Individual- and group-level effects on learning during engineering design tasks in high school biology (Fundamental).

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Individual- and group-level effects on learning during engineering design tasks in high school biology (Fundamental)

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Introduction

The Framework for K-12 Science Education (National Research Council [NRC], 2012) stresses teaching and learning of both scientific and engineering practices in order for students to understand and experience how scientist and engineers work; "how scientific knowledge is produced and how engineering solutions are developed" (p. 3-1). Crucially, the Framework conceptualizes these scientific and engineering practices as overlapping but distinct. Knowledge of both domains, it is argued, will help students to become critical consumers of scientific information, to understand the impact of scientists' and engineers' work on daily life and how this work addresses major societal challenges (e.g., treating of diseases, addressing climate change or generating sufficient and affordable energy), and lead them to consider a career in a STEM field.

This new focus on scientific practices accompanies a call for more sustained emphasis on inquiry and engineering design activities, particularly as part of a constructivist science curriculum centered on collaborative activities done in small groups. While the structure of the task is critical to the knowledge construction process in small group settings, there is little empirical research about the socioemotional resources that high school students bring to group work, and how this mix of resources across group members influences group functioning. This is particularly true for teaching and learning at the K-12 levels in the relatively new curricular area of engineering design. It is critical to understand how small groups in high school can navigate – and how teachers can support -- the challenges of design problems that are open-ended and often ill-defined, demanding cycles of divergent and convergent thinking, design development, refinement and evaluation (Dym, Agogino, Eris, Frey, & Leifer 2005).

It is well-established in the research literature that the social status of individual group members influences the dynamics of the small group or team, both at the K-12 level and in post-secondary science and engineering (Cohen and Lotan, 2014; Bianchini, 1997, 1999; Kittleson and Southerland, 2004). In many of these studies, social status is marked by prior academic ability, popularity or key demographic characteristics such as race/ethnicity and gender. Those with high status not only expect to excel in the group; other members also expect this high status peer to excel (Bianchini, 1997, p. 1041). This line of research highlights for researchers as well as practitioners that what students bring to collective work in small groups or teams influences group functioning. . This paper takes a slightly different perspective on the prior characteristics of individual group members in framing them not as relatively fixed social statuses along a single dimension, but rather as variable stocks of potential resources to promote group functioning. In this, we join Oliveira, et al (2014) in viewing small groups as more complex structurally than a unidimensional status hierarchy with stable roles. However, our perspective retains the notion that how a group member views their capacity to contribute to the group is complemented and reinforced by what other group members bring to the group. That is, a group member's experience of group work is potentially influenced by the resources he or she brings to the collective task "ego-resources"), but also the range of resources that others bring to the group ("other-resources").

This study investigates the following research questions:

RQ1) What is the relationship between an individual student's "ego-resources" (cognitive, social and affective resources) and the student's perception of group functioning over the course of three engineering design tasks, and

RQ2) To what extent do the "other-resources" (cognitive, social and affective resources brought to the group by the *other* members) relate to an individual student's perception of group functioning.

RQ3) How does group functioning as perceived by an individual student relate to learning of engineering design content and practices?

(See figure 1.)

Conceptual Framework

In many ways, the notion that students can manage the complexity of small group work is a rather ambitious expectation. Barron (2003) first extended Teasley and Roschelle's (1993) cognitively focused model of small group problem-solving, to encompass a "dual-space" model of collaboration in which groups must attend to and develop the "content space" and the "relational space" (social interactions in the group). More recently, affect has been shown to impact small group interaction in upper-elementary math tasks (Linnenbrink-Garcia, Rogat, & Koskey, 2011). Consequently, Authors (2014) argue that academically successful small groups must co-construct the "triple problem-solving space" in which content, social/relational, and affective components are developed and maintained. While the quality of the task certainly influences the ability of small groups to engage in meaningful learning together, we recognize that group members bring distinct sets of resources to the challenge of co-construction of a “triple problem-solving space.” We hypothesize that 1) individuals who bring strong “ego-resources” to the group are more likely to report better subsequent group functioning along these dimensions and 2) individuals belonging to groups where “*other*-resources” are strong are more likely to report better group functioning. Other-resources should matter, because part of the benefits of collaborative learning in groups is to bring peer group influence to bear on the academic substance of the work (Smith et al., 2005, Bruffee, 1999).

