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Revisiting the teaching of forces in KS3

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Abstract

This article considers some of the challenges presented by the forces topic for students in the 11–14 age range, as well as for student teachers. Although all young people have studied forces as part of Science in the National Curriculum in England since its inception in 1989, science graduates starting teacher training frequently present with weaknesses in their physics subject knowledge. This article explores possible reasons for these deficits from the perspectives of Piaget's stage theory, conceptual change theory and knowledge-in-pieces. There is a possibility that the cognitive demand of material in the curriculum exceeds the cognitive abilities of learners. Another possibility is that teaching has not been successful in overcoming, or building upon, students' preconceptions. At the curricular level, the article asks whether we attempt to teach ideas that are too complex too early, and suggests a change to the order in which concepts are introduced, based on existing science education research. The article makes practical suggestions for teaching, in particular to take into account students' cognitive abilities, and to address the preconception that forces are needed to maintain motion. It argues that teaching strategies involving sense-making by considering problems that are meaningful to learners, eliciting learners' existing ideas, observing phenomena and developing theories through classroom discussion, comparing the merits of competing explanations, may better support development of understanding. A reduction in content in the curriculum is suggested to make time for this activity, and teachers will need additional professional development opportunities to develop new teaching strategies.

Keywords: forces, preconceptions, pedagogy

1. Introduction

Working as a physics teacher educator in England, I recently encountered a scenario in which a student teacher (ST) in a key stage 3 (KS3) science classroom (students aged 11–14) was struggling to draw and label correctly a force diagram for a tennis ball passing over the net during a rally. Why do children and STs struggle and how can we help them?

That some STs have weaknesses in physics knowledge was evident since I started working in initial teacher training and education (ITTE) in 2010. Subject knowledge tests are commonly used in ITTE to identify STs' strengths and weaknesses. My experience has been that there is a range of subject knowledge amongst physics graduates, and that biology and chemistry graduates may outperform the weakest physicists. In this article, I adopt the term preconceptions for the intuitive ideas students bring with them to lessons, which are often at odds with the scientific view (see, e.g. Driver *et al* 2004). That adult learners have subject knowledge weaknesses is supported by research, both in the UK and internationally, suggesting that both pre-service and in-service teachers may present with similar preconceptions to those held by children, including about forces and motion (see, e.g. Taber and Tan 2011, Sadler *et al* 2013, Admoko and Suliyanah 2023).

England has had a National Curriculum (NC) for Science since 1989 (HMSO 1989). As a result, studying physics has been compulsory from age 5–16. Public examinations at age 16 are regulated, leading to close alignment between knowledge, skills and understanding set out in the NC and that included in specifications of material to be taught, and in its assessment. That being so, why do many science graduates arrive into ITTE courses without a secure understanding of this material? Possibilities include that:

- A chronic shortage of physics teachers means that STs were not taught well themselves (Institute of Physics 2024).
- The curriculum is overloaded.
- Teaching methods are ineffective.
- The cognitive demand of the curriculum exceeds the cognitive abilities of most school students (Adey and Shayer 1994).

The shortage of physics teachers may have an impact. However, my professional experiences in ITTE suggest that even some physics STs with strong physics qualifications may have gaps in some topic areas, so perhaps having more physics specialists is not a panacea. So, could the curriculum be overloaded?

A major criticism of the NC has been that there is 'an overload of factual content' (Toplis *et al* 2010, p 66). This matter was addressed in an updated curriculum from 2006 (QCA 2005), placing greater emphasis on science literacy. However, this innovation was relatively short-lived, and the current curriculum (DfE 2015) focuses on developing substantive knowledge. Perhaps we ask teachers to teach too much in too little time. Could teaching methods also be ineffective?

