Measuring Students Not Just Their Output:

The New Fields of Engineering Cognitiometrics, Physiometrics and Neurometrics

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Abstract

This paper presents results from measuring students' cognition, physiology and neurocognition as an adjunct to measuring students' output as a means of assessing their learning. This contrasts with the paradigm of measuring only students' output as the assessment of learning. Three areas of students' cognitive behavior can be measured: cognition; physiology as a surrogate for cognition and neurocognition. These can be encapsulated as mind, body and brain. Their measurement is in the new fields of engineering cognitiometrics, physiometrics and neurometrics. The paper presents examples from multiple project in these three areas. The paper concludes with a brief discussion on the effects of the availability of tools to measure cognition, physiology and neurocognition.

Keywords: engineering education; design cognitiometrics; design physiometrics; design neurometrics

1. Introduction

Education in general, and engineering education in particular, has used the testing paradigm of summative and formative assessment as the means of measuring students' learning in response to teaching. What both these forms of assessment have in common is that they assess the output of the student after some educational intervention. The performance expressed in the student's output is correlated with the educational intervention to claim some causality. This paradigm of assessment goes back over a century. More recently cognitive testing, initially in the form of IQ tests and then other psychometric tests, were introduced but these were not directly associated with engineering education. These were driven in part by changes in the paradigmatic view of education embodied in Bloom's revised taxonomy [1-2] and Webb's Depth of Knowledge [3]. Although these still are focused on the students' output they increasingly talked about what was required of the student. This have brought the end points of both Bloom's revised taxonomy and Webb's DoK into an alignment with design, Figure 1.

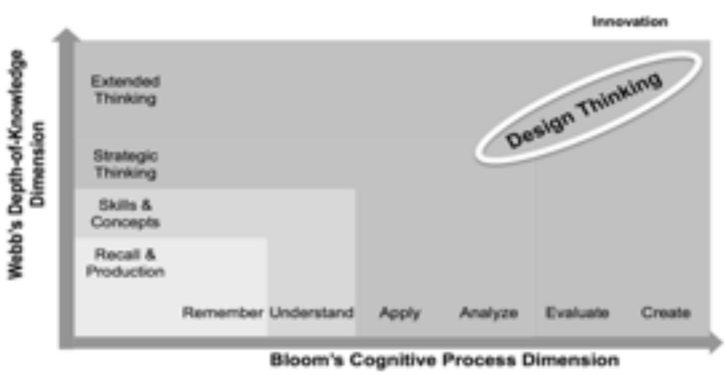

Fig. 1. The relationship between Bloom's cognitive process dimension of "extended thinking", Webb's depth of knowledge dimension as in "create thinking" and design thinking (as in design cognition).

In the last twenty-five years a more directed form of cognitive assessment of students has been developed and has become part of the extended fabric of engineering education research. This change is illustrated in Figure 2 where the traditional assessment approaches correlate the educational intervention with the student output and leave the student as a black box. Measurements of student cognitive behavior open up this student-as-black-box view to a more student-as-white-box view, where the behavior of the student is also measured not just their output.

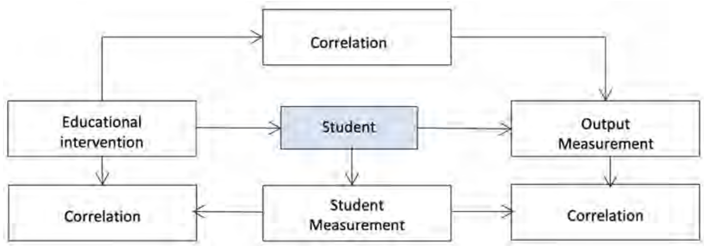

Fig. 2. Relationship between measuring the student as a black box by measuring only their output (top half of figure) and measuring the student as a white box by measuring their cognition, physiology and neurocognition (bottom half of figure).

The remainder of the paper introduces the three areas of engineering cognitiometrics, engineering physiometrics and engineering neurometrics. It presents examples drawn primarily from the author's research carried out with colleagues in multiple labs across the world. Other researchers have been carrying our similar or related research. The paper concludes with a discussion on the implications of the effects of the availability of tools to measure cognition, physiology and neurocognition.