Data and Methods

Small groups of 4 students each completed 3 engineering design tasks (oil spill clean up, designing a protective pill coating, developing a heart valve – modified from lessons available at teachengineering.or in nine introductory biology classrooms in four public high schools located in the Northeast of the United States. The tasks were adapted from teachengineering.org and aligned to state and national curricular standards (NGSS) for high school biology[1], and all teachers received professional development on the engineering design cycle and how to implement the tasks effectively, although there was no specific instruction on how to work with the small groups; teachers were simply asked to interact with the groups as they thought appropriate. In two of the classes, the tasks were undertaken over the course of a full academic year, the length of the introductory biology course in that school. In the others, the three tasks were implemented within a single semester, corresponding to the length of the compressed biology course in those schools. Two of the schools served primarily middle- to upper-middle class student bodies, while the other two schools served a predominantly working-class population. The sample of 185 students was 53.5% female, and 46.5% male. About 10% of the sample were students of color, mostly Puerto Rican or Asian-American, with the highest concentration of students of color in one of the working-class schools, which was located in an urban area. For all students participating in the research, consent from a parent or guardian was secured, and each student granted assent as well. Participating teachers and a school administrator at each of the four schools also signed consent forms.

For the oil spill activity, small groups must design a system to contain and remove vegetable oil colored with black food coloring that has been added to an aluminum baking pan filled with water and gravel, modeling a body of water and its shoreline. Groups are given time to do “materials testing” of a range of items that might be used to absorb or disperse the oil using water in a cup and a small amount of oil. Other materials available to solve the problem included string, popsicle sticks, and other items as a supportive structure for the absorbent. The design is tested by laying a sheet of graph paper on the surface of the water and counting the number of oil droplet over a particular diameter in size.

Groups were also presented with the problem of designing a coating for a pill that would withstand the acidic environment of the stomach. Various edible materials (flour, sugar, cocoa) and liquids (water, corn syrup) were available for the coating prototypes, and Skittles candies were used as pills. Small battery-powered fans were provided to dry the coating in a relatively timely fashion. To model the stomach environment, coated Skittles were placed in a clear cup

[1] Copies of the revised engineering design lessons are available upon request from the lead author.

with Mountain Dew soda, with the design criterion that the coating needed to cover the candy for 10 minutes. Students subjectively rated the pill coating's appearance, taking into account thickness, smoothness and taste.

For the heart valve problem, students were asked to develop a prototype valve that would not allow blood to leak back into the ventrical chamber. To model that, two pieces of cardboard were firmly affixed to either side of the inside of a cardboard file folder box, and students developed a "valve" that was secured between the two side pieces. To test the prototype, approximately 120 marbles were placed on one side of the valve, and the box was tipped in one direction, allowing the marbles to pass through the valve, then tipped in the other direction. Successful valve prototypes would stop marbles from rolling back to the original side.

For all three tasks, students were given a price sheet listing all available materials and their cost, along with a maximum budget. In some classes, if groups wanted to use materials that were not on the price list, the teacher negotiated a price with the group.

Quantitative data on 185 students in 52 groups were analyzed, within a sequential, predominantly quantitative mixed methods approach (Creswell and Plano Clark 2011)[2]. Multiple imputation was used to handle missing data (Schlomer, Bauman, & Card 2010). In each of the 9 classrooms, 2 groups were selected to be videorecorded for each of the three engineering design tasks. Two cameras with external microphones were used to record the video, and the two camera angles were composited into a single video file using Final Cut Pro X. In lieu of complete transcriptions of the videos, we created elaborated running records of each videorecorded group working on a task, and we use this running record to point to examples of the impact (or lack of impact) of individual socioemotional resources on the group functioning (Rogat and Adams-Wiggins, 2014; Authors 2017). Examples from the video data will be presented at the conference to augment statistical results generated from the quantitative data.

Individual Resources Brought to the Group

Prior to assignment to groups, students completed questionnaires to assess individual cognitive, affective and social resources. Domain-specific interest in biology as a field (4 items, α= .77) and class-specific interest (5 items α= .73), were measured and hypothesized to be key **affective resources** to support group functioning and were measured using items adapted from Marsh, et al. (2005). In addition, measures of perceived competence (6 items, α= .91), perceived task choice (5 items, α= .85), and absence of tension-pressure (5 items, α= .82) (all based on subscales of McAuley, Duncan and Tammen's (1987) Intrinsic Motivation Inventory) assessed other elements of affective resources brought to group work.

Individual **social/relational resources** were measured using items based on the Objectives of Social Competence scale including both interpersonal (9 items, α= .88) and intrapersonal (5 items, α= .64) (ten Dam & Volman 2007, Zwaans, van der Veen, Volman & ten Dam 2008) and

[2] Following Creswell and Plano Clark (2011), we use the term "mixed methods" to indicate that we use separate data sources, both quantitative and qualitative in nature. In this case, both types of data are used to address the same set of research questions, though this need not be the case for all mixed methods studies.

