How Well Do Middle School Teachers Understand Newton's Third Law?

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We have administered a short instrument investigating teachers' ideas about Newton's third law to middle school teachers over several years. We report on the results and discuss the implications.

All the forces on a particular body add as vectors. The net result of the sum of forces is related to that body's change in motion, usually instantiated as Newton's first and second laws. Newton's third law is a challenge for virtually all science students, even more so than the first two Newton's laws. In contrast to Newton's first and second laws, which deal with a single body, Newton's third law deals with the interaction of two bodies. Further problems arise from a common description of Newton's third law as the "action-reaction" law. The common formulation is "if body A exerts a force on body B, then body B exerts a force on body A, equal in magnitude and opposite in direction."

That "action-reaction" formulation is nonsensical, but persuasive for many. It is part of a natural idea among humans that cause and effect applies to forces (which is correct), and that human intention is directive in this; for example, a student pushes a friend, the friend reacts and pushes back on the original student. The latter is correct as human cause and effect, but incorrect in terms of the forces involved.

One of the lessons from twentieth-century physics is that the basic interactions of nature are non-contact interactions. The three basic interactions—gravitation, electroweak, and strong—are "mediated" through exchange of gauge particles. The bodies do not touch one another, but exchange particles, the gauge bosons that cause the changes in motion. In the case of gravitation, the gauge particles are called gravitons; in the electroweak case, photons and $W^{\pm}$ and Z bosons; and for the strong interactions, gluons. An often-used analogy is to two people in an ice rink tossing a medicine ball back and forth. With each toss, they move farther apart. The medicine ball is an analog to the gauge boson, and the effect of repulsion is analogous to the effect of gauge bosons mediating repulsive interactions (This analogy does not begin to explain attractive interactions).

All interactions are instantiations of these three basic interactions (or four, if we separate out electromagnetism from the electroweak interactions). Thus, no contact is involved in any force, which, though contrary to our experience in the macroscopic world, is the way nature seems to work. As a result there is only interaction between two bodies, not an action ("initiation") causing a reaction (the response to the initiation).

A further confounding problem is that in common parlance, force, power, momentum, and energy are used indiscriminately. Anyone watching a football game has heard commentators (mis)use these terms virtually interchangeably. Students and teachers alike have embedded these ideas in their approach to the natural world, as they seem suited to that description. Scientists, however, distinguish carefully and use the terms knowingly (for the most part; unfortunately, even some physicists repeat the action-reaction misunderstanding as part of their instruction).

Many teachers have not had to take enough courses to guarantee depth of understanding of science concepts, even as they became science teachers. This is especially true of middle school teachers, who really should have the equivalent of master's degrees in geology, chemistry, biology, physics, and teaching. Of course, this is not possible for most teachers, so projects such as IMPACT [1] try to give content support to help the teachers better understand the subjects they are teaching

This paper describes changes in teachers' understanding of concepts involved with Newton's third law over the three-year period of the current IMPACT grant (2013-2016). I do need to explain as background that there was no direct instruction on the third law except the discussion as described in Ref. 3, but there were many activities involving forces and motion during the grant period. Thus, the changes resulted from teacher assimilation of related ideas into their schemae of behavior of the natural world. As we will show, the teachers gravitated to two prevailing views, one of which is consistent with current understanding.

Method

A short six-item survey (Appendix) was taken by the seventh and eighth grade teachers in the program over the three-year grant period. Teachers were given situations involving a car and a truck with three possible choices, designated A, B, and C. Teacher choices were recorded and gathered when there were several choices chosen by multiple teachers. The best answer consistent with current understanding is B-B-B-B-B-B.

We had teachers take the assessment at the beginning and end of the first academic year of the program and then at the end of each succeeding academic year. We have assessment data from 2013 to 2016. Of 43 teachers involved in the program, we use data from 34: 20 completed all four assessments, two took three assessments, and twelve took two assessments. The remainder took a single assessment (some teachers joined the program after it began, some retired, some left because of family issues, and others just managed to evade taking the assessment).

Results and discussion

One way of looking at the data is to ask how many teachers answered B a certain number of times (N = 43). Figure 1 shows the result for all teachers, and Figure 2 shows the number of teachers who were assessed at least twice on the instrument. The labels show the differing numbers of answerers. Figure 3 shows the choices of the 19 teachers who did all four assessments.

