Int. J. Engng Ed. Vol. 24, No. 2, pp. 246–259, 2008
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Students with Differing Design Processes as Freshmen: Case Studies on Change*

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Through descriptive data of students' design processes at the beginning and end of an engineering programme, we provide insights into questions of: what changes do we see in individual engineering students design processes over the course and how might these design process changes prepare students to become 'the global engineer'?

Keywords: design; problem scoping; change; engineering design task; undergraduate; engineering education research; verbal protocol analysis; case studies; personas

INTRODUCTION

THE PAST DECADE has seen increasing concern with the changes in the global economy, as in publications such as the *Flat World* [1], *A Whole New Mind* [2] and the *Engineer of 2020* [3]. These authors have identified a number of characteristics of the engineer that can succeed in this climate; the global engineer is expected to:

- possess strong analytical skills and be holistic, multidisciplinary thinkers who can recognize complex patterns and opportunities in the global economy and formulate strategies to capitalize on them;
- exhibit creativity in helping their companies stay ahead of the technology development curve and in creating products that are attractive as well as functional;
- possess good interpersonal and communication skills that equip them to establish and maintain good relationships with current and potential customers and commercial partners and build bridges between different cultures;
- have mastered the principles of business and management;
- understand the principles of leadership;
- possess high ethical standards and a strong sense of professionalism;
- possess dynamism, agility, resilience and flexibility;
- be self-directed learners, who can keep acquiring the new knowledge and skills they need to stay abreast of rapidly changing technological and economic conditions.

As expectations regarding the outcomes of an engineering education evolve, educators are tasked with the challenge of determining how to best prepare students for this global role.

Williams [4] suggests that instead of adding more material and more courses to the engineering curriculum, which would likely turn more students away from engineering, engineering educators need to respond by opening up access to engineering, 'mixing [engineering education] with the larger world'. Another approach to the challenge of educating the global engineer is to determine the essential skills and learning experiences that will allow the engineering student to develop and adopt this larger set of competencies. These perspectives and others suggest that design experiences may be an efficient and effective way to support the development of global competencies [5, 6].

Design is a fundamental engineering activity and one focus of recent engineering curricula reforms (see [7] for a discussion four types of curricula reforms). There is also a growing body of research specifically focused on design expertise, including the acquisition of design expertise (see, for example, [8, 9], [10]). Developing expertise in design requires dedication [11] and can be a complex process—design thinking involves many dimensions leading to a number of challenges and opportunities for learning and teaching design, many of which are reviewed by Dym *et al.* [12]. Oxman [13] suggests that acquiring knowledge is not the same as acquiring design skill but rather

* Accepted 25 December 2007.

acquiring design expertise is more about acquiring the ability to use the right knowledge at the right time rather than acquiring knowledge itself. This is related to the idea that learners must understand material in the context of a conceptual framework [14]. A challenge for design educators, then, is to design learning experiences which will help students develop design skills that will enable them to succeed in the global economy.

One strategy for designing for 'users' (in this case, engineering students) is the creation of personas to better understand user needs and perspectives [15]. Such an approach resonates with the How People Learn [14] idea of taking a learner-centred approach and is exemplified in Richard Felder's Meet Your Students column series (e.g. [16]). Felder's personas—fictional descriptions of engineering students—give a face and a story to different theories. For example, Dave, Martha and Roberto help us to understand three different levels from Perry's Model of Intellectual Development [17]. We take a similar strategy in presenting four stories based on actual students. Typically, personas are fictional characters based on aggregated data. The cases we present are based on individual students who are given pseudonyms.

The study builds on three previous studies which explored differences between freshmen and senior engineering students' design behaviour along a number of dimensions [18, 19, 20]. Our most recent dataset is a collection of verbal protocols from freshman and senior engineering students who solved a series of short design problems. Overall, the results of the current study replicated most findings from the previous studies: the seniors spent more time in the decision activity, made more transitions between design activities, showed more progression to later stages of the process and produced higher quality solutions than the freshmen (the results of the study are presented in greater detail in [21]). We also saw that the findings are true for individual students' growth: 18 of the students participated both as freshmen and seniors, providing us with 18 within-subject data points.

The within-subject dataset provided an additional opportunity to investigate change in design behaviour for each individual participant. We classified each of the 18 cases based on changes between freshman and senior participation and saw that the majority of the participants demonstrated positive change. However, in some cases, we saw little change in design behaviour. Finally, in two cases we saw a simplification of design process between the students' freshman and senior performance [22].

One question that arises from these results is: which students exhibit change? Are only the students that begin as freshmen with lower quality solutions and simpler design processes able to exhibit growth? Do all freshmen that begin with lower quality solutions and simpler design process skills exhibit growth? Do the students who begin as freshmen with high quality solutions and sophisticated design processes benefit from their design education as evidenced by improvements in solution quality and design process?

We address the questions of:

- How do students' design processes change over the course of an engineering programme?
- What do these changes tell us about students' preparedness to become 'the global engineer'?

METHODS

Participants

This study began with the collection of data from 32 freshman-engineering students. When these freshmen had reached their senior year of college, 18 agreed to participate again, allowing for 18 within-subject data points. At this time, an additional 43 seniors participated in the study. The average age of the freshmen was 18.0 years. Nine female freshmen and twenty-three male freshmen participated. Thirty of the freshmen were Caucasian, one was African American and one was Asian American. The average age of the seniors was 23.2 years. The senior participants included 34 males, 12 females and one individual who chose not to reveal gender. The senior population included 49 Caucasians, one African American, five Asian Americans and six seniors who did not report ethnicity. The senior group consisted of 16 chemical engineering, nine civil engineering, eight electrical engineering, three engineering physics, 12 industrial engineering, 10 mechanical engineering and three materials science and engineering students.

The within-subject participants showed the same freshman-senior differences as the larger group, with the exception of amount of time spent making decisions. In consideration of a possible pretest effect, we saw very few differences between the within-subject participants and the other participants; there were no differences between the two groups of freshmen, while the within-subject seniors spent more time on the second problem than the other seniors, and had higher quality of solutions on the first problem than the other seniors.