5 items (α= .82) from the assertion subscale of Gresham and Elliott's (1990) Social Skills Improvement System Rating Scale. (See also Lane, Pierson & Givner 2004.)

Pretest measures of biology content knowledge, inquiry and engineering design process were developed collaboratively with participating teachers and administered before the groups worked on the first task and serve as one measure of **cognitive resources** members bring to the group.

Measures of Group Dynamics in Triple Problem-Solving Space

In addition to these quantitative measures of individual resources brought to the group, instruments measuring student perceptions of group dynamics were administered after the first and last task. Perceptions of the ***cognitive dimension*** were measured with the Group Interaction Questionnaire (Visschers-Pleijers, et al., 2005). Perception of the ***social/relational dimension*** was assessed using Sargent & Sue-Chang's (2001) Social Cohesion scale and the Social Loafing and Positive Group Interaction scales (Linnenbrink-Garcia, et al. 2011). The ***affective* component** of the problem-solving space was measured using Edmondson's (1999) Psychological Safety scale. Reliabilities on all of these measures were above α= .70.

Measure of Learning: Engineering Content and Practices

For each of the three tasks, measures of learning of engineering design content and practices were developed in consultation with participating teachers. Items included both multiple choice and open-ended response questions. The engineering design "content" items included multiple choice questions on advantages of having a four-chamber heart, the purpose of heart valves, naming two methods for cleaning an oil spill. An open-ended content item, following the pill coating task, asked students to explain what happens when food reaches the stomach. Thus, the content learning items focused on knowledge of particular facts or discrete concepts related to the group task. Items intended to measure student learning about engineering design as a practice included multiple choice questions to specify a next step after constructing a prototype of a lawn tractor (after heart valve task) and naming two design requirements in the pill coating task. An example of an open ended question assessing learning of engineering design practices asks why it can take engineers years to develop a product that can be sold in stores.

In total, eight items measured content knowledge, five multiple choice and 3 open-ended response items. Seven items assessed practice knowledge, three multiple choice and 4 open-ended response items. Open-ended responses were scored by two graders on a scale of 0 (no relevant information give) to 3 (full and accurate answer) with inter-rater agreement over 95%. In cases where graders did not agree, their scores were averaged.

Findings and Analysis

At this initial stage of analysis, individual-level ordinary least squares regressions have been calculated based on scales described above, addressing research question 1 regarding the relationship between "ego-resources" and group functioning. To address research question 2, the mean of the levels of various resources of the other group members "other-resources" was calculated and taken as a predictor in OLS regressions of an individual student's report about group quality along the dimensions of cognitive, social and affective. In addition, the overall measure of an individual student's perception of the quality of their group's functioning was calculated as the mean cognitive, social and affective measure of the group, and this overall measure was taken as a dependent variable. Measures of specific ego-resources and other-resources were entered individually into the regression models, and all models controlled for the gender of the individual student.

Do the resources that an individual student brings to a small group relate to subsequent self-reports about group functioning (RQ1)? Preliminary quantitative analysis shown in table 1 shows that ego-resources in the form of interest, whether disciplinary or class-specific, relate positively and statistically significantly to later reports about the group's functioning, especially its social and cognitive functioning. Other affective ego-resources, such as feelings of competence and self-concept are also strongly related to self-reports of group functioning, but only on the social and cognitive dimensions. Interestingly, ego-level cognitive resources as indicated by Biology pre-test scores were not related to the student's subsequent reports of any aspect of group functioning. Interactional ego-resources in the form of interpersonal competence (e.g.,"I listen to classmates" "I respect my classmates") were associated with more positive reports of group cognitive and social functioning as well. Intrapersonal competence (e.g., "I receive criticism well" "I control my emotions when working with classmates") was positively related only to the social functioning of the group. Students who reported an assertively participatory interaction style ("I ask questions when confused" "I interact with the teacher" "I question rules that may be unfair") prior to the first task were not more likely to report positive group functioning, however.

Do the resources that *other members* bring to the group relate to subsequent self-reports about group functioning (RQ2)? Another way to think about that question is whether an individual student can benefit from the "other-resources" present to the group, with the benefit measured in terms of the individual student's perceptions of group functioning. In table 2, we see that the influence of "other-resources" on an individual student's experience of the group is more muted, but detectable. When *other* group members bring, on average, strong interest, feelings of competence and positive self-concept, an individual student tends to report stronger cognitive functioning of the group. The interest and self-concept "other-resources" also appear to provide a modest boost to an individual student's perception of the affective life of the group, such as levels of psychological safety. Interestingly, when others bring interactional resources in the form of interpersonal competence, intrapersonal competence, or assertive participation styles, this does not appear to improve the individual's perception of group functioning along any of the dimensions of the triple problem solving space. Having group mates who scored well on the biology pre-test does not tend to produce a more positive experience in terms of group functioning either.