2. Engineering cognitiometrics

Engineering cognitiometrics is the measurement of engineers' cognition. Typical studies drawn from psychology are input-output experiments, where the students' cognition is inferred from the change in behavior caused by a change in input. An exemplary input-output experiment is Purcell and Gero's [4] study on fixation. In that study the control group was given a textual set of requirements and the experiment group was given the same textual set of requirements plus a sketch indicating the level of detail expected in the design. The sketch happens to be a design for the set of requirements. The sketch contains identifiable features, Figure 3.

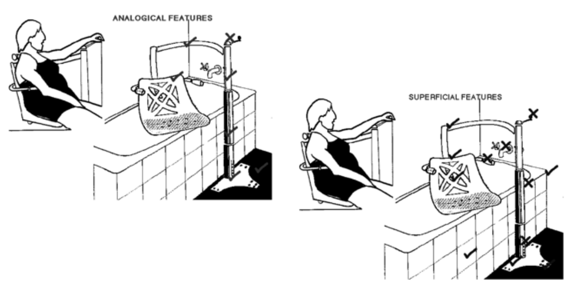

Fig. 3. Sketch given to experiment group showing positive and negative design features in the top sketch and immaterial features in the bottom sketch [4].

Results from such experiments can indicate the cognitive effects of the intervention, Table 1. In this case there was evidence of substantial fixation amongst mechanical engineering students and, unexpectedly, a novel discovery of inverse fixation amongst industrial design students. These results have implications for the use of precedents as a form of pedagogy.

Table 1. Comparison of control and experiment groups in terms of the features in their designs for both mechanical engineering students and industrial design students [4]

Feature	Mechanical Engineers		Industrial Designers	
	control %	experiment %	control %	experiment %
Fixed	30	65	33	43
Fixed to floor	0	35	22	0
Column	0	53	11	0
Lifting mechanism	0	41	11	0
Handle on column	0	6	0	0
Boom	0	47	11	0
Seat	35	71	44	43

More recently, cognitive studies of engineering students have made use of study richer methods that allow quantitative analyses that produce a more nuanced understanding of student cognitive behavior before and after an educational intervention than previously, based the *protocol analysis* method [5-6]. An example of such a result from a protocol analysis using the FBS coding [7] of undergraduate engineering students at a state university, where their cognitive behavior is measured before they declare their major and again after they are one year into their major [8]. The differences between these two measurements are presented in Figure 4. What this shows is that there is a statistically significant effect on students' cognition due to their major. This has implications for the formation of engineers.

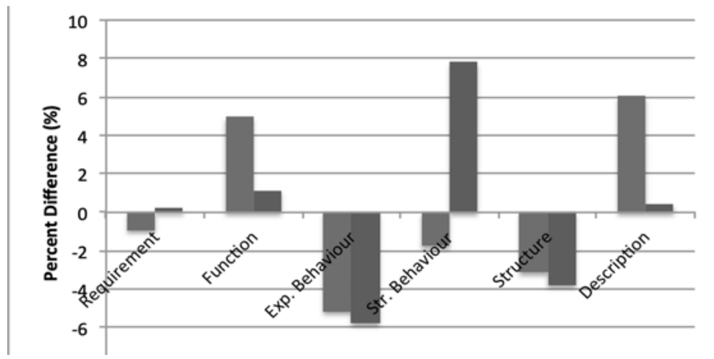

Fig. 4. Changes in cognitive behaviour of two cohorts of mechanical engineering undergraduate students after they have had one year of their selected major. Light gray is engineering mechanics majors and dark gray is mechanical engineering majors [8].

From the same protocol analysis data, a wide range of other behaviors can be determined. In a protocol analysis-based cognitive study of engineering students designing in teams, the effect of the gender diversity in teams was measured using a co-design model based on the FBS coding scheme [9]. The results are shown in Figure 5 and indicate that more collaboration occurs in mixed gender teams than in all male teams in this experiment.