Study tasks

The participants in this study were asked to solve a series of design problems (Fig. 1). This paper focuses on the first two problems while the third is discussed in another paper in these proceedings [23].

The first problem, the ping pong problem, asks students to design a device that will launch a ping pong ball. This problem was chosen to represent a student's typical homework problem. The second problem, the street crossing problem, asks the participants to design a means for crossing a busy street. This street is part of the students'

Ping Pong Problem

In an attempt to avoid boredom at Benedum Hall, creative engineering students developed a challenging new game. A ping-pong ball is to be launched at a bull's-eye target, and points are awarded according to the accuracy of the landing. However, the ping-pong ball cannot be thrown at the target. It is up to you to design a device which will lift the ping-pong ball into the air and land it at the target. An accurate landing is desired while also maintaining a long flight time. Given that the center of the landing area is 5 metres away from the launch site, and the entire launching assembly must not be greater than 1m x 1m x 1m in dimension, design a ping-pong ball launcher for this game.

Your work should contain a detailed description of your design and should include any relevant diagrams and calculations. Please clearly state all assumptions which are needed in your analysis and try to keep your design simple yet effective.

PROBLEM TWO:

Street Crossing Problem

College campuses are often overcrowded with pedestrians crossing the streets, since walking is a popular form of transportation for college students. One busy intersection [on campus] is the crossing of Fifth Ave. in front of the bookstore. Dangers at this intersection include heavy traffic and busses which run against the general traffic flow. The University would like to design a cost effective method to cross Fifth Ave. which would reduce the possibility of accidents at this intersection.

Your work should contain a detailed description of your design and should include any relevant diagrams and calculations. Estimate both the costs and the benefits associated with your design. Please clearly state all assumptions which are needed in your analysis and try to keep your design simple yet effective.

PROBLEM THREE:

Midwest Flood Problem

Over the summer the Midwest experienced massive flooding of the Mississippi River. What factors would you take into account in designing a retaining wall system for the Mississippi?

Fig. 1. Problem statements.

campus and the problem was designed to have a familiar context. The participants were given half an hour to complete each problem. A study administrator monitored the students and prompted them to continue to think aloud if they became silent for a period of time.

Verbal protocol analysis

To gain insight into the design behaviour of students as well as faculty members we have used verbal protocol analysis (VPA), a well-documented method of investigating cognitive activity [24]). To perform verbal protocol analysis, we have asked our study participants to 'think aloud' while performing study tasks. These verbal protocols are then transcribed, segmented into idea units and coded according to a predefined coding scheme (see Table 1). To ensure the reliability of the data, the segmenting and coding is performed independently by two coders. If the coding is at least 70 per cent consistent then the coders discuss the discrepancies until a consensus is reached. However, if the reliability level for a given transcript is below 70 per cent the transcript is recoded.

The coded transcripts were imported into MacSHAPA [25] for additional analysis: the MacSHAPA software allowed us to calculate the total amount of time each participant spent on each problem as well as the total amount of time each participant spent in each particular design activity on each problem. Additionally, MacSHAPA tabulated the number of transitions between design activities for each participant on each problem. Finally, MacSHAPA was used to create timelines of each participant's design process. These timelines map design activity to a point in time during the participant's design session. Time is presented from left to right and each design activity is listed along the horizontal axis. As a participant spent time in a design

Table 1. Coding scheme for verbal protocol data [18]

Design Activity (abbreviations used for Figs 2 and 3)	
Identify need:	Identify basic needs (purpose, reason for design)
Problem definition (PD) :	Define what the problem really is, identify the constraints, identify criteria, reread problem statement or information sheets, question the problem statement
Gather information (GATH):	Search for and collect information
Generate ideas (GEN):	Develop possible ideas for a solution, brainstorm, list different alternatives
Modelling (MOD):	Describe how to build an idea, measurements, dimensions, calculations
Feasibility Analysis (FEAS):	Determine workability, does it meet constraints, criteria, etc.
Evaluation (EVAL):	Compare alternatives, judge options, is one better, cheaper, more accurate
Decision (DEC):	Select one idea or solution among alternatives
Communication (COM):	Communicate the design to others, write down a solution or instructions
Implementation:	Produce or construct a physical device, product or system