The third research question addresses whether various dimensions of reported quality of small group functioning are associated with individual student learning of engineering design – whether content or practices. Table 3 shows an overview of OLS results that engage this question with respect to learning about engineering design practices. The models run on the full sample of students showed weaker effects on learning than the literature might suggest. An individual student's report on their group's cognitive functioning (including such aspects as knowledge building and handling cognitive conflict) is not statistically related to learning of engineering practices. The perceived social/relational and affective (psychological safety) of the group are only marginally related in a statistical sense to learning about practice ($p<.10$ in both cases). Yet, taken together as the "triple problem solving space" the overall measure of group quality (calculating the mean of the 3 group functioning dimensions) does have a positive and statistically significant relationship with learning about engineering practices ($p=.026$).

Further investigation revealed that except for the cognitive dimension, boys and girls rated their group functioning differently, with girls' mean reports of social, affective and overall group quality being significantly higher than those of boys in the sample. This difference suggested that models of the effects of group quality on learning might work substantially differently for boys and girls. Moreover, prior research suggests that girls and women rely on and benefit more from collaborative learning approaches, such as groupwork (Stout, et al. 2011, Stump, et al. 2011). Thus, models in table 3 were run again separately for boys and girls. The statistical analysis suggests that girls' learning was less dependent on the perception of small group functioning than boys'. Only the affective dimension of the group – psychological safety – came close to approaching statistical significance in explaining learning of engineering practices for girls. In contrast, reported group functioning had broader types of effects on learning for boys with cognitive and social dimensions of the group positively related to learning of engineering practices ($p=.014$, $p=.007$ respectively). For boys, the affective dimension, i.e., psychological safety, had a positive but not statistically significant effect on learning. Taken together, the overall group quality – across all 3 dimensions of the triple problem solving space that small groups must confront – had a positive and highly significant effect on boys' learning of engineering design practices ($p=.002$).

In results not shown, regression models of engineering design content learning showed no significant effects of a) the reported cognitive functioning of the group, b) social/relational group functioning, c) affective group functioning or d) overall group quality (mean of all 3 dimensions). This lack of statistically discernable effects was also seen for the models of all girls and all boys.

Significance of findings

The use of small group work and collaborative team learning situations is very prevalent in science teaching at all grade levels, primary school through college/university levels. Yet, science teachers and instructors have little guidance about how to assemble groups for optimal functioning and how best to monitor groups without disrupting the constructivist learning process that groups must engage in. Moreover, considering how often we ask students to work in small groups or teams, the evidentiary base for how group dynamics can support learning is weaker than it should be. While the research literature on team dynamics is fairly robust when focusing on engineering students at the college level (Kittleson & Sutherland, 2004, Berge, et al. 2012, Stout, et al. 2011, Stump, et al. 2011), there is almost no research base for understanding these dynamics at the secondary school level in the relatively new curricular topics in engineering.

The novelty of the engineering design cycle, in which students need to collectively wrestle with design constraints, develop and test iterations, and make judgements about designs, presents particular challenges for small group work and so teachers need support as they implement these sorts of activities. The results here suggest that teachers need awareness of the resources brought by each member to the group's task. Strong prior knowledge, i.e., "cognitive resources," does not appear to constitute a meaningful stock of resources for the group; more important for spurring better group functioning is interest in science as a discipline and the class in particular. This is true not only in terms of the cognitive, knowledge-building aspects of group functioning, but also in terms of the social/relational functioning (social cohesion, absence of social loafing), and to a lesser extent the group's affective dimension, such as maintenance of feelings of psychological safety. Other key resources that appear to redound benefits (in the form of quality group functioning) to oneself and others in the group are feelings of competence and positive self-concept.

In constructing group membership, particularly in the longer term, teachers may be wise to assess these varied sets of resources and balance groups accordingly. Our results suggest that it is perhaps more important to stock groups with at least one member with social/relational strengths as well as strong and positive affect. Prior knowledge of the engineering content or design practices is a less important criteria for constructing groups than teachers might think.