Traditional science teaching is sometimes characterised as transmission of propositional knowledge and previous research is critical of such approaches (see, e.g. Loughran 2014). Whilst children pass standardised tests, often by rote learning, is understanding developing? Previous research suggests not, because transmission does not address learners' intuitive ideas. Driver (1983) suggests learners can learn concepts at any age, provided we reduce the complexity of tasks and build on their prior experiences. However, others (e.g. Shayer & Adey, 1994) subscribe to Piaget's stage theory of cognitive development. So, could cognitive demand explain the weaknesses observed?

Previous analysis of the science curriculum suggested that much of the material taught in the 14–16 age range demanded formal operational thinking—a level that most students have not yet developed. Writing about the first NC, Adey & Shayer (1994, p 33) state:

There is still a significant gap between cognitive demand of attainments expected of 14-year-olds and of 16-year-olds and the levels of thinking currently available in the population.

So, perhaps cognitive demand of the curriculum is a factor.

In this light, what could we do? I suggest improving children's learning when they first encounter topics in schools. I start by describing the difficulties the tennis ball scenario presents, linked to literature. Then, I review relevant theoretical perspectives. I suggest strategies for teaching, as well as implications for the curriculum and teachers' professional learning.

2. Challenges presented for teachers and learners

At first glance, the scenario looking at the forces on a tennis ball passing over the net might seem quite simple, and it might seem like a good example because we are asked to apply our physics knowledge to a real-life scenario. We might also consider that sports examples can be powerful because they appeal to our students. However, I suggest there are three main challenges, as well as a fourth possibility, as I explain.

Firstly, forces are invisible so they can be hard to visualise (de Winter 2021). The abstract nature of forces might make them difficult to learn for those not yet thinking at the level of formal operations.

Secondly, a common preconception is that forces are needed to maintain motion (Osborne & Freyburg, 1985), which makes Newton's laws counterintuitive to learners. Newton's first law states that we do not need a force to keep things moving once they have started. In the tennis ball scenario, however, it is likely that learners think there must be an ongoing force on the ball, keeping it moving as it goes across the net.

Thirdly, the tennis ball is a projectile, with motion in both the horizontal and vertical dimensions. The two-dimensional nature of this problem adds complexity. When science education researchers looked at a ball moving vertically—simplifying this problem to just the vertical dimension—only about half of 16–17 year-old physics students were correctly able to label a diagram demonstrating a Newtonian view (Osborne and Freyberg 1985). The Newtonian view is that the only force acting is the weight of the ball, acting downwards towards the centre of the Earth, regardless of whether the ball is moving upwards, at the top of its flight, or moving downwards. The other half of the students thought there is always a force in the direction of the motion, and no force when the ball is at the top of its flight. Hence, it is likely that the two-dimensional tennis ball problem is very challenging and therefore not suitable for most students in KS3.

Fourthly, do students have sufficient experience of tennis to make it a real-world example for them? Tennis is historically a middle-class sport (Lake 2011), and although efforts have been made to widen participation, I do not think we can assume all our students have had opportunity to play. Whilst this might seem like a minor point, we know many groups are underrepresented in physics (IOP 2020), so perhaps we need to be more careful with our examples, to support more people in feeling a sense of belonging in physics.

Hence, we can see that the problem might present several challenges for learners, where many:

- find it hard to visualise invisible forces;
- think forces are needed to maintain motion, leading to difficulties even with one-dimensional vertical motion;
- lack real-life experience of teachers' chosen scenarios.

Next, we take a deeper look at why these challenges occur.

3. Theoretical perspectives

In this section, I describe some theoretical perspectives which suggest different pedagogical approaches to overcoming misunderstandings in science, going beyond presenting young people with substantive knowledge to be memorised.

Many are introduced to conceptual change research, pioneered by Ros Driver (see, e.g. Driver *et al* 2004), during ITTE. In essence, children come to science lessons with preconceptions about science phenomena, e.g. heavier objects fall more rapidly than light objects. These ideas are often hard to shift. To overcome these difficulties, teachers could teach in ways that:

- 'help children exchange, evolve, or extend their existing ideas…
- Present new ideas so that they appear intelligible, plausible and useful…
- Order the topics of the curriculum to better take into account the learners' intuitive ideas.' (Osborne and Freyberg 1985, p. 41)

It is not as simple as showing learners evidence that they are wrong, e.g. through a demonstration or practical activity. Conceptual change emphasises time for learners to develop their thinking through discussion of ideas and evidence.