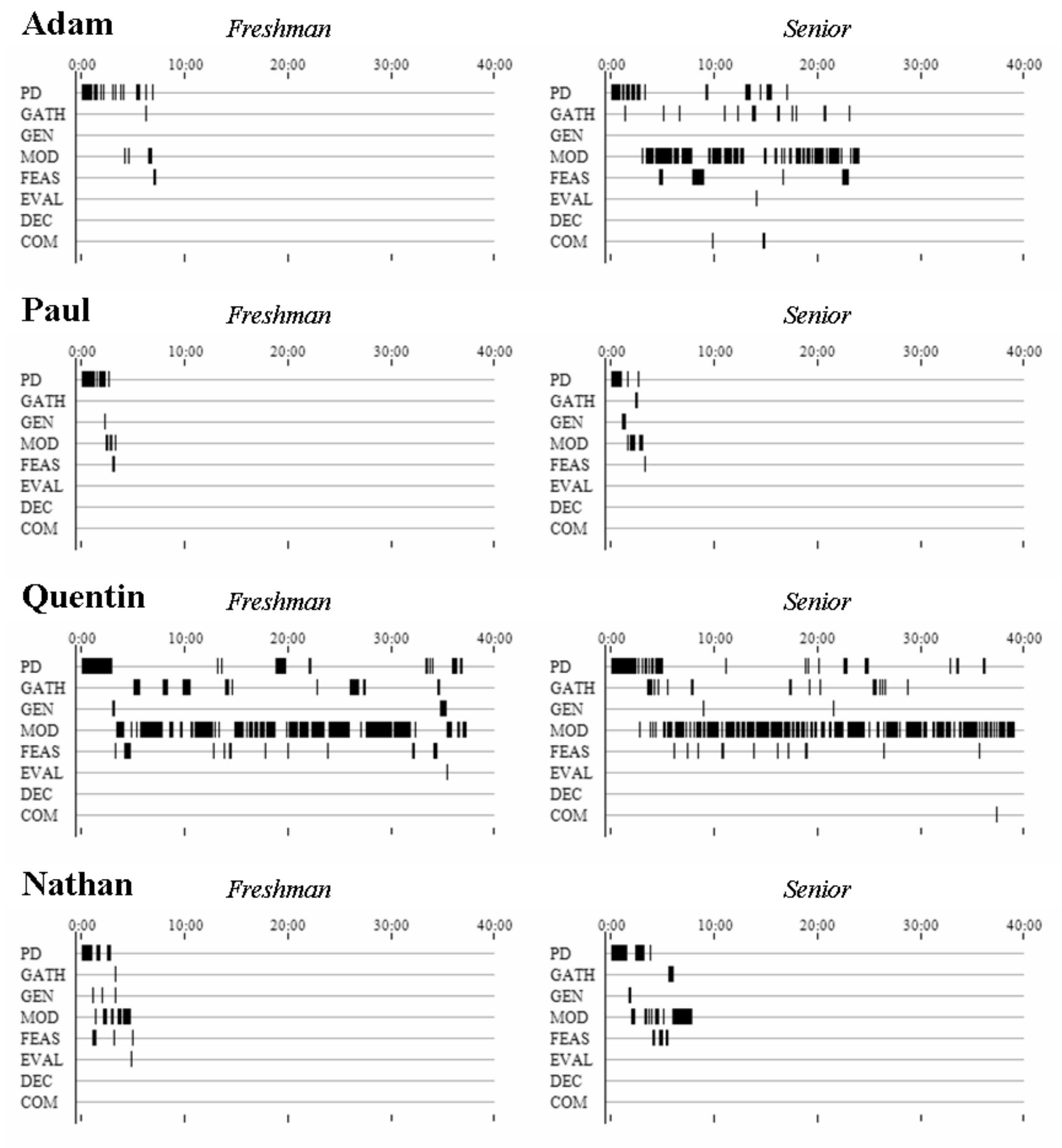

Fig. 2. Ping pong problem timelines.

activity, a block is placed on the line for that activity. The length of the block represents the amount of uninterrupted time that the participant spent in the activity. Longer blocks suggest that the participant is staying in one activity rather than transitioning between activities. These timelines are presented in Figs 2 (Ping Pong problem) and 3 (Street Crossing problem) (see Table 1 for definitions of terms).

Each participant's solution to each problem was also scored using a scoring instrument developed by a team of experts in order to assign a 'quality of solution'. More details about the scoring process and the scoring instrument can be found elsewhere [19, 21].

Finally, we classified each of the 18 within-subject participants based on changes between freshman and senior participation using measures associated with successful seniors (seniors able to complete the task with an average or above-average solution): spending adequate time on the problem, making many transitions between design activities, progressing to latter stages of design process. Four researchers independently classified and then discussed the classifications until a consensus was reached. The majority of the participants demonstrated positive change (higher quality of solution score, more time spent on the task, more transitions, inclusion of more design activities). However, in some cases, we saw little change

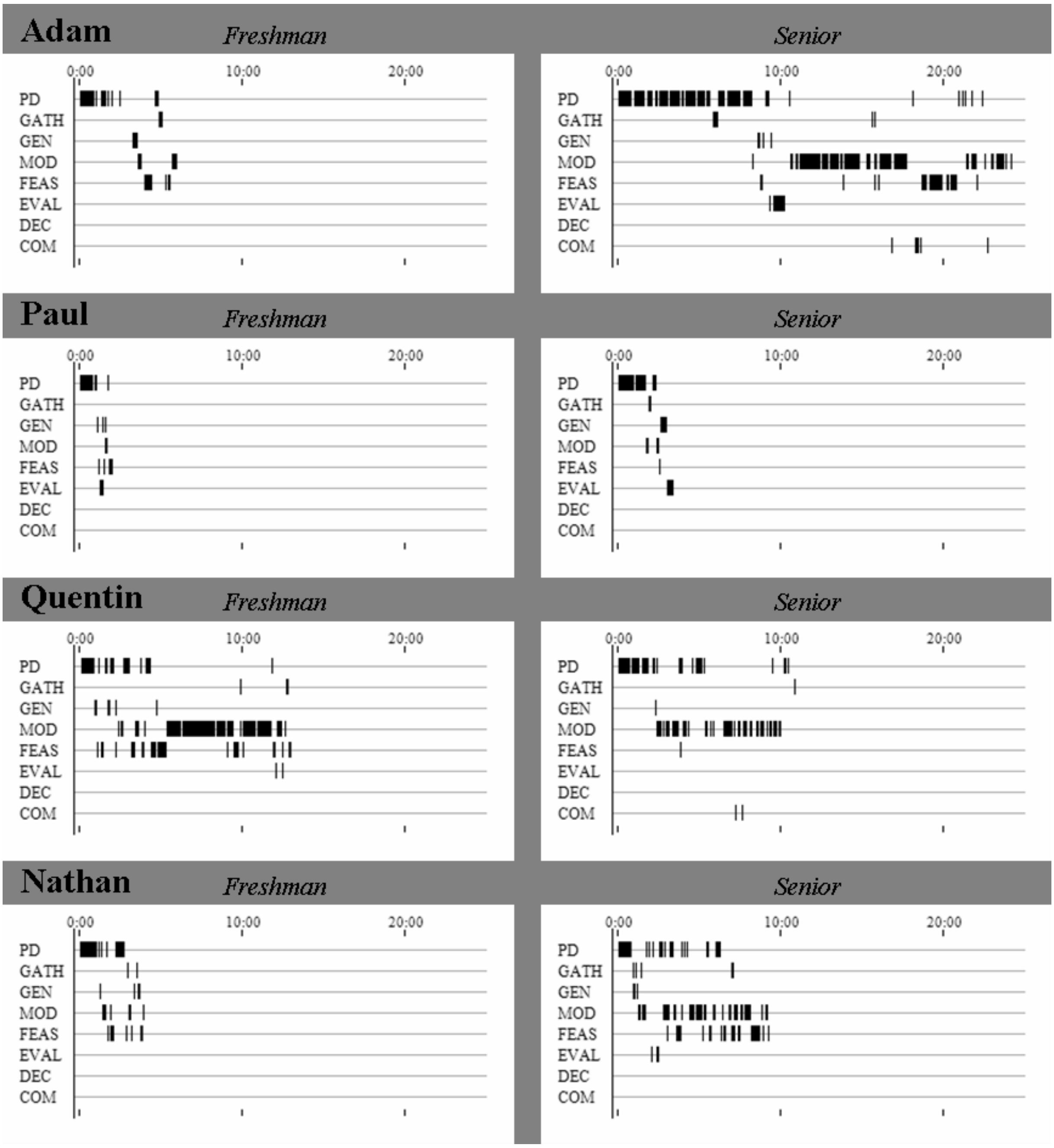

Fig. 3. Street crossing problem timelines.

in design behavior—some participants simply spent more time while engaging in the same pattern of a design process while others did not even spend more time on the task. Finally, in two cases we saw a simplification of design process between the students' freshman and senior performance.