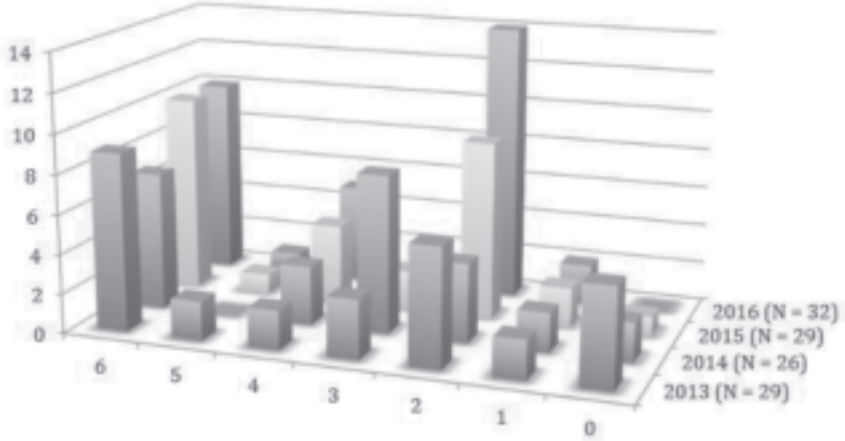

Fig. 1. Number of teachers choosing options with the listed number of answers B.

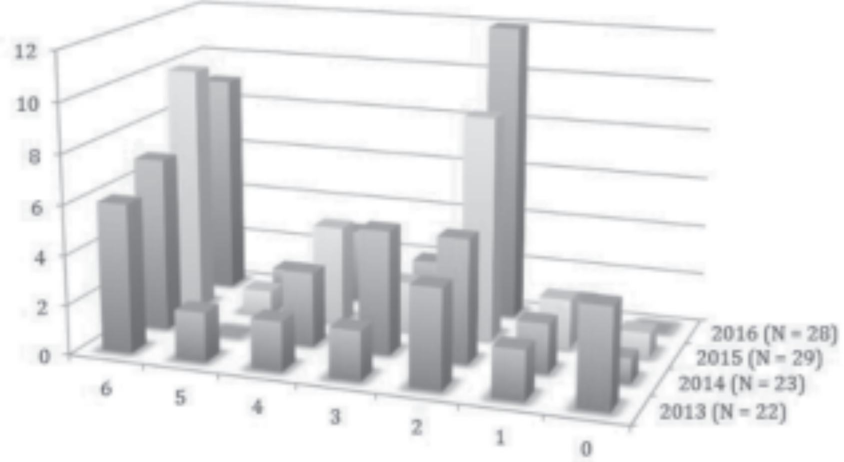

Fig. 2. Number of teachers who completed at least two assessments choosing options with the listed number of answers B.

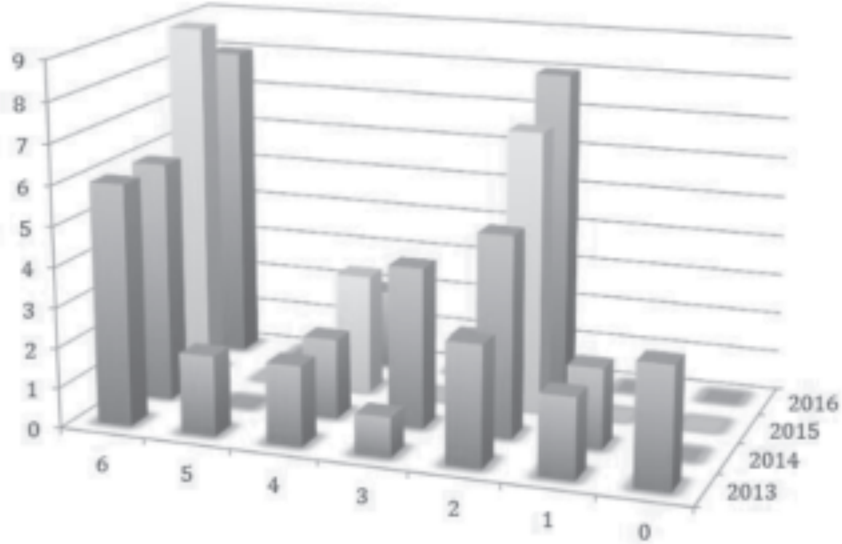

Fig. 3. Choices of the 19 teachers who completed all four assessments.

Another way is to ask how many teachers chose B what proportion of the time. In Table 1, we present the results from all 43 teachers. Table 2 shows the results for the 34 teachers who took more than one assessment.

Table 1. Proportion of all teachers choosing answer B by year.

