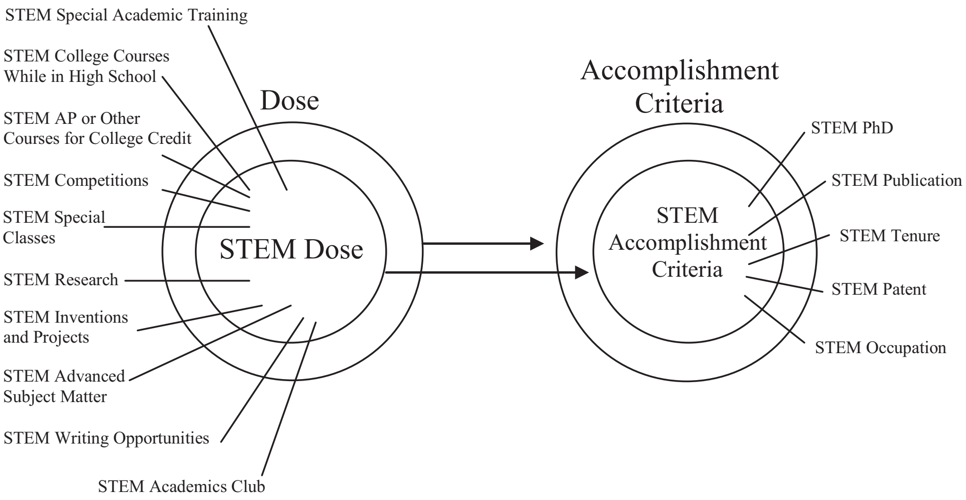

Figure 2. Illustration of the hypothesized relationship between STEM educational dose and STEM outcomes. The STEM educational dose components are listed on the left, and the STEM achievement outcomes are listed on the right. Descriptors in Table 1 are appropriate for this figure as well but are restricted to STEM educational experiences. STEM = science, technology, engineering, and mathematics.

includes 501 participants who scored SAT-M ≥ 700 or SAT-V ≥ 630 before age 13. Academic talent searches are conducted every year across the United States. Typically, college entrance exams such as the SAT, specifically the math (SAT-M) and verbal (SAT-V) sections, designed for college-bound high school seniors, are given to participants before the age of 13. This is considered above-level testing, and the idea is that students who are scoring at the very top of their within-grade standardized achievement tests are measured more accurately with a psychometric tool that has enough "ceiling" to adequately capture the scope of their intellectual capacity.

From these cohorts (viz., Cohort 1: 1972–1974, Cohort 2: 1976–1978, and Cohort 3: 1980–1983), three mathematically precocious subsets were formed: The first two subsets were Cohort 1 and 2 participants who scored SAT-M ≥ 500 by age 13 (those in the top 1 in 200 in quantitative reasoning ability for their age) and who also had 20-year follow up data. The final subset included Cohort 3 participants who scored SAT-M ≥ 700 by age 13 (those in the top 1 in 10,000 in quantitative reasoning ability for their age) with 20-year follow-up data (Lubinski & Benbow, 2006).

The reason for restricting our focus to participants with high SAT-M scores is because we wanted to ensure that all participants had great promise for STEM accomplishments (Lubinski & Benbow, 2006; Park, Lubinski, & Benbow, 2007, 2008; Wai, Lubinski, & Benbow, 2009). The SAT-M is ideal for identifying STEM talent because of the abstract and novel nature of the questions for 13-year-olds (Benbow, 1988). Restricting selection criteria to the SAT-M resulted in the following sample sizes, by sex, for each talent search cohort: 1972–1974 talent search (boys = 518, girls = 258); 1976–1978 talent search (boys = 341, girls = 126); and 1980–1983 talent search (boys = 203, girls = 21).

STEM educational dose. STEM educational dose was the focal predictor. Thus, within each cohort, STEM educational experiences beyond the typical fare were weighted equally (each given a weight of 1), and within each talent search cohort the number of different STEM educational experiences were summed to index the dose level. As a clarifying example, a STEM dose level of 3 could equal AP or course taken for college credit plus special academic training plus college courses in high school, or 3 could equal research plus special classes plus academic competition. Participants in the 1972–1974 talent search (Cohort 1) had the fewest opportunities, and participants in the 1980–1983 talent search (Cohort 3) had the most (see Table 2). The opportunity for

Table 1
Description of Educational Dose Components Found in Figures 1 and 2

Dose component	Description
Special academic training	Having learned a subject outside of the regular curriculum or having any special training from parents, relatives or other adults, schools, or others.
College courses while in high school	Having taken a college course while still in high school.
Advanced Placement or other courses for college credit	Having taken an Advanced Placement or College Board Achievement Test for college credit.
Science fair/math competitions	Having participated in a science fair or math competition.
Special classes	Having taken a special class.
Research	Having conducted research.
Inventions and projects	Having an invention or a special project.
Advanced subject matter placement	Having taken advanced subject matter placement.
Writing opportunities	Having edited a paper or publication, written a published magazine article, presented a paper or participated in a colloquium, written a published scientific article or book chapter, written a published news article, or having a publication in preparation.
Academics club	Having participated in an academic club.

Table 2
STEM Educational Dose Components for Each of the Talent Search Cohorts

Dose component	1972–1974 talent search (Cohort 1)	1976–1978 talent search (Cohort 2)	1980–1983 talent search (Cohort 3)
Special academic training	Yes	Yes	Yes
College courses while in high school	Yes	Yes	Yes
Advanced Placement or other courses for college credit	Yes	Yes	Yes
Science fair/math competitions	Yes	Yes	Yes
Special classes		Yes	Yes
Research		Yes	Yes
Inventions and projects		Yes	Yes
Advanced subject matter placement			Yes
Writing opportunities			Yes
Academics Club			Yes

Note. STEM = science, technology, engineering, and mathematics.

educational experiences beyond the norm has changed over time, with more recently identified cohorts having more opportunities available. In accordance with this, the median level of dose for each of the talent search cohorts is different, increasing over time, but also as a function of ability level (see Table S2 in the online supplemental material).