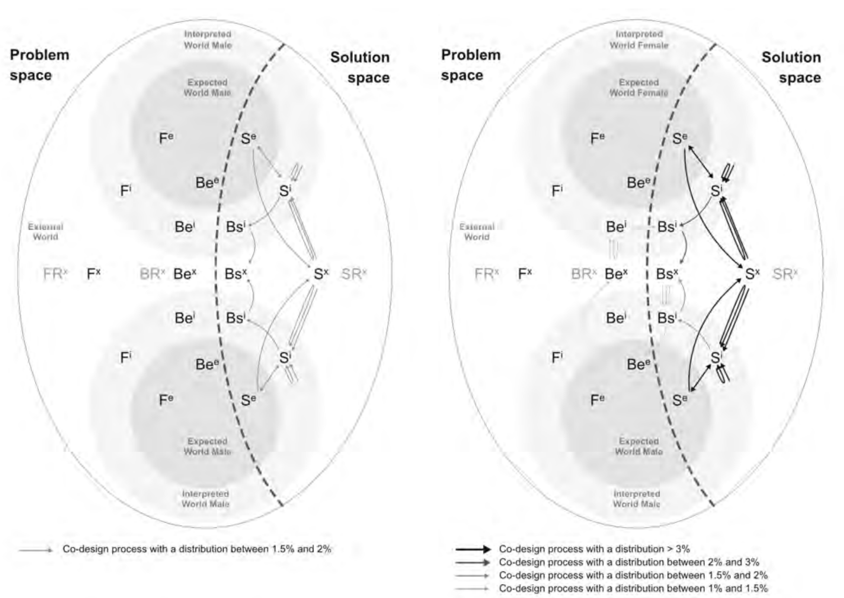

Fig. 5. Collaboration, indicated by processes, between two team members: left-hand shows all male teams and right-hand show mixed gender teams; each diagram is the result of 10 or more teams. The darker the arrow the higher the percentage of that collaborative process [10].

Protocol analysis produces a rich data source. For example, in a study of the design of product-service systems the temporal distribution of time spent of the problem or the solution can be calculated and is show in Figure 6. Where it is of interest to see that the design team started with exploring a solution very early in the design session before spending time on the problem.

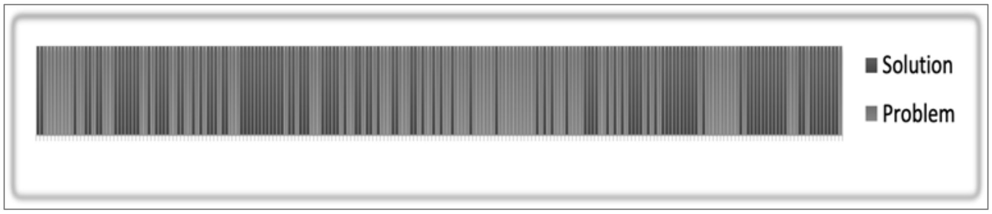

Fig. 6. Temporal distribution of time spent on problem or solution, the horizontal axis is time [11].

Data analysis techniques, novel to engineering education, are starting to be applied to a variety of empirical, cognitive data. These include Markov modeling [6], correspondence analysis [12] and sentiment analysis [13], that produce results in dimensions not previously used in engineering education research.

3. Engineering physiometrics

Engineering physiometrics is the measurement of an engineer's physiological response. Whilst engineering is a mental activity, the mind is embodied and there is a nascent awareness that a person's physiological behavior plays a role in their mental behavior and vice versa. Tools for measuring physiological response have been increasingly cheaper. Physiological responses include heart rate, epidermal analysis as surrogate measures of emotion, and eye-tracking. Emotion can be measured at a distance from an analysis of the muscle behavior of the face.

The cost of eye-tracking measurement instruments has reached the point where an acceptable instrument can be purchased for $500. The availability of such measurement tools has opened up new avenues of research including engineering education research. An example of eye-tracking results is shown in Figure 7 where the student is designing using a parametric modeler.