	6	5	4	3	2	1	0
2013 (N = 29)	34%	3%	7%	10%	21%	10%	14%
2014 (N = 26)	27%	0%	12%	31%	15%	8%	8%
2015 (N = 29)	34%	3%	14%	7%	31%	7%	3%
2016 (N = 32)	34%	0%	9%	3%	44%	6%	0%

Table 2. Proportion of teachers assessed at least twice choosing answer B by year.

	6	5	4	3	2	1	0
2013 (N = 22)	27%	9%	9%	9%	18%	9%	18%
2014 (N = 23)	30%	0%	13%	22%	22%	9%	4%
2015 (N = 29)	34%	3%	14%	7%	31%	7%	3%
2016 (N = 28)	32%	4%	11%	7%	43%	4%	0%

Table 3. Proportions of the 19 teachers choosing B who completed all assessments.

	6	5	4	3	2	1	0
2013	32%	11%	11%	5%	16%	11%	16%
2014	32%	0%	11%	21%	26%	11%	0%
2015	47%	0%	16%	0%	37%	0%	0%
2016	42%	0%	11%	5%	42%	0%	0%

However, the graphs and tables hide significant details. Why did the numbers of teachers choosing two Bs rise, for example? What combinations are represented most? The choice A-A-C-B-C-B was picked by one of the 19 teachers of Table 3 in 2013, three in 2014, six in 2016, and seven in 2016. Just four of these 19 teachers chose something other than B-B-B-B-B-B or A-A-C-B-C-B in 2015 and 2016. The trend is more pronounced among "veteran" teachers, but underlies it for the whole group, because most other teachers chose other choices.

As noted above, the issue was never addressed directly in instruction except as discussed in Ref. 3, though some force probes were used by teachers. So the question is why did both the accepted answer and this alternative rise (B-B-B-B-B-B from 6 to 8 or 9; A-A-C-B-C-B from 1 to 8) between the beginning of the project and the end?

Obviously, we could ask the teachers, but we chose not to, in part because we were planning to do some direct instruction in the new grant period (the proposal was never reviewed). Thus, we are left with inferences. Something in the kinematics professional development activities or associated discussions may have pushed the teachers into the choice B-B-B-B-B-B.

As for the alternate popular choice, A-A-C-B-C-B, we need to examine teachers' possible thinking about collisions in more detail.

Most teachers have taken at least one introductory physics course. In that course, they would be likely to encounter momentum, defined non-relativistically as $\mathbf{p} = m\mathbf{v}$. They are also likely to have encountered Newton's second law, usually defined as as $\mathbf{F} = m\mathbf{a}$. As physicists know, Newton's second law is simply the derivative of the momentum equation assuming that mass is invariant. Such a course makes a big deal out of conservation of momentum, which occurs when there are no external forces. Acceleration is recognized in these courses as the rate of change of velocity.

Choices 4 and 6: B

This is pertinent to the choices for answers 4 and 6 (Appendix), both of which are B in the alternative popular choice. The fact that velocity is stated to be constant seems to educe $\mathbf{F}_{net} = 0$, hence either the teachers assume the forces of truck on trailer and trailer on truck "cancel" or that there is no force between them, both of which are incorrect but lead to the correct answer (the instrument is unable to distinguish these incorrect answers from a correct answer, but this is unlikely because the teachers do not choose a correct answer for the other choices). The "cancellation" idea would be a misapplication of Newton's first law (a single body relation) to the case of two bodies. The idea that the net force is zero means that the individual forces are zero is belied by the simple example of a motionless book on a table: the book has weight (it is near Earth) and the book is in contact with the table, which will exert a force on it. These two forces add to zero (Newton's first law) because they act on a single body, but the fact that the net force is zero does not mean that the weight, for example, is zero.

Therefore, in this context of the other four incorrect answers, their choice of the correct answer does not imply understanding of Newton's third law.

Choices 1 and 2: A

Choices A in 1 and 2 (Appendix) seem to indicate that the person believes that the body with more mass (and therefore more weight) can exert a greater *force* on the body of lesser mass. This confuses acceleration with force. Because people know that if a large-mass body hits a small-mass body, the small-mass body rebounds and the large mass body seems barely to slow. This is interpreted as larger versus smaller force, while it is actually larger versus smaller acceleration.

