Supplemental Material

CBE—Life Sciences Education

Scott *et al.*

Supplementary Material 1

Developing an Analytical Framework to Characterize Student Reasoning About Complex Processes
Emily E. Scott, Charles W. Anderson, K. K. Mashood. Rebecca L. Matz, Sonia M. Underwood, Vashti Sawtelle

Interview Protocols for Phenomena

Egg Phenomenon: When an egg is boiled, the clear fluid inside the egg becomes a white solid.

1. When you hard boil an egg, the translucent egg white turns in to a white solid. Can you describe what you think is happening to the egg?
2. Can you draw a molecular-level picture of what you believe happened to the egg during this process?
    a) Can you please explain the drawing you just created? (if they did not do this when drawing their response above). Be sure to ask them to describe in detail about what they are trying to depict in their drawing and how that explain what is happening to the egg.
    b) How does your drawing help you explain what you believe is happening during this process?
    c) When you heat up something there is energy added into the system (egg).How is energy transferred?
        i) What does the input of energy do to the system?
        ii) Can you draw a representation that traces the energy flow for the system?
3. If students talk about a chemical reaction, ask:
    a) What does it mean when you say a chemical reaction has occurred?
    b) Please explain why you think there is a chemical reaction occurring?
4. What if I told you that the change in the egg white observed occurs due to proteins being present in the egg white.What does this new information mean to you?
    a) If the student still needs help, specifically mention denaturing of the proteins in the egg: Can you describe what you think this means for the system (the egg)?
    b) Can you draw a molecular-level picture of what you believe happened to the egg during this process? Can you please explain the drawing you just created? (Be sure to ask them to describe in detail what they are trying to depict in their drawing and how that explain what is happening to the egg.)
    c) How does your drawing help you explain what you believe is happening during this process?

Heatburn Phenomenon: You touch a hot pan sitting on a stove and burn your finger. A blister forms where you touched the pan.

1. Imagine a hot pan sitting on a stovetop. A person reaches out and touches the pan, resulting in a severe burn that blisters the skin. Can you draw a picture of what you think happens to the hand from when they touch the pan to when the blister forms? (Prompt the student for a molecular level or macroscopic level.)
    a) Can you explain the different aspects of your drawing?
    b) How does your drawing help you explain what is going on during this process?
    c) Does your drawing not represent anything that you think *is* important during the process?
    d) How does your drawing account for the raised fluid-filled form of the blister?
2. Can you create a diagram that would show the flow of energy through this process? (Prompt for thermal energy from the pan all the way to where the energy goes when the blister is formed.)
    a) How does this diagram help you explain what is going on during this process?
    b) Does your drawing not represent anything that you think *is* important during the process?
    c) If I reminded you that energy must always be conserved in a system, how would that change your diagram? (Note: prompt here to think about what “breaks” when the layers of skin and where the energy goes during this process.)
3. You’ve probably heard about not popping the blister that forms on the outside layer of skin. Can you explain why that would be a bad idea?

Protein Phenomenon: How do actors build large muscles?

1. What do you think is happening on a cellular scale when an actor builds muscle? (If they get stuck, "how does our hair grow?" or "how do our fingernails grow?")
2. Can you draw a diagram that helps explain what you think is going on?
   a) What kinds of materials do you think are being added to the growing cell? (ask about protein if the student doesn't mention it)
   b) Where do the raw materials to make the new protein come from? What are they?
   c) What happens to them inside the cell? (get to protein synthesis)
3. When a cell builds proteins, it links up a series of amino acids. Can you describe the process by which the amino acids link together to form a chain?
4. Can you tell the energy story of this situation? Does this process require energy? (Answer: yes because you break a C-OH bond and an H-N bond, and form only a single C-N bond)
   a) Where does this energy come from?
   b) How does ATP provide energy for this process?
   c) What is it about ATP going to ADP that gives you extra energy to work with? (If they imply that the energy somehow comes from "breaking the bond between ADP and P_i, then go into an exploration of how they understand the relationships between bonds and energy.)
   d) **Are there high-energy bonds that release energy when they break?**(Eventually come back to the structures ATP, ADP, and P_i. Point out that there are some extra Hs and Os in ADP and P_i.)
      i) How many bonds are formed/broken during this process? Does that help us with the energy story?
      ii) Is the water molecule an important part of this story?
   e) Does all the energy in the ATP go into making the peptide bond? What happens to the rest?

Sneeze Phenomenon: Sneezing near someone can make them sick.