Case studies

The five cases were selected by comparing each participant's activity to the average freshman or senior participant, and then determining if that participant was below average (low), similar to average, or above average (high) in terms of quality of solution, amount of time spent on the problem, number and frequency of transitions and progression to later stages of the design process. For our discussion we selected: a freshman who started out low and showed change (Adam) a freshman who started out low but did not show change (Paul), a freshman who started out high and did not show change (Quentin), a freshman who started out high yet still showed change (Nathan) and a student who provides some insights into what happened in between the freshman and senior administrations of the study (Ethan). Numerical results for these five participants are introduced in Table 2 below. For each case study, we provide a qualitative description of the student and the student's design process as both a freshman and a senior. Additionally, we represent the students' design processes using timelines.

Adam: a student who started low and changed

Before beginning college, Adam earned a B+ grade average in high school and studied physics, chemistry and calculus. He first participated in this study after finishing a semester of college. At that time, he intended to study engineering (but did not yet know which specific discipline), even though he did not consider himself to be technically or mechanically inclined. On both problems his design process resembled that of an average freshman. His solutions were rated low; however, many of the 32 freshmen who participated in the study received no credit (i.e. a score of 0.0) on at least one of the two problems.

By the time Adam was a senior, he had decided to major in industrial engineering 'because it was not as technically/mechanically focused as other disciplines'. Adam showed growth in terms of spending more time on each problem and more progression to cover all eight design activities as a senior, and did not think that his previous participation affected his senior performance.

On the first problem, Adam added communication and evaluation design activities to his design process as a senior by spending some time in these activities. Adam also spent more time modelling design solutions as a senior. However, Adam consistently did not spend time generating ideas. On the second problem, Adam also added the design activities of communication and evaluation and did spend time generating ideas. In this we see some consistent within-subject growth—adding communication and evaluation as a senior for both problems—and consistent across-problem differences—spending time generating ideas only on the Street Crossing problem, both as a freshman and as a senior.

Despite the change in design process, Adam's quality of solution did not change at all for the first problem and only increased slightly for the second problem. Adam started as a freshman with a reasonable quality of solution score, but certainly left room for growth. Because Adam's quality of solution score was exactly the same for the first problem, we might wonder if the solution itself is exactly the same. In both administrations, Adam designed a catapult and included arm, base and launch mechanism elements. As a freshman Adam also included an adjustable release point; as a senior, he included a place for ball. The minor difference in design resulted in no difference in score. For the second problem, Adam designed a bridge during both administrations, but considered more bridge elements as a senior. Furthermore, the particular elements differed—as a freshman, Adam considered the bridge location, that it should be straight rather than an arc and the bridge's impact on traffic flow. As a senior, Adam again considered location and the shape, but then considered the bridge materials, that it should have a restraining device, and that it needed steps.

Adam's transcript gives us additional insights into changes in his design process. As a freshman, on the first problem Adam made a number of statements showing a lack of comfort and confidence: 'I don't know, I'm confused, I don't know what they want', 'Design a ping pong ball launcher? I don't know' 'I don't know what they want me to . . . I never did anything like this'. 'I guess um . . .' He also began by describing his solution as a 'device' rather than identifying it as a 'catapult'. On the second problem, Adam began several sentences with 'Alright' and expressed 'I don't know' on only one occasion. As a senior,

Table 2. Quantitative results for each case study

Participant	Ping Pong Problem				Street Crossing Problem			
	Time	Trans	Quality	Change	Time	Trans	Quality	Change
Adam fr	4.4	7	1.07	Yes	3.7	7	0.25	Yes
sr	20.7	41	1.07		19.6	33	0.34	
Paul fr	3.0	6	0.00	No	1.7	10	0.17	No
sr	2.8	7	1.73		3.2	7	0.54	
Quentin fr	33.3	53	1.16	No	11.9	37	0.34	No
sr	30.5	78	1.61		8.2	22	0.69	
Nathan fr	4.7	15	1.73	No	3.2	17	0.56	Yes
sr	7.4	13	1.73		8.7	44	0.69	
Ethan fr	4.0	10	1.21	Yes	5.7	19	0.44	No
sr	11.8	32	1.88		11.1	40	0.39	
Average fr	6.2	10	1.00		4.7	11	0.30	
sr	11.8	19	1.50		12.1	26	0.50	

Time: total time (in minutes) spent on each problem
Trans: number of transitions between design activities
Quality: quality of solution score
* range for Ping Pong Problem: 0.00–3.618
* range for Street Crossing Problem: 0.00–1.28
Change: overall change in process—senior performance compared to freshman performance.

Adam often began statements with 'okay' on the first problem, though at one point did confess that 'I don't know how . . . to make this work cause I have no idea'. While solving the second problem as a senior, Adam showed similar comfort and confidence, which may be attributable to familiarity with the problem's topic: 'I'll start by drawing the intersection that they're talking about and since I walk across it all the time I think I have pretty idea of how to draw this', but in the end realized 'I don't know how I'm just supposed to list down everything I'm going to need this and estimate cost'.