Knowing that Newton's third law says that $F_{\text{truck on car}} = F_{\text{car on truck}}$, that is, the magnitudes are equal. The result $F_{\text{truck on car}}$ is $m_{\text{car}}\ a_{\text{car}}$, according to Newton's second law. Likewise, the result for the truck $F_{\text{car on truck}}$ is $m_{\text{truck}}\ a_{\text{truck}}$, So, this means $m_{\text{car}}\ a_{\text{car}} = m_{\text{truck}}\ a_{\text{truck}}$, or $a_{\text{car}} = m_{\text{truck}}\ a_{\text{truck}}/\ m_{\text{car}}$. This means that the car accelerates much more than the truck, resulting in a bigger change in motion (as observed). If the forces were greater on the truck than the car by the expected factor, each would have had the same change in motion, not observed.

Choices 3 and 5: C

These ask about a trailer being pulled by a car (choice 3) or a truck (choice 5). Newton's third law says that the magnitude of the force of the car (truck) on the trailer is equal to that of the trailer on the car (truck). The alternate view that C describes the situation means that the person thinks that the car (truck) has to pull the trailer with greater force than the trailer pulls the car (truck) for the trailer to be pulled.

The car (truck) and trailer are not moving at constant speed, which seems to key the response that there is acceleration (correct), but that it must be greater for the car (truck) than the trailer because the trailer is being *pulled* (incorrect). The car (truck) and trailer are yoked together and move together. They are speeding up at the same rate.

Conclusion

The alternate view, A-A-C-B-C-B, is a coherent model that reflects a belief that Newton's first and second laws apply to the objects: at constant speed, the answer B indicates that the forces are equal rather than Newton's third law. When the car and truck accelerate, the people apply

Newton's second law once again. In this model, Newton's third law might be seen as a special case of Newton's first and second laws, rather than as something different that applies to two bodies rather than a single body as for Newton's first and second laws.

In 2006, Bao and Redish [4] suggested that answers to multiple choice can allow researchers to determine whether students embrace model 1, model 2, or a mixture of the models. In the present case, we can see the mixed model diverging for teachers into the two models (actual understanding of Newton's third law) and the alternative understanding over the three years of the program. The confusion originally between the correct B-B-B-B-B-B, and miscellaneous ideas coalesced into the correct view and a strong alternative.

The teachers have at least achieved coherent views. The kinematics experiences did result in changes in the teachers' views, pushing many of them into the alternate model and a few of them into the correct model.

If we are able to follow up, we hope to give teachers experiences in coming years that will help them move from the incorrect model to the correct model.

Acknowledgments

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Appendix

Name: __________________________ Date: __________________________

1. A car and a truck are moving at equal speeds towards each other. The truck weighs
much more than the car. Consider the forces that they exert on each other at the moment
they hit.
A. The truck pushes on the car more than the car pushes on the truck.
B. The truck pushes on the car exactly as much as the car pushes on the truck.
C. The truck pushes on the car less than the car pushes on the truck.

2. Two cars are moving towards each other at unequal speeds. The two cars have the same mass. Consider the forces that they exert on each other at the moment they hit.
A. The fast car pushes on the slow car more than the slow car pushes on the fast car.
B. The fast car pushes on the slow car exactly as much as the slow car pushes on the fast car.
C. The fast car pushes on the slow car less than the slow car pushes on the fast car.

3. A car is pulling a trailer that weighs a lot more than the car. The car speeds up. Consider the forces that they exert on each other while they speed up.
A. The trailer pulls on the car more than the car pulls on the trailer.
B. The trailer pulls on the car exactly as much as the car pulls on the trailer.
C. The trailer pulls on the car less than the car pulls on the trailer.

4.The same car and trailer now move at constant speed. The trailer still weighs more than the car. Consider the forces that they exert on each other while they move at constant speed.
A. The trailer pulls on the car more than the car pulls on the trailer.
B. The trailer pulls on the car exactly as much as the car pulls on the trailer.
C. The trailer pulls on the car less than the car pulls on the trailer.

5. The trailer is now hitched up to a truck. The truck and the trailer weigh exactly the same as each other. The truck speeds up. Consider the forces that they exert on each other while they speed up.
A. The trailer pulls on the truck more than the truck pulls on the trailer.
B. The trailer pulls on the truck exactly as much as the truck pulls on the trailer.
C. The trailer pulls on the truck less than the truck pulls on the trailer.

6. The truck and trailer now move at constant speed. They still weigh exactly the same as each other. Consider the forces that they exert on each other while they move at constant speed.
A. The trailer pulls on the truck more than the truck pulls on the trailer.
B. The trailer pulls on the truck exactly as much as the truck pulls on the trailer.
C. The trailer pulls on the truck less than the truck pulls on the trailer.

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