1. Why can sneezing near someone else make them sick?
2. What comes out of your body when you sneeze? (Get at the idea that the droplets are a mixture of water, colloids (mucus), dissolved ionic and molecular solids, dissolved gases, and suspended viruses and bacteria.)
   a) If interviewee says mucus or something else "high-level" (e.g., snot, phlegm, boogers), ask:What do you think that is made of?
   b) If interviewee only talks about "healthy" people sneezing (i.e. because of pollen in the air), ask: What additional molecules and particles might be included when a sick person sneezes?
   c) Draw a picture of how these molecules and particles are arranged in an example droplet.
3. Where does this stuff go?(Get at the idea that the energy for the droplets to move through the air must have come from somewhere because of conservation of energy, and that intermolecular forces help the droplet stay a droplet as it moves through the air.)
   a) Can you draw a representation that shows where these molecules and particles go once they leave the nose and mouth?
   b) If interviewees are stuck, consider asking:
      i) For the molecules and particles to move through the air, they must have some energy. Where did this energy come from? (We don't want to prompt them initially with specific terms, i.e., kinetic, potential, but we can offer these terms as tools to help them explain if they offer a "canned" conservation of energy response. If they do use specific terms, consider asking what they mean, i.e., what do you mean by kinetic energy?)
      ii) What is happening in your nose, mouth, and lungs as you sneeze?
      iii) How is it that the droplet sticks together as it travels through the air?
4. How can this stuff get someone else sick?(Get at the idea that bacteria and viruses must interact with cells and tissues in the body to make some sick.Also getting at the idea that many of the processes involved in getting sick are random and indeterminate, and we also have defense mechanisms, e.g., physical barriers like skin, so every person that you sneeze near will not necessarily get sick.)
   a) How does the stuff in the droplet get someone else sick?
   b) If the interviewee is stuck, consider asking:
      i) What happens to the droplet once it enters your body? Does it stay whole?

ii) Where would the stuff in a droplet need to go in or on someone's body to make them sick?If interviewee is stuck, consider telling them that you could get sick if you breathed in a bacterium or virus, or if a bacterium or virus settled in the lining of your nose.

5. Why is it that every person that you sneeze near does not necessarily get sick?

Ultrasound Phenomenon: When a tech uses an ultrasound to create an image of a fetus [gallbladder], s/he puts the wand on the outside of the body and an image of the fetus [gallstone] inside the body appears on the screen.

1. When a tech uses an ultrasound to create an image of a fetus [gallbladder], s/he puts the wand on the outside of the body and an image of the fetus [gallstone] appears on the screen (provide image here). Can you draw a picture of what you think happens as the sound waves leave the ultrasound wand and travels through the body to the baby/gallbladder?
   a) Can you explain the different aspects of this drawing?
   b) How does your drawing help you explain what is going on during this process?
   c) Does your drawing not represent anything that you think ***is*** important during the process?
   d) What aspects of your drawing correspond to the different parts of the ultrasound image? (Prompt student for 2D construction of image; prompt for different brightness/colors.)
2. When the tech starts this process, they put a gel on the outside of your skin, can you use your drawing (or another drawing) to represent what purpose this gel is serving?
3. If at this point the student has only talked about the waves at the macroscopic level, push them to describe what's going on at the cellular level. What happens when a sound wave interacts with a muscle/tissue cell?
4. What if I told you that not all the waves produced by the ultrasound are scattered/reflected, but some are absorbed. How would that change (if at all) the representation you've drawn here?
5. Using the explanation you constructed, could you articulate why we use ultrasounds and not x-rays to image fetuses?