Criteria. Five outcomes constituted the criterion variables for this study: STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations. At approximately age 33, participants from each of the talent search cohorts were surveyed through either the Internet, mail, or by phone (Benbow, Lubinski, Shea, & Eftekhari-Sanjani, 2000; Lubinski, Benbow, Webb, & Bleske-Rechek, 2006).

Whether an individual had earned a STEM PhD was determined through the age 33 follow-up surveys and was augmented by an Internet search. Some participants who did not report that they had earned a STEM PhD, or who did not respond to the age 33 survey, reported that they had earned a STEM PhD on their websites. For those participants who had attained a position in the professoriate or who had earned a doctorate by the time of the age 33 follow-up, whether or not they had achieved tenure was determined through their academic websites. To ensure that each participant found on an academic website was indeed the correct person, we used additional information (e.g., college attended or major) for verification. In order to update participants' achievement data, we used Google patents to determine whether they had secured a patent (www.google.com/patents). We used Google scholar (www.google.com/scholar) to determine whether a participant had secured a peer reviewed publication, with the program Publish or Perish, which utilizes Google scholar, as the primary tool used (www.harzing.com/pop.htm). Occupational data were obtained utilizing the age 33 follow-up surveys. For all three cohorts, these follow-up data were collected at least a quarter of a century after the participant's initial identification with the exception of occupational data, which were collected 20 years after initial identification.

Phase 1

First, for each cohort separately, we established high and low STEM dose groups using a median split for analytic purposes. Utilizing a median split instead of a finer resolution seemed appropriate not only because of the relatively small within cohort sample sizes and low base rate of the STEM outcome criteria, but also because some components of STEM dose are likely more important than others, and not all opportunities in the same category were uniformly rigorous.

The group scoring at the median was included in either the high- or low-dose group to achieve as close to a 50/50 split as possible. When we examined the STEM dose frequencies by cohort in Table S2, this strategy resulted in the median being included in the low-dose group for Cohorts 1 (*n*s: low = 435, high = 341) and 3 (*n*s low = 115, high = 109), and the median being included in the high-dose group for Cohort 2 (*n*s: low = 196, high = 271). Following this classification, for each cohort, we plotted the high-dose versus the low-dose groups on all criteria: STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations. Moreover, these analyses also take SAT-M ability differences into account in the following way.

For the low- and high-dose groups for each cohort, we plotted age 13 SAT-M means on the x-axis, and the proportion earning a particular STEM outcome on the y-axis. Independent sample t tests were utilized to test whether there is a significant difference between the average age 13 SAT-M scores for the high- and low-dose groups. Finally, confidence intervals around the differences between (high versus low) proportions as well as confidence intervals around the ratios of proportions or gain ratios are computed (Agresti, 2002, 2007). What we call *gain ratio* throughout this article is statistically equivalent to what is normally termed *relative risk*. Since in our study the outcome is positive (rather than negative, which is typically the case in epidemiology), we changed the terminology to make it more conceptually appropriate and potentially less confusing.

Results. Figure 3 graphs the percentages earning a particular STEM outcome, for each cohort, as a function of STEM dose. First, we examined the SAT-M mean differences between the high- and low-STEM-dose groups within each cohort: Cohort 1 (low = 557, high = 583, difference = 26 points, $t = 6.59$, $p < .001$), Cohort 2 (low = 557, high = 581, difference = 24 points, $t = 4.84$, $p < .001$), and Cohort 3 (low = 728, high = 730, difference = 2 points, $t = 0.43$, $p = .671$). Although the SAT-M mean differences for Cohorts 1 and 2 were statistically significant and cannot be dismissed, these differences may not mean much