Questions remain, however. Is it enough, for example, for one student in the group to bring strong interest resources to the group, or do they need to be distributed more equally to induce quality group functioning, and ultimately better learning for everybody? The finding that reported group quality along several dimensions seems to benefit boys' learning more than girls' is a surprising finding. Girls tend to perceive their small group as functioning at a higher level than boys do, yet the learning benefits of a better group – particularly along cognitive and social dimensions – seem to accrue more to boys. Further investigation should rule out the possibility of a "ceiling effect" for girls related to the measures of group functioning, and closer analysis of available video data may shed light on this interesting gender dynamic. For example, boys may benefit more from the managerial roles that girls in the groups are often seen enacting (such as maintaining the group's attention on-task, time management) in our video groups.

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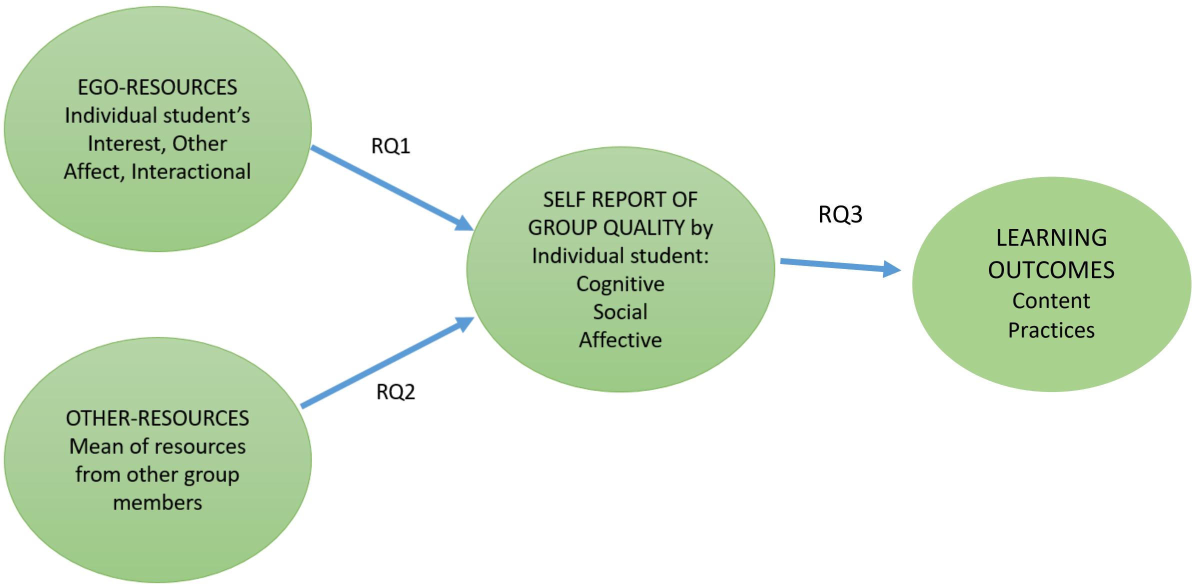

Figure 1: Key Research Questions

	Self-Resources	Self-Report of Group Functioning:			
		Cognitive	Social	Affect	OVERALL
Interest	Discipline	++	++	+	++
	Class Specific	++	+++	++	+++
Other Affect	Perceived Competence	+++	+++		+++
	Absence of Tension				
	Perceived Choice	+			+
	Self-Concept	+++	++		+++
Social/Relational	Interpersonal	+	++		+
	Intrapersonal		++		
	Assertive Participation Style				
Cognitive	Biology Pre-Test				
+ p<.05, ++ p< .01, +++ p<.001					

Table 1: Effects of ego-resources on self-reports of small group functioning

OLS Regressions, controlling for student gender, biology Pre-Test score (n=185)

	Mean of Other-Resources	Self-Report of Group Functioning:			
		Cognitive	Social	Affect	OVERALL
Interest	Discipline	+		+	+
	Class Specific	+		+	+
Other Affect	Perceived Competence	+			
	Absence of Tension	+			
	Perceived Choice	+			
	Self-Concept	++		+	++
Social/Relatonal	Interpersonal				
	Intrapersonal				
	Assertive Participation Style				
Cognitive	Biology Pre-Test				

+ p<.05, ++ p< .01, +++ p<.001

Table 2: Effects of other-resources on self-reports of small group functioning

OLS Regressions, controlling for student gender, biology Pre-Test score (n=185)

	Individual Student's Engineer Design Practice Score		
Group Functioning	-- Full Sample	-- Girls Only	-- Boys Only
Cognitive			**+**
Social/Relational	**(+)**		**++**
Affective	**(+)**	**(+)**	
Overall	**+**		**++**
(+) p < .10, + p<.05, ++ p< .01, +++ p<.001			

Table 3: Effects of self-reported group functioning on learning of engineering design practices

OLS Regressions, controlling for student gender in full sample, Engineering Design Pre-Test score for full sample (n=185), girls only (n=99), boys only (n=86)