However, a weakness of conceptual change theory is the idea that learners come to lessons with 'conceptions'. It is sometimes argued that their ideas are not well developed enough and not coherent enough to qualify. di Sessa's theory of knowledge-in-pieces addresses this issue (Harlow & Bianchini, 2020). He calls learners' preconceptions phenomenological primitives (p-prims). P-prims can be thought of as pieces of a cognitive jigsaw puzzle. Learners' ideas make sense to them, and they are not correct or incorrect per se, but rather they work in some contexts and not in others. For example, di Sessa (1993, cited by Harlow and Bianchini 2020), suggests two p-prims relevant to the forces topic:

- 'more effort implies more result; more resistance implies less result' (p 391)
- 'pushing an object from rest causes it to move in the direction of the push' (p 392)

Campbell *et al* (2016) suggest using learners' p-prims as stepping-stones on a pathway towards developing a better understanding of the scientific view. They propose that learners are presented with real-world problems, which they are encouraged to explain using their existing ideas, as well as science ideas, comparing the merits of different explanations and evidence through group discussion. This approach emphasises sense-making, rather than replacement of students' preconceptions with the accepted view. It is argued that if we attempt replacement of ideas, rather than working with and building on them, learners memorise the 'right answer', but are unable to apply these ideas to scenarios they meet in real life, once beyond the exam or test for which the material was memorised.

Finally, I return to cognitive demand. Previous analysis of curriculum demand (Adey and Shayer 1994) was based on Piaget and Inhelder's work on stages of cognitive development. Whilst there is debate about whether thinking is domain-specific or generalisable to different contexts, as a physics educator the idea that there are general thinking skills is attractive. The reasoning patterns of formal operations include control and exclusion of variables, ratio and proportionality, constructing and using formal models (including mathematical equations), and logical reasoning (Adey and Shayer 1994). That children struggle with physics because they might not yet have developed these modes of thinking seems plausible. Whilst these reasoning patterns are discussed as general thinking skills in wider educational literature, perhaps we might consider them to be physics subject-specific. Possibly further research is needed to elucidate whether they are transferable from one physics topic to another.

Where Piaget and Inhelder suggested the stage of formal operations was reached at about age 11, Adey and Shayer (1994, p 31) reported that 'fewer than 30% of 16 year-olds were showing the use of even early formal operations' in England and Wales. Furthermore, Shayer and Ginsburg (2009) suggest there was a decline in children's cognitive abilities between 1976 and 2006/7. Perhaps these observations could explain why many children have difficulties with complexity, abstract thinking, and multivariate problems in physics, although further research is needed to find out whether or not the decline has continued to the present day.

Rather than waiting for children to achieve readiness to learn, i.e. for the stage of formal operations, Adey and Shayer (1994) suggest stimulating cognitive development in lower secondary, giving learners classroom experiences which provide:

- Cognitive conflict, i.e. challenging learners' initial thinking by exposing them to examples that cannot be explained using their current modes of thinking.

- Opportunities to interact with others to develop their ideas.
- Opportunities for metacognition, i.e. to think about their thinking

So far, I have described several theoretical perspectives about learners' difficulties in learning science, as well as relevant pedagogical approaches. So, how might learners' difficulties be addressed?