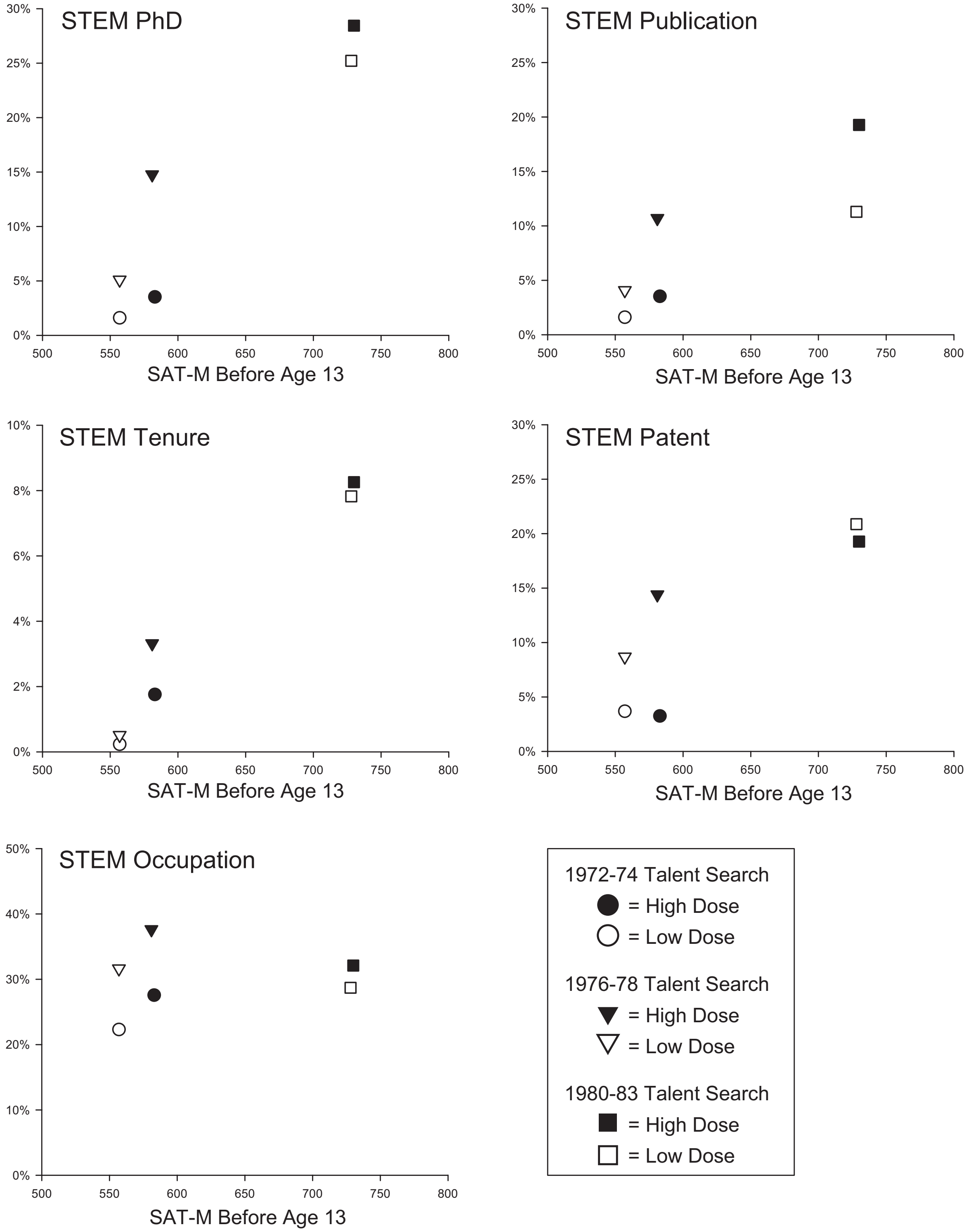

Figure 3. The data within each cohort examining the relationship between a high- or low-STEM dose and the proportions earning a particular STEM outcome (i.e., STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations). For each graph, circles indicate Cohort 1, triangles indicate Cohort 2, and squares indicate Cohort 3. Low-dose groups are denoted by an open or unfilled shape, whereas high-dose groups are denoted by a closed or filled shape. SAT-M scores before age 13 are plotted on the *x*-axis for the low- and high-dose groups, and the proportion of each group earning a particular STEM outcome is plotted on the *y*-axis. STEM = science, technology, engineering, and mathematics; SAT-M = math section of the Scholastic Assessment Test.

substantively (Lykken, 1968; Meehl, 1978). For example, within the top 1% of math ability, when comparing the top quartile to the bottom quartile on some of these important STEM outcomes in an earlier study involving 1,975 participants (Wai, Lubinski, & Benbow, 2005), the SAT-M difference was >160 points (age 13 SAT-M for Quartile 1 = 455, whereas Quartile 4 = 620), and this ability difference was associated with a doubling of the gain ratio of achieving such outcomes. Therefore, the 26- and 24-point SAT-M differences are not likely to be the full explanation for any differential STEM outcomes of a substantive nature between the low- and high-dose groups for Cohorts 1 and 2, respectively.

Turning to the longitudinal outcomes reported in Figure 3, for all three cohorts combined and across all five criteria, 13 of 15 contrasts (87%) were in the hypothesized direction. For STEM PhDs, STEM publications, STEM tenure, and STEM occupations, each of the high-dose groups earned a higher percentage of a particular outcome than the low-dose group. The exception was the reversed trends for STEM patents for Cohorts 1 and 3, although the hypothesized contrast was confirmed for Cohort 2. The overall pattern is marked by trends in the hypothesized direction for these STEM outcomes as a function of STEM educational dose.

In order to determine whether the percentage differences between the high- and low-dose groups for each outcome variable were statistically significant, we computed 95% confidence intervals around the differences between proportions and 95% confidence intervals around the ratios of proportions (gain ratios). As the sample sizes for these outcomes within each cohort were relatively small, Table 3 presents data aggregated across cohorts to establish more stable results.

In Table 3, the 95% confidence intervals around the differences between proportions and gain ratios did not include zero or one, respectively, with the exception of those computed for STEM patents, which fell just short of not including zero or one. An additional analysis examining the percentage of participants in the high- and low-dose groups who had earned at least one of the STEM outcomes was also computed and found to be significant (see Table 3). Overall, the pattern of findings in Figure 3 combined with nearly all the statistical test confidence intervals not including zero or one found in Table 3 suggest that having a higher in comparison to a relatively lower STEM educational dose is associated with a significant difference in the STEM accomplishments, even when taking ability into account.[1]

Phase 2

This phase focused on each particular component of STEM educational dose as a function of the five STEM outcome criteria utilized in Phase 1. While we anticipated a higher proportion of STEM outcomes as a function of having participated in each component of STEM dose, we thought it would be valuable to detail the proportion of participants falling in each STEM dose component as a function of whether they accomplished a particular STEM outcome. If our thinking about educational dose is at least somewhat correct, we reasoned that there should be a fairly consistent pattern throughout (i.e., those earning a particular STEM outcome would have higher proportions in each STEM dose component in comparison to those who did not earn that STEM outcome).