The change in Adam's comfort with the first problem between his freshman and senior administrations may be attributable to his increased content knowledge. As a senior, Adam mostly treated the problem as a design problem until the last third of his session—then he treated the problem as a physics problem. In terms of design content knowledge, Adam employed strategies of questioning the constraints until he fully understood them and checking all of his assumptions. For the physics content knowledge he said that he was 'trying to remember back 'til four years ago. I learned something in physics but I have no idea'. He also incorporated the Pythagorean Theorem, but remembered it incorrectly—he solved it as if a2+b2=c rather than if a2+b2=c2.

A major change in Adam's approach to the second problem was his consideration of cost. Although the problem statement asks the students to identify the costs identified with the solution, Adam neglected this problem requirement as a freshman. As a senior, Adam frequently returned to this requirement, even though he suggested that he was unable to sufficiently estimate cost.

Paul: a student who started low but did not change

Before Paul started college, he earned a B+ grade average in high school and had studied physics, chemistry and astronomy. He participated in the study at the beginning of his freshman year, before completing even a semester of college. At this point in time, his major was 'engineering' and he considered himself to be technically and mechanically inclined. On both problems, his design process resembled that of a typical freshman. His solutions were rated with low quality scores, which is also typical for the freshmen participants.

By the time Paul was a senior, he had decided to study industrial engineering because it was 'more interesting and less 'dry' than the others. Also, more opportunities to branch out'. Paul spent more time on both problems as a senior but otherwise did not show any change in design process. Paul did, however, receive higher quality of solution scores, compared to his performance as a freshman.

Looking at Paul's timelines in Figs 2 and 3 above, we see that his design process is similar across freshman and senior participation. For the first problem, the only difference revealed in the two timelines is the addition of a small amount of time spent in the gathering information activity. On the second problem Paul did show some progression to the evaluation activity as a senior, and did spend more time in the modeling step. However, Paul's distribution of time across the eight activities is largely similar when comparing freshman and senior timelines—the senior timeline simply shows a little bit more time spent but in the same pattern captured in the freshman timeline.

As both a freshman and as a senior Paul designed a slingshot for the ping pong problem. As a freshman, Paul simply draws a device and a target, decides that the device should be a sling shot and then suggests that he will 'do a lot of different trials until I found the perfect angle to launch it'. As a senior, Paul drew in details of the platform and launch area, specified the materials the slingshot should be made from, discusses the kinematic equations he might bring in to predict the projectile motion and specifies 'some type of a cup' for the ball to rest in; specifying these elements of the slingshot resulted in a higher quality score. On the street crossing problem, Paul considered two main solutions: constructing a bridge and hiring a crossing guard. As a freshman, Paul ultimately chose to construct a bridge, noting the benefit that 'nobody's going to get killed by a bus like they do every year, and then they won't get sued or anything like that so that's a good benefit'. As a senior Paul decides that the bridge would be too expensive and so settles on the crossing guard idea.

It is interesting to note Paul's conceptions of design in relation to his Street Crossing problem solution—as a freshman he considered hiring a crossing guard 'and not design anything'. Paul's conceptions of cost are also interesting. As a senior, Paul strives to produce an inexpensive solution for the ping pong problem, even though cost is stated as a constraint in only the street crossing problem text. On the street crossing problem, Paul decides that 'hiring an employee to regulate the traffic would be a lot more cost effective than building some type of pedestrian bridge'. As a freshman, he considers the fact that the bridge would cost 'a lot of money, but the university has a lot of money also'.

Another change that we see in Paul's transcript is in the tools that are available for him. As a freshman, the main tool that Paul used was sketching. On both the ping pong and street crossing problems, Paul did not write down any notes or calculations, but did create sketches to define the problem—a sketch of the target for the ping pong problem and a sketch of the area surrounding the intersection for the street crossing problem. He also made detailed sketches as a senior, augmented with the word 'inexpensive'. As a senior, he also brought in tools of kinematic equations and simulation methods. However, his simulation strategy was limited—'after building the simulation I'm not sure what information I would get from it'. This was because he was learning about simulation during the semester of his senior participation, and did not 'have much experience with simulation yet'. Thus, he was primed to see the problem as a simulation, but lacked sufficient knowledge at that point to know if this would be helpful.

Quentin: a student who started high and did not change

Quentin began his engineering programme with a more sophisticated design process and a more impressive high school transcript in comparison to Adam and Paul. Quentin earned an A/A+ average grade in his high school classes and had studied physics, chemistry, biology and calculus in high school. He first participated in the study after finishing his first semester of college, and at that time intended to major in civil engineering. He considered himself to be technically and mechanically inclined, and his design process included more design activities than most freshmen's. He spent considerably more time solving the problems and received a higher quality of solution score than most freshmen.

When Quentin participated as a senior, he was still planning to graduate with a civil engineering degree; he chose to study engineering because he 'enjoyed mathematics and physics and thought I'd do well' and chose 'Civil Engineering (specifically Structural Engineering) because I like the design and building of structures'. He still considered himself to be technically and mechanically inclined and rated his comfort with participating in the study high. He thought that his previous participation did have some effect on his senior participation (rating of 3 on a 1 to 5 scale), yet his timelines and transcripts suggest little change between the two participations. Additionally, he spent the summer after his junior year inspecting bridges with the state's department of transportation.

Quentin's timelines (Figs 2 and 3 above) show that he started with a relatively sophisticated design process. While many freshmen get caught up in trying to define the problem and then never spend time developing solutions, Quentin succeeded in both defining the problem and developing solutions. The amount of time he spent on each problem actually decreased (in comparing his senior performance to his freshman performance), but as a freshman he spent much more time solving the problems than the average freshman. He tended to spend a lot of time modelling solutions on the ping pong problem (nearly 90 per cent of his total time spent on the ping pong problem) but he distributed his time more evenly on the street crossing problem. The other main difference between Quentin's freshman and senior experiences was an increase in quality of solution score on both problems.

Though Quentin thought that his previous participation affected his senior participation, he chose to solve the ping pong problem with two different solutions—a slingshot as a freshman and a catapult as a senior. On the street crossing problem, however, he chose a bridge both times (only with more details as a senior). Both times he designed a straight bridge with restraining devices and steps in a specified location. As a freshman he also specified that the bridge should be constructed of concrete slabs; as a senior, he also specified the bridge's height and length, and added a roof. As a freshman, he quickly dismissed an idea of rerouting traffic and he justified the bridge approach by saying that 'the benefits—obviously that way people don't have to fight with the PAT buses won't kill people' and that with the bridge, crossing the street would be 'easier, be a lot quicker, don't have to wait for the light'.