4. Possibilities for practice

Firstly, teaching could start with simpler problems. A group of international experts (Harlen *et al* 2015) suggests limiting ourselves to situations involving stationary objects with balanced forces in KS3. Unfortunately, England's curriculum currently states that students must learn about both balanced and unbalanced forces, not just in KS3, but for key stage 2 students (KS2) (aged 7–11) (DfE 2013). Hence, perhaps teachers could use one-dimensional problems initially (i.e. no projectiles, no circular motion). Furthermore, do we need to start with examples of objects speeding up, slowing down, remaining at rest, continuing to move in a straight line at a steady speed, and changing direction, all at once? Might this not confuse learners? So, how might we proceed?

de Winter (2021) suggests using cardboard cutouts of arrows of different lengths to represent forces, rather than starting with diagrams of forces arrows. This approach makes the abstract concrete, adapting to most learners' cognitive abilities. To further reduce complexity, we do not necessarily need to name forces—weight, tension, etc. de Winter suggests beginning with arrows labelled with just FORCE.

In line with Harlen *et al* (2015), teaching could start by focusing on stationary objects with balanced forces, such as floating, building bridges and stretching strawberry laces. With floating, I suggest not teaching density yet, preferring to teach multivariate problems in key stage 4 (KS4) (students aged 14–16) when students' cognitive abilities are better developed, instead focusing on the idea that if the upthrust is equal to the weight then the object floats. Students could make simple comparisons between the weight of objects and the weight of fluid displaced (upthrust).

In bridge-building (e.g. NPESScience20+ 2022), the best bridge exerts the greatest upward force on the load before failure. Teaching could foreground examples of types of bridges in students' local environment, e.g. suspension, cantilever, arch. Bridges with cables for support lead into properties of materials in tension.

The *Stretchy Sweets* activity (Institute of Physics undated a) starts with qualitative observations. At this stage, teachers could emphasise that when the tension is equal to the weight the mass is supported, but when the weight exceeds the tension provided, the lace breaks.

So far I have suggested using simpler scenarios, making forces visible with cardboard arrows, referencing real-life applications, and including simple practical activities. Next, I consider recommendations from conceptual change research, and from the knowledge-in-pieces perspective, to address learners' preconception that forces are needed to maintain motion.

Osborne and Freyberg (1985) suggest a different sequence for teaching forces, starting with eliciting students' preconceptions, then proceeding from the idea that something *is* involved in maintaining motion, and that something is *momentum*. Subsequently, we establish that forces are pushes and pulls, distinguishing between forces and momentum. Only then do we move on to the idea that unbalanced forces cause changes in momentum. Teachers found this approach made sense to children (Schollum *et al* 1981). So, what would a lesson introducing momentum look like in KS3? table 1 shows a possible sequence.

Thus, in the tennis ball scenario, in which learners often think there is a force maintaining the forwards motion of the tennis ball, we establish that there is not a force, but rather the ball has momentum.

So far, we have seen that conceptual change research suggests a change of sequence, starting with momentum. However, perhaps this approach attempts to replace preconceptions, rather than to develop thinking, so what else could we do?

From the knowledge-in-pieces perspective, we treat the idea that forces maintain motion as not necessarily wrong (Campbell *et al* 2016). We use

Table 1. Teaching sequence adapted from Schollum *et al* (1981).

Activity	Description
Whole-class discussion of examples	Which vehicle would be harder to stop and why? E.g. two similar trucks, one unloaded and one loaded. Students might say the loaded truck has more force.
Teacher exposition about momentum (qualitative)	Moving objects have momentum. Bigger loads have more momentum than small ones. Faster-moving objects have more momentum than slower ones.
Written work and peer discussion of examples	Which vehicle has more momentum, and by how much (a lot/a little)?
Demonstration/practical activity	A ball is rolling up a slope. In terms of momentum, what happens when the ball: • Rolls up the slope • Stops moving • Rolls back down
Written work and peer/class discussion	Students consider scenarios in which momentum is changing, identifying what is happening in terms of momentum, e.g. a car hitting a brick wall.

it as a stepping stone, building towards an understanding of the scientific view, by first considering contexts where the idea is helpful to us. In daily life, we experience motions with a lot of friction or air resistance (drag). On the bus there is a driving force, ultimately coming from the engine and keeping the tyres pushing back against the ground, which needs to keep going to overcome rolling resistance. Without that force the bus would slow down and stop. The learner's preconception that we need a force to maintain motion works when there is considerable drag, but falls down in scenarios with little drag. In the tennis ball scenario, the idea that a force is needed to maintain motion does not help us because the effect of air resistance is small.