To illustrate graphically the extent to which these hypothesized relationships hold, we either unshaded or shaded each contrast to form a hit/miss density graph (see Table 4). Contrasts not in the hypothesized direction are shaded in light gray, while contrasts in the hypothesized direction are unshaded. Those regions in the table with data unavailable were left blank. What is anticipated is a primarily unshaded table of contrasts indexing the amount of support for the hypothesized relationships. To give readers a more precise descriptive profile of these educational experiences for each outcome, we provide the percentage of participants in each cell also for all three talent search cohorts.

Results. Data for the STEM dose components by STEM outcome are found in Table 4. Overall, the table is primarily unshaded, illustrating a relatively high density of confirmed predictions. For the three talent search cohorts combined, 76 of the 105 contrasts (72%) were in the hypothesized direction. While these results are suggestive, a more detailed examination of these data provides a more informative picture.

When these data are examined by cohort, for Cohorts 1 and 2, the vast majority of the contrasts were in the hypothesized direction: Cohort 1 = 85%, Cohort 2 = 91.4%. In addition, for these two cohorts, there were similarities in the average difference across all contrasts: That is, the difference between the high- and low-dose groups was computed for each contrast; and then, an average of all these differences was taken for each cohort. For Cohorts 1 and 2, these average percentages were 11.1% and 11.8%, respectively, both fairly impressive and in the hypothesized direction. For Cohort 3, however, only 54% of the contrasts were in the hypothesized direction; and, furthermore, the average difference across all contrasts was a miniscule 1.1%. Something appears to be different about this profoundly gifted cohort, whose participants were identified by scoring in the top 0.01% in mathematical reasoning ability. A clue may be found in Table 4.

In Table 4, those components that were more individualized for Cohort 3 (i.e., research, inventions and projects, and writing opportunities) had 14 of the 15 contrasts (93%) in the hypothesized direction. And the average difference among these 15 contrasts was 11.4%. The one contrast that was not in the hypothesized direction was for STEM patents, which seems to be a different phenomenon from the other outcome variables. Therefore, for whatever reason, when restricting the analysis to components more tailored to the individual, the findings for Cohort 3 align with those found in the other talent search cohorts. At least 85% of comparisons were in the predicted direction in all 3 Cohorts.

Discussion

Findings in Study 1 suggest that the number of precollegiate STEM educational opportunities beyond the norm that mathematically talented adolescents experience is related to subsequent STEM accomplishments achieved over 20 years later. Moreover,

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[1] In addition to computing the 95% confidence intervals around proportion differences and gain ratios for cohorts combined weighted by *N* (adding up the numerators and denominators of the proportions across cohorts), we also computed the same statistics combining the cohorts by weighting each proportion equally (adding up the proportions for each cohort and dividing by three). The results of these analyses were very similar to those in Table 3 and can be found in Table S5.

Table 3
Descriptive Statistics of Low- and High-STEM-Educational-Dose Percentages by STEM Outcome Variable

Cohorts combined (weighted by *n*)	Low dose	High dose	95% CI proportion differences	Gain ratio	95% CI gain ratio
STEM PhD	6.2%	11.5%	[0.025, 0.082]	1.865	[1.320, 2.636]
STEM publication	3.8%	8.6%	[0.024, 0.073]	2.291	[1.483, 3.539]
STEM tenure	1.6%	3.3%	[0.001, 0.033]	2.068	[1.042, 4.104]
STEM patent	7.6%	9.9%	[−0.007, 0.051]	1.289	[0.924, 1.799]
STEM occupation	25.7%	32.0%	[0.017, 0.109]	1.245	[1.059, 1.463]
At least one of the above	30.7%	39.5%	[0.040, 0.137]	1.288	[1.119, 1.483]

Note. Shown are 95% confidence intervals around the proportion differences, gain ratios, and 95% confidence intervals around the gain ratio values. STEM = science, technology, engineering, and mathematics.

the methodology utilized in this investigation affords quantitative statements about the likelihood of individual STEM outcomes, and the potential payoff of being in the higher versus the lower dose group. For example, for STEM publications, those in the high-dose group were approximately 2.3 times as likely to produce a STEM publication as those in the low-dose group. Similar statements can be made about the high-dose compared to the low-dose group for STEM PhD (≈1.9 times as likely) and STEM tenure (≈2.1 times), and to some extent STEM occupation (≈1.2) and STEM patent (≈1.3), which highlights how the family of STEM outcome functions covary with STEM educational dose. Obviously, other outcomes could be added to these in subsequent research.

Keep in mind that the STEM achievements under analysis here are rare phenomena. Thus, it is noteworthy that having a higher compared to a lower dose might approximately double the likelihood of earning one of these low-base-rate accomplishments. While ability differences among intellectually talented students do make a difference in achieving educational and occupational accomplishments in STEM (Benbow, 1992; Park et al., 2007, 2008; Wai et al., 2005), the small SAT-M ability differences observed between the high- and low-STEM-educational-dose levels within each cohort are unlikely to account for all the differences in STEM outcomes observed. For example, other findings have suggested that SAT-M differences of around 160 points are required for this population to double the gain ratio of the outcomes under analysis here (Wai et al., 2005). Thus, rather than the statistically significant differences in SAT-M means among the high- and low-dose groups of Cohorts 1 and 2, namely, 26 and 24 points, respectively, generating these outcomes, some combination of the richness of their early STEM educational experiences and other personal attributes beyond mathematical talent are more likely candidates.