One question that the timelines raise is why did this participant spend so much more time than the average freshman on these problems? Turning to the transcripts, we see that Quentin treated the ping pong problem as a physics problem both as a freshman and a senior. His design process relied on many pages of sketches and calculations, with many iterations of distance, velocity and acceleration equations as well as basic trigonometry relationships; as a senior he also estimated the weight of the ping pong ball and included force equations. Occasionally he considers design decisions such as the materials he will use: 'would a rubber band work? Yeah, definitely', but generally he was consumed by all of the equations. His uncertainty in solving the equations ('I have no idea what I'm doing') prolonged his design session and also prevented him from recognizing the game element of the task (few students attended to the game aspect). He may have recognized that he was attending to the equations too much when he commented 'I'm probably making this a lot more complex than it really is'. One of the complicating factors during his freshman participation was determining when it would be appropriate to estimate. At one point he determined that 'you can't arbitrarily pick numbers here' although he had earlier decided to do just that: 'let's arbitrarily pick, I don't know, any time I guess'. As a senior he was more comfortable with estimating and choosing arbitrary numbers, but ran into a problem because he 'screwed up metres and feet' —his final design 'would work for something five feet away, 16 feet tall' rather than something five metres away, as the task requires.

Quentin also created a multi-page solution to the street crossing problem, although in this case the pages only contained sketches. He considered the intersection first, and then designed his bridge to fit into the surrounding area 'a good idea would be to connect a crosswalk from the towers court yard to cross the street, that would be a lot more beneficial for the students instead of having to go down and then back up some steps to go across'. During his freshman participation, the building and intersection constraints of the location catalysed a unique solution that he soon dismissed: 'wait a second, maybe we could put a diagonal one . . . but there's traffic lights and stuff through here, so that would interfere with the lights'. In place of this unique idea, and like most of the study participants, he turned to an existing bridge at a nearby intersection for additional information: 'simple overpass, I guess, kind of like the one on Forbes Ave'. As a senior he also referred to the existing bridge; in particular, the Forbes bridge inspired one of the bridge features he added as a senior: 'make it a covered bride like that one over at, over Forbes Avenue'. He considered this feature a bit, 'Let's not make it covered. Let's make it a regular bridge with a railing on it. Nah, we can cover it', showing that he considered multiple options here, though he did not provide the rationale for his final decision to cover the bridge.

While much of his senior street crossing design process resembled his freshman process, one distinguishing feature was his consideration of the user as a senior. Quentin's consideration of the cars and trucks travelling under the bridge led him to consider the height that the bridge needed to be. He also talked about how the pedestrian users would 'just come here and walk down'. As he envisaged the way that the pedestrians would use the bridge, he considered the steps and the handrails that became part of his bridge system.

Nathan: a student who started high yet still changed

Like Quentin, Nathan started college with an exceptional transcript—an A/A+ grade average and completion of physics, chemistry and calculus—and a relatively sophisticated design process. He considered himself to be technically and mechanically inclined. He first participated in the study after completing a semester of college, and earned high quality of solution scores at this time.

As a senior, Nathan still considered himself technically and mechanically inclined and during this administration indicated that his major was Chemical Engineering. He chose this major because 'I was good in chemistry and higher math' and 'I was good in and enjoyed chemistry'. The study administrator noticed, however, that 'he often noted that he was not a Civil or Mechanical engineer; he felt that he was at a disadvantage due to the nature of the problems'. He did admit an advantage from having participated in the study as a freshman—he rated the effect of previous involvement to be moderately high (four on a 1–5 scale).

Looking at Nathan's timelines (Figs 2 and 3 above), we see that he is an example of a student who showed no change on one problem but growth on the other. Nathan earned the same quality score on the ping pong problem and spent more time on it as a senior, but had a lower transition rate and did not spend time in the evaluation activity, as he did as a freshman. Overall, there were no significant changes in Nathan's performance on the ping pong problem, and the minor changes were a combination of positive and negative changes in sophistication of design process. On the street crossing problem, however, there is evidence of positive change—Nathan spent much more time on the problem as a senior and spent time in two more activities as a senior than as a freshman. In addition to adding the evaluation and decision activities, Nathan also earned a higher quality score on the street crossing problem as a senior than as a freshman.

As both a freshman and a senior, Nathan solved the ping pong problem with a slingshot with launch mechanism and support. As a senior Nathan first considered a generic solution—'some type of ball and a catapult or a slingshot setup'—that he refined into slingshot that was a more technically sophisticated than his freshman slingshot. He added a calibrated release point and a release mechanism in his senior design but overlooked including a place for the ping pong ball (which was part of his freshman design). As a senior he also paid extra attention to the slingshot's materials: 'you'd want a band type of sort that would allow you to stretch it without breaking but have a very, very tight stretch'.

On the street crossing problem, he designed a bridge both times. In both instances he also briefly considered rerouting the buses before settling on the bridge solution. As a freshman he addressed the costs associated with constructing a bridge by reasoning that 'they have enough money to do it at Forbes so at Fifth I'm assuming they have that much money also'. His freshman design included traffic flow considerations, the bridge's location, the bridge's materials, nonslip treading, a roof, steps and a straight shape. As a senior he chose an arc shape, considered the traffic flow, included both steps and a ramp, and addressed the height, width and location of the bridge.

Nathan created sketches during both participations; generally his senior sketches were very similar, yet clearer versions of his freshman sketches. For example, on the ping pong problem he drew and labeled a device with a parabolic arrow connecting it to a target showing the ping pong ball (with a parachute to slow it down) along the arrow trajectory. Above this sketch he drew a basket (representing a basketball net). The basketball net and parachute he added as part of his strategy to 'tamper with the ball . . . to do something to the ball to make it fall slower'.