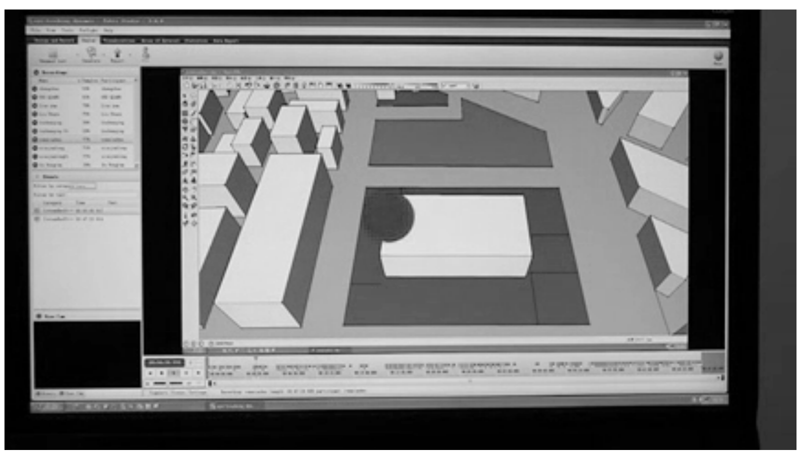

Fig. 7. Example of eye-tracking output indicating the location of viewing, the size of the circle represents the amount of time spent at that location for a student designing using a parametric modeler [14].

Engineering physiology research is still in its infancy and only in recent years has it started to produce results that relate to cognition and inform us about student behavior [15-16].

4. Engineering neurometrics

Engineering cognitiometrics measures the mental activity of engineers, engineering neurometrics measures the brain activity of engineers. Non-invasive brain measurements have relied of functional magnetic resonance imaging (fMRI), where measures of increased blood flow are surrogates of mental activity [17]. Designing is a temporal activity and fMRI has a very low temporal resolution with a very high spatial resolution. Further fMRI requires that the participant keep their head completely still, which is a limitation. Other devices have been available that trade off lower spatial resolution for higher temporal resolution., coupled with increased participant mobility. Low cost EEG devices that measure the electrical signals in locations at the surface of the brain have opened up high temporal resolution data capture during designing. The data capture with a $799 EEG device is shown in Figure 8. Exemplary results are shown in Figure 9 for cohorts of industrial designers and mechanical engineers carrying out the same design task, where the axes of the spider plot are the different brain surface measurement channels in standard locations and the distance from the origin for each channel represents the aggregate brain activation in that channel across a design session.

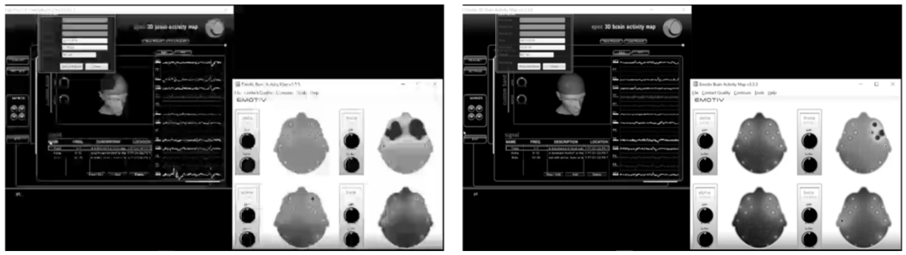

Fig. 8. Data capture during an EEG session under two different design tasks [18].

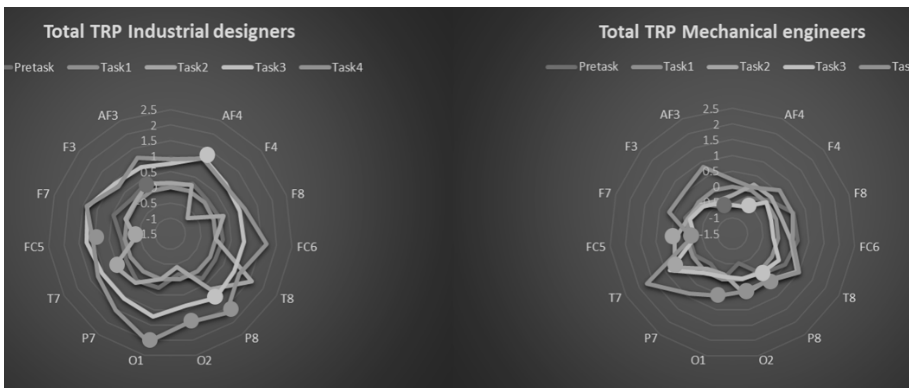

Fig. 9. Brain activations, measured by a low-cost EEG device, averaged for 18 industrial designers and 18 mechanical engineers, while working on four different design tasks, graded by their reduction in constraints. The dots indicate where there statistically significant differences between tasks in that location was measured [19].