Whereas earning a STEM PhD, writing a STEM publication, obtaining STEM tenure, and entering a STEM occupation are related (e.g., a STEM PhD is needed to get STEM tenure, which is a STEM occupation), STEM patents seem to be a different phenomena. In order to earn a STEM patent, for example, a STEM PhD is not required (e.g., an engineer with a STEM bachelor's degree, or even no degree at all, can earn a STEM patent). In addition, traditional STEM educational components (such as an AP calculus class) may not facilitate earning a STEM patent. Therefore, it seems important to investigate what personal attributes and educational experiences are associated with earning STEM patents.

In a more nuanced examination of the particular components of STEM educational dose as a function of STEM accomplishments, the findings were both revealing and suggestive of further research. The pattern of relationships among the individual components of STEM dose and the five outcome variables were similar within two of the three talent search cohorts, with ≥ 85% of the contrasts resulting in the hypothesized direction for Cohorts 1 and 2; and the magnitude of these differences was also impressive, 11.1% and 11.8%, respectively. When restricting the analysis to components that were more individualized (i.e., research, inventions and projects, and writing opportunities) and, thus, could be more responsive to the special needs of the profoundly gifted, the findings for Cohort 3 become aligned with those of the other two talent search cohorts. When coupled with other findings on individual differences in outcomes between the modestly gifted and the profoundly gifted (Benbow & Stanley, 1996; Colangelo et al., 2004; Lubinski, Webb, Morelock, & Benbow, 2001; Park et al., 2007, 2008; Stanley, 2000), these findings suggest that future researchers should routinely take individual differences in ability into account when crafting interventions for intellectually talented youth. Because intellectually talented adolescents are not a categorical type (Achter, Lubinski, & Benbow, 1996), it is likely that multiple educational opportunities in different amounts are required to meet their learning needs.

Study 2

One of the contributions of Study 1 is that it is based on participants who were identified as possessing the mathematical reasoning abilities to excel in STEM. This is important, because there is much written about developing and retaining STEM talent without taking into account the dimensions of human individuality that are important for the development of exceptional STEM professionals (Lubinski, 2010, pp. 230–235). Mathematical ability is one of them. However, there are other attributes that characterize exceptional achievers in STEM, such as motivation (Ceci, Williams, & Barnett, 2009; Geary, 2005; Lubinski & Benbow, 2000, 2006; Lubinski, Benbow, Shea, Eftekhari-Sanjani, & Halvorson, 2001). Perhaps the reason that the talent search participants in the high-dose groups achieved more is because they were more motivated? That is, they participated in more advanced STEM learning opportunities and subsequently achieved more in STEM than the low-dose groups because they simply were more motivated. Motivation may be the causal, catalytic or multiplicative (Simonton, 1999), variable rather than educational dose. This is an important competing explanation for the findings in Study 1. Therefore, Study 2 focuses on a fresh cohort of highly motivated

Table 4
Contrasts for the Talent Search Cohorts (Cohorts 1, 2, and 3) Representing a Hit/Miss Density Graph

	STEM PhD		STEM publication		STEM tenure		STEM patent		STEM occupation	
Dose component	Y	N	Y	N	Y	N	Y	N	Y	N
Special academic training										
Cohort 1	42.1	38.2	47.4	38.0	71.4	38.0	33.3	38.5	41.9	37.1
Cohort 2	80.0	62.4	78.4	63.0	90.0	63.7	75.0	62.8	66.5	63.0
Cohort 3	75.0	77.4	79.4	76.3	72.2	77.2	77.8	76.5	80.9	75.0
College courses while in high school										
Cohort 1	10.5	13.1	15.8	12.9	14.3	13.0	18.5	12.8	17.8	11.5
Cohort 2	50.0	27.3	48.6	28.1	50.0	29.3	42.9	28.0	32.3	28.4
Cohort 3	40.0	44.5	41.2	43.7	33.3	44.2	37.8	44.7	39.7	44.9
Advanced Placement or other courses for college credit										
Cohort 1	94.7	61.4	78.9	61.8	85.7	62.0	74.1	61.8	66.5	60.9
Cohort 2	76.0	61.4	81.1	61.4	80.0	62.6	67.9	62.3	64.6	62.0
Cohort 3	61.7	70.1	61.8	68.9	44.4	69.9	57.8	70.4	64.7	69.2
Science fair/math competitions										
Cohort 1	47.4	31.2	47.4	31.2	71.4	31.2	22.2	31.9	36.6	29.9
Cohort 2	68.0	62.6	73.0	62.3	80.0	62.8	66.1	62.8	60.4	20.5
Cohort 3	65.0	61.0	64.7	61.6	66.7	61.7	53.3	64.2	54.4	65.4
Special classes										
Cohort 1										
Cohort 2	34.0	21.6	21.6	23.0	40.0	22.5	28.6	22.1	27.4	20.5
Cohort 3	90.0	87.2	88.2	87.9	88.9	87.9	88.9	87.7	88.2	87.8
Research[a]										
Cohort 1										
Cohort 2	30.0	9.6	21.6	10.9	10.0	11.8	23.2	10.2	11.0	12.2
Cohort 3	33.3	15.9	41.2	16.8	33.3	19.4	17.8	21.2	23.5	19.2
Inventions and projects[a]										
Cohort 1										
Cohort 2	40.0	26.9	29.7	28.1	30.0	28.2	42.9	26.3	29.3	27.7
Cohort 3	86.7	78.7	91.2	78.9	94.4	79.6	88.9	78.8	83.8	79.5
Writing opportunities[a]										
Cohort 1										
Cohort 2										
Cohort 3	30.0	21.3	38.2	21.1	44.4	21.8	26.7	22.9	32.4	19.9
Advanced subject matter placement										
Cohort 1										
Cohort 2										
Cohort 3	28.3	31.7	29.4	31.1	22.2	31.6	37.8	29.1	33.8	29.5
Academics club										
Cohort 1										
Cohort 2										
Cohort 3	10.0	15.2	11.8	14.2	5.6	14.6	8.9	15.1	13.2	14.1

Note. An unshaded contrast denotes a result in the hypothesized direction (e.g., proportion of participants participating in a STEM dose component was greater for the group earning a particular STEM outcome than for the group that did not earn that outcome). A contrast shaded light gray denotes a result not in the hypothesized direction. STEM = science, technology, engineering, and mathematics.
[a] These are the opportunities tailored to the individual highlighted in the text for Cohort 3.

participants selected by a different criterion: graduate study in exceptional STEM programs.