The Ambitious Science Teaching approach is grounded in the knowledge-in-pieces perspective. In this approach, teaching focuses on developing understanding of how forces affect motion. Further details of a teaching sequence supporting learners' abilities to reason with Newton's Laws of motion can be seen on the Ambitious Science Teaching (2024) website. Teaching includes:

- Eliciting students' ideas about forces.
- Supporting students to articulate their initial theories.
- Choosing scenarios that are meaningful to the teacher's own students, e.g. rollerblading.
- Providing opportunities to observe phenomena and develop theories through talk and discussion.
- Scaffolding talk and writing to support development of arguments.
- Emphasising developing reasoning based on evidence, rather than 'correct' answers.

However, teaching in this way requires a considerable amount of time—nominally 12 days for this sequence. Even if this represents 12 hours of classroom time, that would be considerable, bearing in mind that England's KS3 students typically have three to four hours of science per week. However, perhaps spending more time on developing understanding of foundational ideas would be worthwhile if it resulted in more learners getting to grips with important concepts, such as that forces are not needed to maintain motion.

5. Conclusions and recommendations

Despite all students having studied physics from 5 to 16 since the inception of the NC in England, many STs present with insecure understandings of physics, even for teaching in the 11–14 age range. In England, we are in the relatively fortunate position that the curriculum is currently being reviewed, so a future curriculum and future teaching could respond to improve matters. What might we do differently?

Previous research suggests that even post-16 students have difficulty in labelling force diagrams correctly, showing an understanding of Newton's Laws (Osborne and Freyberg 1985). Perhaps Harlen *et al*'s (2015) suggestion that we look only at stationary objects, where the forces are balanced, in KS3, could be considered for inclusion in an updated curriculum, so that we are not asking learners to do too much too soon.

Conceptual change research suggests a change of sequencing. In current and previous curricula in England, the concept of momentum has been introduced in KS4 or beyond. Research suggests that introducing momentum earlier, in a simple way, makes sense to learners (Schollum *et al* 1981). Their preconception that something maintains motion can be satisfied by calling it momentum, which is an explanation more in tune with accepted physics ideas. Perhaps an updated curriculum could implement Schollum *et al*'s (1981) suggestion that a simple introduction to momentum could precede teaching about forces as pushes and pulls. Again, consideration of the appropriate stage for its introduction is needed—should we really be introducing forces in KS2 or KS3, where abstract concepts are beyond many learners' cognitive abilities, according to Adey and Shayer (1994)? Perhaps further research is needed owing to the time elapsed since Schollum *et al*'s (1981) and Adey and Shayer's (1994) research was carried out.

Furthermore, perhaps we need to reconsider how physics knowledge is to be acquired. Colleagues internationally are having success with approaches developing sense-making through classroom discussion of competing ideas. The challenges presented are two-fold:

The quantity of material included in the NC needs reducing to create time for approaches involving development of reasoning through discussion.

Many teachers would need professional learning opportunities to develop the pedagogical approaches involved. Such courses would need to address both the preconceptions that learners, including teachers, may hold, as well as pedagogical approaches for overcoming them, including the rationale for changes in sequencing. Since we know that learners' preconceptions may be difficult to shift, and that teachers may need time and support to put new approaches into practice, longer term professional development projects, similar to those pioneered by Bell and Gilbert (1996), may be required.

The potential benefit is in more people developing a better understanding of physics. Additionally, perhaps by better matching the demand of the curriculum to the needs of learners, more students will feel successful in physics, leading to better retention post-16, helping to solve the chronic shortage of physics teachers, as well as meeting the needs of industry for skilled workers.

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