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Supplementary Material 2

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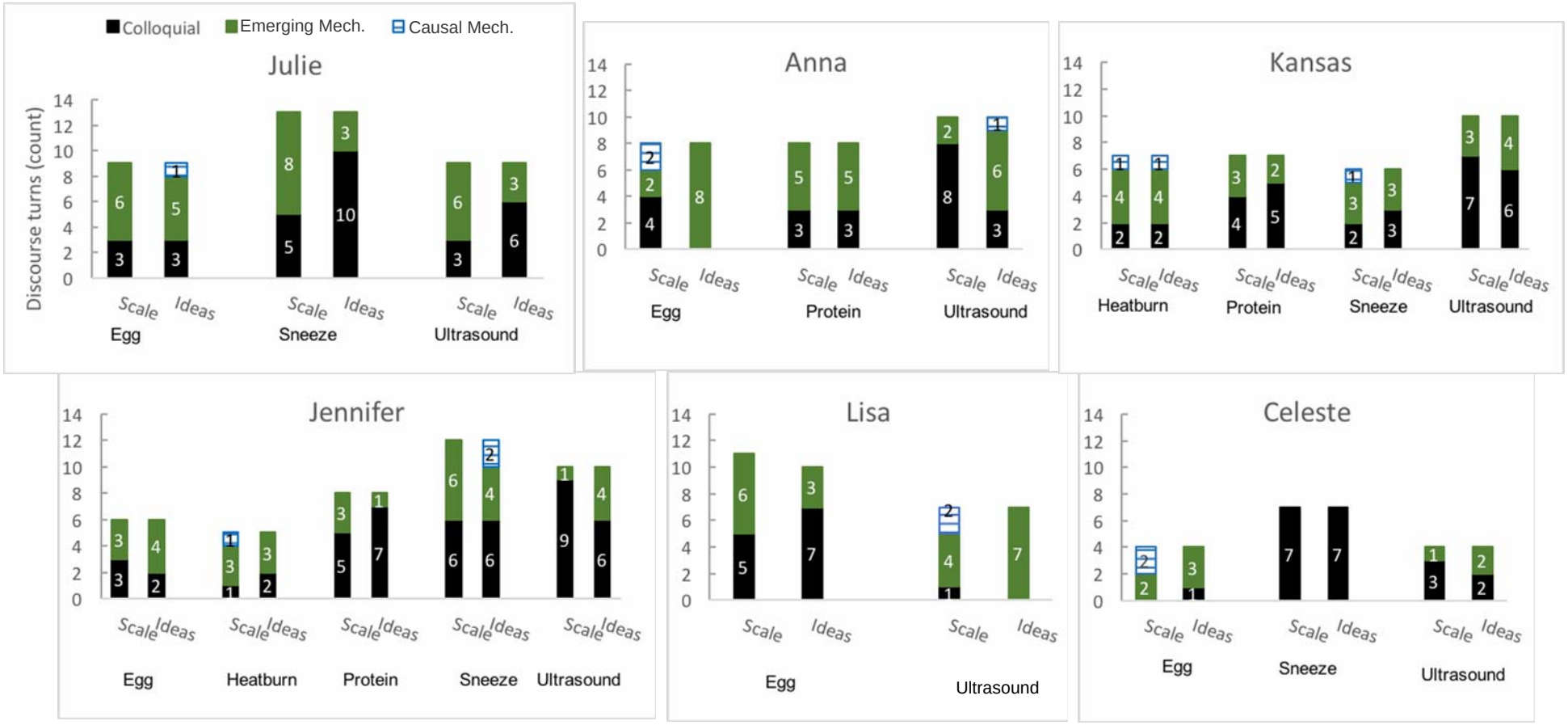
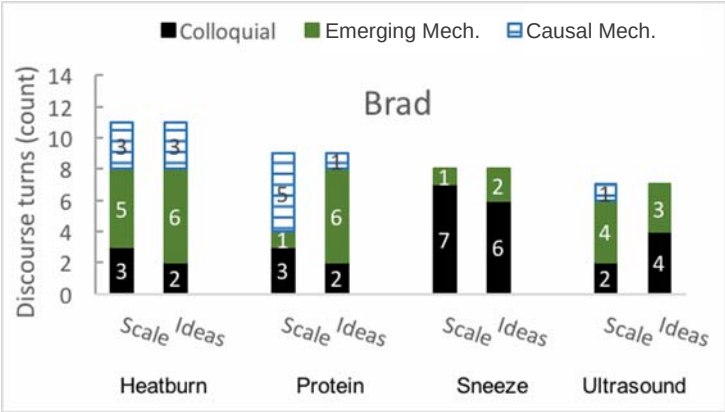
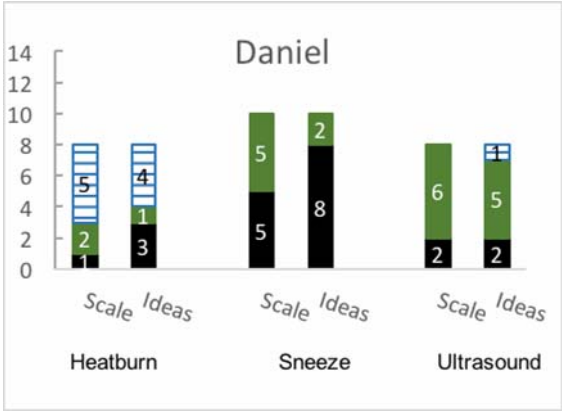
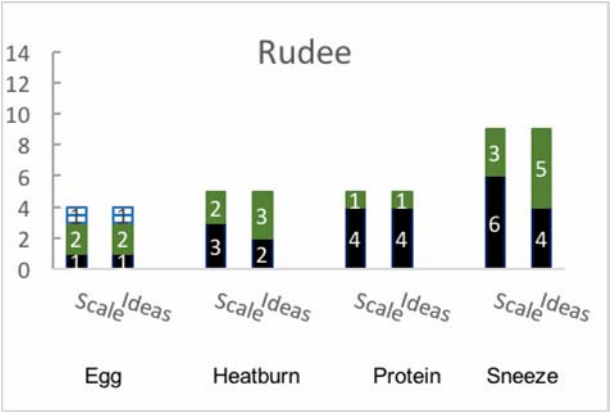
The number of discourse turns across all phenomena and interview participants containing conceptual resources about *multiscale processes* (“scale”) and *scientific ideas* (“ideas”) that aligned with *colloquial*, *emerging mechanistic*, and*causalmechanistic* explanatory frames.