The ability level of these participants was similar to SMPY participants identified by SAT-M ≥ 500 by age 13 (Lubinski, Benbow, et al., 2001), but, beyond their mathematical reasoning ability, essentially all of these graduate students were highly motivated and successful in achieving in STEM. They had a long history of being motivated and applying themselves. After all, they all gained admission into top STEM graduate training programs in the United States. Therefore, we thought it would be compelling to examine their educational histories in detail and to determine whether, even for this highly select and motivated group, the density of their precollegiate advanced educational experiences in STEM is related to their subsequent STEM accomplishments. In addition, because there is a large enough sample of men and women to make reliable comparisons, we also profiled their components of STEM educational dose by sex against the five STEM criteria utilized in Study 1. To our knowledge, a fine-grained analysis of the educational experiences of top STEM graduate students has never been conducted for meaningful real-world accomplishments in STEM or as a function of sex.

Method

Participants and procedure. In 1992, a sample of 714 top STEM first-and second-year graduate students in the United States was identified by SMPY (Lubinski & Benbow, 2006). They were initially surveyed at approximately age 25 (Lubinski, Benbow, et al., 2001) and again at approximately age 35 (Lubinski, Benbow, et al., 2006). The current study consists of 368 men and 346 women.

Two phases paralleling Study 1 will follow, using the same criterion variables (either secured in their 10-year follow-up survey at age 33 or using the web search methods described in Study 1). By drawing on data collected in their Time 1 survey (Lubinski, Benbow, et al., 2001), we retrospectively profiled their precollegiate STEM educational experiences. These components included college courses while in high school, AP or other courses for college credit, science fair/math competitions, special classes, and research. Table S3 in the online supplemental material provides breakdowns for STEM dose level for the full sample and by sex.

Phase 1

As in Study 1, we established high- and low-STEM-dose groups using a median split. And again, the median itself was included in either the high- or low-dose group to achieve as close to a 50/50 split as possible for the total group and each sex separately. From the STEM dose frequencies (see Table S3), this strategy resulted in the median being included in the low-dose group for the total sample as well as men and women separately. Following this classification, we determined the proportion of participants in the high-dose versus the low-dose groups on all criteria: STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations. Finally, confidence intervals around the differences between (high versus low) proportions as well as confidence intervals around the gain ratios were computed (Agresti, 2002, 2007).

Results. As seen in Table 5 for the total sample, four out of five contrasts (80%) were in the hypothesized direction for all STEM outcomes, with STEM patents as the exception. For men, five out of five contrasts (100%) were in the hypothesized direction. For women, three out of five contrasts (60%) were in the hypothesized direction, where in addition to STEM patents, STEM publications were the exception. Overall, the hypothesized trends for these STEM outcomes as a function of educational dose were supported, with STEM occupations being especially more likely as a function of STEM educational dose across all three groups. The average differences among the high- versus low-dose groups for all five criteria was as follows: total = 6.1%, men = 6.6%, and women = 5.5%.

The 95% confidence intervals around the differences between proportions and gain ratios were utilized to assess statistical significance. In Table 5, for the analyses examining participants who earned at least one STEM outcome, the results were statistically significant for the total sample as well as for men and women separately. For the individual outcomes, the results were generally significant or suggestive of significance for all three groups as well. The overall pattern seems to be consistent with the higher dose group earning significantly more STEM outcomes than the lower dose group, with the exception of STEM publications and STEM patents (for the total sample and men and women separately). STEM PhDs and tenure for the men, and STEM tenure for

Table 5

Data for the Graduate Student Sample (for Men and Women Combined, and Men and Women Separately) Examining the Relationship Between a High- or Low-STEM Dose and the Percentages Earning a Particular STEM Outcome (i.e., STEM PhDs, STEM Publications, STEM Tenure, STEM Patents, and STEM Occupations)