In a number of ways, Nathan's senior design process resembled his freshman design process. For example, on the ping pong problem, using a 'rubber band type system' was one of the first design elements he considered. He also thought of multiple alternatives during both administrations—as a freshman he considered 'taking it up on the ceiling and dropping it through a bunch of complicated devices' before deciding to use a slingshot and he considered a cannon, a rubber band, a catapult and finally a slingshot as a senior. He was also very concerned about maintaining a long flight time both as a freshman and as a senior. As a freshman, he thought of ways to slow the ball down—attaching a parachute to the ball or directing the ball through a basketball net. As a senior, he decided that 'if you're going to be maintaining a long flight time its important I would say to build a tall slingshot that's stationary on the ground'.

Nathan also considered multiple alternatives on the street crossing problem. He considered rerouting the busses at the end of his freshman design session and remembered that idea at the beginning of his senior street crossing design session and also considered a tunnel option as a senior. Both as a freshman and senior Nathan considered the need for the bridge to be adequately tall enough for traffic to pass beneath it, and further considered the bridge's location by choosing to build onto existing stairs. Nathan considered the affect that the bridge would have on traffic during both administrations, but as a freshman Nathan considered how the bridge would improve both vehicular and pedestrian traffic while as a senior Nathan considered the negative effect the construction of the bridge would have on traffic. Likewise, Nathan considered cost during both administrations, but assumed that the money would be available as a freshman and listed what the actual costs would be as a senior.

Further differences in Nathan's design process as a senior include his attention to the bridges' supports—the bridge's ability to support weight and the beams and posts that would need to be built to support the bridge. Even the Civil Engineering majors often neglected to consider this. Nathan also considered the potential handicapped users and decided that 'you would need to build . . . some type of ramp going up to it' during his senior design session. On the ping pong problem, Nathan also showed some maturation in his design considerations. As a senior he realized that he needed 'something adjustable' so that the user could experiment with the device until the user successfully hit the target. He also realized that 'it doesn't say how big the target is' as a senior. Perhaps the greatest difference between his freshman and senior participations, however, is that as a senior Nathan realized that he was designing a device for a game. While he thought about the equations relevant to the system, just as many of the study participants did, he put the responsibility on the game player: 'come up with an equation for how to hit the target. You should come up with an initial guess and from that you should be able to move it forward or backward and line it up like that'.

What happened between administrations of the study?

The disparity in change in freshman and senior participation deserves discussion about what took place in between the two administrations. The students took classes, worked on projects and for the most part participated in a coop or internship programme. Some students, like Ethan, actually created ping pong ball launchers in their physics classes, and both personally reflected on the problems and discussed the problems with others. For example, Ethan discussed the street crossing problem with a roommate and indicated that his freshman participation had a large effect on his senior performance. 'It affected my performance very much, since after the first study I had time to reflect on the questions and possible solutions in a conscious and subconscious way'. It is possible (and perhaps likely) that the different experiences that different students encountered inside and outside of the classroom affected the extent of their change in design process behavior. In the case of Ethan, these experiences include both the in-class activity of designing ping pong ball launchers and his own agency in reflecting on the study he had participated in. It is also possible that the students followed different learning trajectories, or that the administration of the study tasks captured different students' design growth at different points along a common yet complex learning trajectory [26].

DISCUSSION

What changes do we see in individual engineering students design processes over the course of an engineering programme?

Which students exhibit change?

Do all freshmen that begin with lower quality solutions and simpler design process skills exhibit change?

Both Adam and Paul were freshmen that started with lower quality scores and less sophisticated design processes; in this way both had a lot of room for growth. While Adam exhibited change in design process as a senior, Paul's senior design process was virtually unchanged.

Are only the students that begin as freshman with lower quality solutions and simpler design processes able to exhibit change?

Adam and Nathan both exhibited more sophisticated design processes as seniors than as freshmen even though they had started in two different places. While Adam started out with a novice-like process, Nathan started with a more sophisticated design process. Adam and Nathan may not have exhibited the same level or type of change, but both did display some change.

Do the students who begin as freshmen with high quality solutions and sophisticated design processes benefit from their design education as evidenced by changes in solution quality and design process?

Unlike Nathan, Quentin did not show change. Quentin started with a sophisticated design process and a relatively high quality score and did not show much change as a senior. It is not too surprising that Quentin did not show much change because his freshman participation already resembled a senior's. However, participants like Nathan show us that it is still possible for students who start with advanced design skills to learn and change.

Overall, regardless of their starting point, it is possible for any student to exhibit change and it is also possible for any student to not exhibit a change. To some extent the undergraduate engineering education can 'level the playing field'—regardless of a student's natural ability or precollege design training, a student can finish a programme with a sophisticated design process and an ability to produce high-quality design solutions. This point coincides with Williams [4] and Katehi [6]'s suggestion that we open access to engineering education to nonengineering students. However, it is important to note that there is still some advantage for the students who start with a more sophisticated design process: while they may not show much change, they are unlikely to demonstrate an unsophisticated design process with a poor solution. If a student who has started low does not change, they may still exhibit a lack of design process skill and may still produce poor solutions.

What do the kinds of changes observed suggest regarding 'the global engineer'?

A 'complete' design process In each of the studies we have conducted, we have noticed differences in participant's design processes. Many students have spent little or no time in some design activities: Evaluation of design alternatives, making design Decisions, and Communication of design decisions. However, we have also noticed that more experienced designers tend to spend more time in these activities than less experienced designers (seniors spend more time than freshmen; practitioners spend more time than students) [20, 21, 27]. Spending adequate time in each of these design activities and covering the full space of design activities is important for the global engineer—the engineer who "exhibits creativity in helping their company stay ahead . . . and creating attractive and functional products" must be able to evaluate and choose the best design alternatives. Likewise communicating design decisions is important for the engineer who needs to 'possess good interpersonal and communication skills . . . and build bridges between different cultures'.

Design solutions. Another change that we explored in the cases studies was change in solutions. Some participants had more complete design solutions as seniors—they had thought about additional features of the design that needed to be included. In many cases these were additional mechanical or technical features, but especially in the case of the Street Crossing problem, the solutions were more complete because the participant had given additional thought to the user. This kind of consideration of the user will help the student become the global engineer who will "possess high ethical standards and a strong sense of professionalism."