Colloquial
Emerging Mech.
Causal Mech.
Discourse turns (count)
Brad
Scale Ideas
Heatburn
Protein
Sneeze
Ultrasound


Daniel
Scale Ideas
Heatburn
Sneeze
Ultrasound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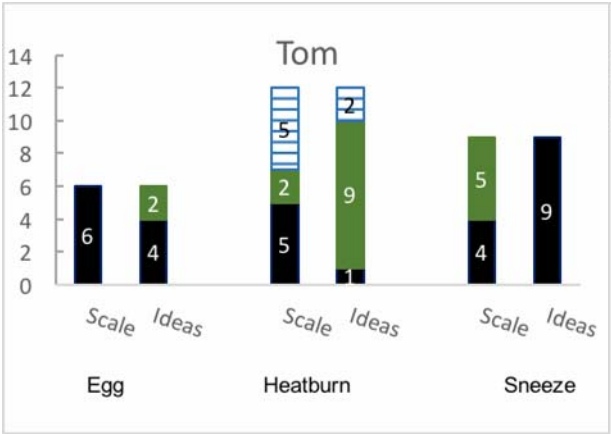
Scale Ideas
Egg
Heatburn
Protein
Sneeze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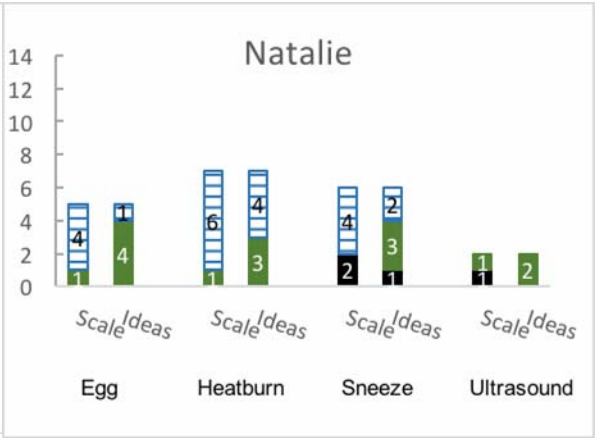
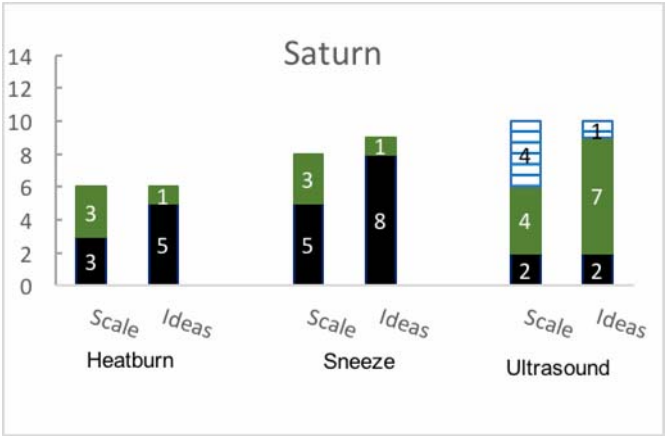
Scale Ideas
Egg
Heatburn
Sneeze


Natalie
Scale Ideas
Egg
Heatburn
Sneeze
Ultrasound


Saturn
Scale Ideas
Heatburn
Sneeze
Ultrasound