More recently the brain measurement method of functional near-infrared spectroscopy (fNIRS) was developed and has just started to be used in engineering education research. fNIRS provides a temporal, objective measurement of brain activations associated with cognition. It is simpler to use and unlike EEG measures neuro-cortical activity. An example of the results that can be obtained using fNIRS is presented in Figure 10, which shows the average activation, of 12 engineering students, of the left and right hemispheres during concept generation using brainstorming along with the temporal change in hemispheric dominance [20]. The left hemisphere dominates during the initial phases of brainstorming and as the rate of concept generation decays that dominance changes.

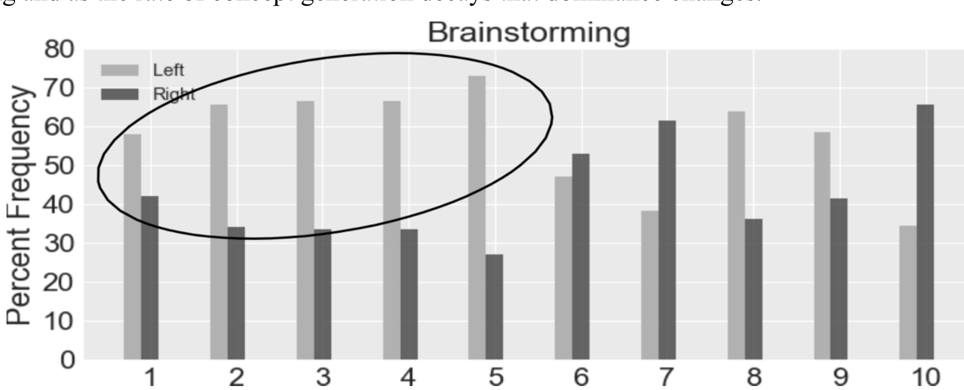

Fig. 9. Average brain activations of left and right hemispheres across temporal deciles of 12 engineering students while brainstorming. The dominance of left hemispheric activation in the first half of the design sessions is indicated by the ellipse [20].

5. Discussion

Measuring engineering students' cognition, physiology and neurocognition in addition to measuring students' output provides opportunities for both triangulation of results and the ability to measure changes over time. It will be possible to determine whether learning is persistent by measuring objective changes in cognitive and neurocognitive behavior.

Measuring design cognition has developed a strong suite of methods and results over its history. The first attempt ot studying designer's cognition was carried out by C. M. Eastman in 1969 [21]. However, since the US National Science Foundation commenced funding engineering education centers and then university departments, there has been a significant body of research published using a variety of measurement techniques. The most commonly used method remains protocol analysis. A good recent survey of protocol studies of design can be found in Hay, et. al. [22]. Cognitive studies have generated much of the data to date about measuring students rather than just their output. They do not take the place of measuring output as the structure and cost of obtaining results is prohibitively expensive to allow it to be applied generally. However, as means of testing the effects of different pedagogies and the effects of different educational interventions on cohorts of students, it provides a well-grounded approach.

The availability of low-cost physiology measuring devices has opened up a new field in engineering education research. It is still at the exploration stage developing correlations between human body behavior and cognition and student output.

Bringing together results from using concepts and methods of computer science, cognitive science and neuroscience with design science [23-24] in engineering education will enhance our ability to predict and test the effects of educational interventions.

New measurement tools provide opportunities to generate novel data about engineering student behavior under various education interventions and ecological conditions. They provide a means to test existing and new hypotheses concerning the education and formation of engineers. It is expected that they will drive new experiments to produce greater validity of the results.

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Biography

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