Other participants showed change in design solutions in that they either chose a different solution type as a senior, or they considered alternative solutions before choosing to use the same solution type that they had used as a freshman. Considering multiple alternatives can help the global engineer 'exhibit creativity in . . . creating products that are attractive as well as functional'. Other researchers have measured the number of alternatives considered as a way of assessing designers' innovation (as opposed to an efficient approach of considering a single or few alternatives) [28]. Some of the participants also displayed innovation in that they used a different solution type as a senior. This type of innovation may be linked to the global engineer's 'dynamism, agility, resilience and flexibility'.

Content knowledge

A final dimension of change that we explore in the case studies was the participants' use of mathematics and physics content knowledge. Some of the participants chose to bring their knowledge of mathematical formulas or physics principles into their design process; in particular, some participants chose to treat the ping pong problem as a physics problem. We also explored the accuracy of the mathematics and physics that the participants used. To succeed as a global engineer, students must learn how to integrate their mathematics and science content knowledge into their design processes, to show that they 'possess strong analytical skills'.

Reflection. In the final case study we examined some of the experiences of the study participants that occurred during their 'change' period—during their engineering programme. One of the experiences reported by one participant was a process of reflection on the study tasks, which led the student to continue to continue to refine his design solution informally in conversations with peers and his own internal reflections. This process of reflecting on his study participation enabled this participant to be a 'self-directed learner, who can keep acquiring the new knowledge and skills they need to stay abreast of rapidly changing technological and economic conditions'.This theme is further explored in another paper on the prospect of educating reflective engineering practitioners [26].

Design Tasks. As we have noted in this paper and elsewhere [21] the participants' design process differed across the two design problems. Differences in the structure of the two tasks, which may have prompted the students to exhibit different design practices, and may also allow students to practice different 'flat world' skills.

The Ping pong problem was:

- relatively context free;
- somewhat disciplinary (in that it reminded students of a physics problem);
- likely similar to the kinds of problems students worked on;

- more solution-focused (not as likely to see consideration of multiple alternative solutions);
- less tied to real people and more artificial;
- not related to business issues such as cost.

The Street Crossing problem, on the other hand, was:

- context-rich (the participants were familiar with the location and the need for a solution);
- somewhat multi-disciplinary (while the problem seemed like a 'Civil Engineering problem' to some participants, the study participants could readily apply perspectives from other engineering as well as non-engineering disciplines);
- not likely to be the kind of problem students worked on in their coursework;
- more problem-focused (participants tended to consider more alternatives and spend more time scoping the problem);
- tied to real people and real casualties (which likely prompts ethical and professional considerations);
- more related to business issues such as short- and long-term costs and issues of funding.

These differences in the structure of the tasks may affect students' use of 'analytical skills', their 'holistic, multidisciplinary thinking', their tendency to 'exhibit creativity', the extent to which they exhibit 'high ethical standards and a strong sense of professionalism' and their use of 'the principles of business and management'.

FUTURE WORK

The case studies not only help us as educators understand some things about our students, but also raise a number of questions for future exploration.

Adam and Nathan demonstrated that any student, regardless of starting level of design expertise, can demonstrate positive change. Because starting level did not inhibit growth, we wonder what factors may have prevented Paul and Quentin from displaying a similar positive change. It is possible that they simply did not choose to invest sufficient effort in the study's design tasks. It is also possible that a similar motivation factor may have impacted their approach to their undergraduate education and to learning. Alternatively, perhaps participation in a different type of course or curriculum (see 7, 29 for examples) would have led to positive change in Paul and Quentin's design process behaviour.

IMPLICATIONS

These students resemble those enrolled in a typical engineering course—students entering the course with different levels of experience and expertise. Alan and Nathan remind us that any student, regardless of staring point, can show change. Alan and Nathan give us hope that any student can be taught. Paul and Quentin remind us that it is also possible for any student, regardless of starting point, to not show change. Paul and Quentin remind us of the challenge to continue to seek innovations in engineering education, until we exhaust the space of resources and supports that we can provide for the students who are not yet showing change in their level of engineering design expertise.

These cases of change also provide insights into how we might prepare students to work effectively in the 'flat world'. The descriptions of the changes in these students' design processes enable us to further explore the possible characteristics and competencies of a global engineer. For example, one of the aspects of design that we explore in this paper is the 'completeness' of students' design processes. One aspect of a 'complete' design process is engaging in all eight design activities. Generally the activities that students were most likely to skip were Evaluation, Decision and Communication. Each of these activities is important for success in the global economy.

Additionally, the two different design tasks discussed above provided students with opportunities to engage in different types of practices, and represent opportunities for educators to carefully consider the tasks that they use to teach and assess design process skills. In particular, the nature of the Street Crossing problem could have prompted students to think about business implications—such as short- and long-term costs of the solution—as well as ethical implications related to the safety and wellbeing of the people crossing the street. This broad thinking—which would include social and environmental considerations in addition to technical concerns—could help the engineering student become 'the global engineer'.

Acknowledgements—This research was made possible in part by National Science Foundation grants DUE-9254271, RED-9358516, DGE-9714459, EEC-9872498 and REC-0125547 as well as support from the GE Fund. We would like to gratefully acknowledge the students who participated in the study, and also thank the students and staff from two universities who helped us to collect, transcribe, code and analyse the data. University of Pittsburgh: Heather Nachtmann and Justin Chimka who ran the data collection and initial analysis of the Senior Follow-Up Study, as well as Karen Bursic, Mary Besterfield-Sacre, Rona Colassimo, Stefanie Lozito, Carie Mullins, Jamari Atkinson, Georgette Diab, Anthony Horton, Jennifer Kreke, Terra Mitchell, Pamela Moore, Jill Nagel, Jason Saleem, Gwen Staples, Nick Tettey, Chris Yarsky, Lisa Younger and Maryland Vick. From the University of Washington: Jacob Burghardt, Louise Cheung, Jennifer Chin, Julie Christianson, Yimin Chen, Katherine Deibel, Ashley Lam, Jana Littleton, Ian Louie, Eddie Rhone, Alison Schwerzler, Cathie Scott, Roy Sunarso, Rober Tai, Jennifer Temple, and Bettina Vuong.

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