Graduate student	Low dose	High dose	95% CI proportion differences	Gain ratio	95% CI gain ratio
Men and women					
STEM PhD	54.9%	64.9%	[0.028, 0.172]	1.182	[1.048, 1.334]
STEM publication	54.2%	56.8%	[−0.047, 0.100]	1.049	[0.919, 1.197]
STEM tenure	10.6%	16.2%	[0.006, 0.107]	1.533	[1.048, 2.241]
STEM patent	17.5%	16.6%	[−0.065, 0.046]	0.947	[0.682, 1.314]
STEM occupation	21.4%	34.4%	[0.064, 0.196]	1.606	[1.261, 2.045]
At least one of the above	69.0%	85.4%	[0.104, 0.224]	1.238	[1.143, 1.341]
Men					
STEM PhD	56.9%	65.4%	[−0.015, 0.185]	1.149	[0.976, 1.353]
STEM publication	55.0%	60.4%	[−0.048, 0.155]	1.097	[0.921, 1.308]
STEM tenure	13.4%	19.5%	[−0.016, 0.138]	1.456	[0.912, 2.325]
STEM patent	18.2%	20.1%	[−0.062, 0.101]	1.107	[0.726, 1.690]
STEM occupation	21.1%	32.1%	[0.019, 0.202]	1.524	[1.078, 2.155]
At least one of the above	69.9%	85.5%	[0.074, 0.240]	1.224	[1.097, 1.366]
Women					
STEM PhD	52.8%	64.4%	[0.013, 0.220]	1.221	[1.022, 1.458]
STEM publication	53.3%	53.0%	[−0.109, 0.104]	0.995	[0.815, 1.215]
STEM tenure	7.6%	12.8%	[−0.014, 0.117]	1.675	[0.881, 3.186]
STEM patent	16.8%	12.8%	[−0.115, 0.035]	0.761	[0.451, 1.284]
STEM occupation	21.8%	36.9%	[0.054, 0.247]	1.692	[1.207, 2.371]
At least one of the above	68.0%	85.2%	[0.086, 0.259]	1.253	[1.115, 1.408]

Note. Shown are the proportions of participants in each group earning each STEM outcome, 95% confidence intervals around the proportion differences, gain ratios, and 95% confidence intervals around the gain ratio values. STEM = science, technology, engineering, and mathematics.

the women were suggestive of significance. With the exception of STEM patents, the gain ratios for these outcomes averaged 1.35 for these rare events.

Phase 2

Paralleling Phase 2 of Study 1, this phase took a nuanced look at each component of STEM educational dose as a function of the five STEM outcome criteria. However, in addition to examining these particulars for the total sample, we also examined these components and outcomes by sex.

Results. Table 6 includes proportions for each STEM dose component by STEM outcome for the total sample (top panel) and by sex (bottom two panels). As before, cells representing contrasts that were not in the predicted direction are shaded in light gray. For the total sample, the table has all cells unshaded, illustrating a 100% hit rate for confirmed predictions. And the magnitude of these percentage differences averaged 8.5%.

For the graduate student men, 96% of the contrasts were in the hypothesized direction, but this value dropped to 76% for women. By looking more closely at the female data, however, it becomes evident that four of the six contrasts in the nonhypothesized direction were very close in magnitude. Therefore, the average difference across all contrasts might be a more relevant measure of comparison between the men and women. Indeed, for men this average percentage was 8.4% and for women it was slightly higher at 8.7%. This suggests that there is similarity overall between the top STEM graduate student men and women in the importance of the density of their STEM educational experiences for subsequent STEM outcomes.

Discussion

The pattern of findings on educational dose and subsequent STEM outcomes was in line with those of Study 1 with 12 of the 15 contrasts (80%) resulting in the hypothesized direction for men and women combined and separately. The high-dose groups consistently earned a greater proportion of the STEM outcomes than the low-dose groups, with the exception of STEM patents for the total sample and STEM patents and STEM publications for the graduate student women.

For the analysis involving the proportion of participants earning at least one STEM outcome, the results were consistent for the total sample and for men and women separately with gain ratios running from 1.22 to 1.25. These values correspond with 1.29 observed in Study 1 for the mathematically precocious participants for earning at least one outcome. For the graduate students, however, the gain ratio values for STEM occupation were especially high: total = 1.61, men = 1.52, and women = 1.69. This is important because there is quite a bit of contemporary discourse devoted to retaining STEM talent in STEM occupations. It seems that early experiences in STEM are related to subsequent STEM occupations later in life among highly motivated and able individuals. Our other criteria are exceedingly rare and involve a creative component (patents, publications, academic tenure). They were chosen to highlight the relationship between these early leaning

Table 6
Contrasts for the Graduate Student Cohort Representing a Hit/Miss Density Graph With Men and Women Combined, and Men and Women Separately

	STEM PhD		stem publication		STEM tenure		STEM patent		STEM occupation	
Graduate student	Y	N	Y	N	Y	N	Y	N	Y	N
Men and women										
College courses while in high school	22.7	12.7	22	14.4	32.3	16.6	18.9	18.6	22.8	17.1
Advanced Placement or other courses for college credit	55.8	43.6	52.2	49.2	57	49.9	51.6	50.7	61.1	47.0
Science fair/math competitions	56.0	38.8	51.6	45.8	49.5	49.0	52.5	48.3	62.7	44.0
Special classes	78.5	62.2	74.4	68.7	82.8	70.2	77.9	70.6	89.6	65.3
Research	22.7	17.2	21.5	19.1	28.0	19.3	20.5	20.4	24.9	18.8
Men										
College courses while in high school	26.5	12.4	26.5	13.4	32.2	18.8	24.3	20.1	22.1	20.5
Advanced Placement or other courses for college credit	53.8	42.8	52.1	45.9	55.9	48.2	54.3	48.3	62.1	45.1
Science fair/math competitions	55.2	40.7	52.6	45.2	47.5	49.8	55.7	48.0	61.1	45.4
Special classes	72.6	62.1	69.7	66.9	81.4	66.0	71.4	67.8	83.2	63.4
Research	22.4	17.2	22.7	17.2	25.4	19.4	21.4	20.1	23.2	19.4
Women										
College courses while in high school	18.5	13	16.8	15.4	32.4	14.4	11.5	17.0	23.5	13.3
Advanced Placement or other courses for college credit	58.0	44.5	52.2	52.5	58.8	51.6	48.1	53.1	60.2	49.2
Science fair/math competitions	57.0	37.0	50.5	46.3	52.9	48.1	48.1	48.6	64.3	42.3
Special classes	85.0	62.3	79.9	70.4	85.3	74.4	86.5	73.5	95.9	67.3
Research	23.0	17.1	20.1	21.0	32.4	19.2	19.2	20.7	26.5	18.1

Note. An unshaded contrast denotes a result in the hypothesized direction, whereas a contrast shaded light gray denotes a result not in the hypothesized direction. STEM = science, technology, engineering, and mathematics.

experiences and rare phenomena indicative of creativity, but it is good not to lose sight of STEM occupations in general. Moreover, the particulars of their STEM educational profiles found in Table 6 paint a clear picture of the magnitude of educational experiences that these exceptional graduate students participated in at an early age. This is their educational history, and it is noteworthy how it consisted of a rich mix of advanced and enriching STEM educational experiences, which seems to have served them well in securing acceptance in top STEM graduate training programs. Finally, these opportunities appear to be equally important for both sexes.

General Discussion

This investigation introduced the concept of educational dose, namely, the number of precollegiate educational opportunities beyond the norm that students participate in. This concept was further restricted to STEM educational dose, because we were interested in uncovering the effects of educational opportunities for mathematically talented and highly motivated adolescents who subsequently go on to achieve real-world accomplishments in STEM (viz., STEM PhDs, STEM publications, STEM tenure, STEM patents, and STEM occupations). Study 1 found that a richer and deeper density of advanced educational experiences in STEM (e.g., STEM AP courses, math or science fairs, tutoring in mathematics) is associated with noteworthy accomplishments in STEM among mathematically talented and motivated young adolescents. A key question arises: Is the relationship causal or merely indicative of self-selection of brighter, more motivated students into enrichment activities? Either explanation (or indeed a combination of them) is consistent with the data. While we freely admit that the jury is still out on the issue of causality and that future research is needed to shore up our knowledge, the present results, despite their limitations, are still quite suggestive. First, our data show little differences in standardized ability scores between high- and low-dose groups. Moreover, Study 2 replicated these findings by surveying top STEM graduate students about their precollegiate educational experiences; even for this highly specialized and highly motivated group, the density of their STEM educational experiences also covaried with subsequent STEM accomplishments. Hence, motivation for STEM, at least not exclusively, does not seem to be a viable explanation for these results. In addition, the importance of these early experiences appeared to be similar for male and female STEM graduate students. For both sexes, their early learning experiences were marked by a rich concentration of advanced learning opportunities to develop expertise in STEM. Yet, those who went on to accomplish more in STEM experienced more of these opportunities.

The fact that the low- and high-dose groups do not differ substantially on ability measures and the fact that the dosage effect persists even among highly motivated graduate student populations does not rule out self-selection, but in our opinion it certainly makes it far less likely. Future research, intensely examining the personality and motivational characteristics of students at the time of participation in educational acceleration and enrichment activities, may shed additional light on this issue.

Other limitations of the current investigation are highlighted by the exceptions to the general trends that we noted in our data. First, most of the components of STEM educational dose failed to produce a consistent pattern for the profoundly gifted (viz., participants in the top 0.01% in mathematical reasoning ability) and, second, of the five longitudinal criteria examined, findings were fairly robust for STEM PhDs, STEM publications, STEM occupations, and STEM tenure but less clear cut for STEM patents. With respect to the former, a fine-grained examination of the educational experiences of the profoundly gifted revealed that they appeared to profit most from more individualized opportunities. Therefore, possibly the reason why a less consistent pattern in the profoundly gifted was observed might be that the STEM dose components examined here were not especially challenging for them (e.g., a STEM AP course). That is, the typical advanced educational opportunity provided to the gifted may not be enough for these profoundly gifted outliers. Yet, opportunities that were individualized exhibited much stronger effects, for example, opportunities to conduct research, scientific/technical projects, and STEM writing generated results for the profoundly gifted commensurate with those found in the other cohorts of talent search participants and the graduate students.

With respect to STEM patents, they seem somewhat different from the other STEM outcomes. Unlike the other criteria, STEM patents are less tied to advanced educational opportunities; and indeed, other psychological attributes might surface as highly important for achieving a STEM patent, for example, spatial ability, which was not assessed here but is an important personal resource for achieving in STEM. Selection and experimentation on this neglected dimension of cognitive functioning seems especially called for in programs for talented youth aimed at developing STEM expertise (Wai et al., 2009). Also calling out for additional research is the differential weighting of the components of STEM educational dose examined here (as well as other advanced educational opportunities). Some educational opportunities are likely to be more powerful than others (Benbow & Stanley, 1996). Moreover, perhaps different opportunities should be weighted differently, and perhaps some are moderated by the level and pattern of personal attributes among students (Corno et al., 2002). We believe that the findings presented here warrant future research on these topics.

In conclusion, there is much talk nowadays about developing future innovators in STEM (American Competitiveness Initiative, 2006; Friedman, 2005; National Academy of Sciences, 2006). Like exceptional performances in athletics and music, rare accomplishments in STEM appear to emanate from rich talent development opportunities experienced early in life. We introduce the concept of STEM educational dose to communicate the idea that there are multiple ways to meet the needs of mathematically talented youth. It may not matter so much what they get but that they get something in a sufficient dose and that a sufficient dose is likely to enhance creative production in STEM. How the components of educational dose should be weighted and individually tailored (especially for the most able) are important empirical questions in need of subsequent research. Affording intellectually talented youth different opportunities for talent development, monitoring choices, and tracking subsequent outcomes are likely to lead to more effective ways to nurture their vast range of individuality and the multidimensional potential they harbor for creative accomplishments.

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Received July 29, 2009
Revision received February 15, 2010
Accepted March 10, 2010 ■