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Students' talk about rotational motion within and across contexts, and implications for future learning

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The investigations reported in this article are part of a larger study concerned with understanding learning as it emerges from the enacted curriculum which in itself is mediated by: students' views of the nature of science, beliefs about learning, views of laboratory learning environments; teacher's beliefs about knowing and learning science and knowledge of student ideas about content. In this article, the results of two studies of students' discourse about rotation phenomena are presented with a particular focus on the consistency of this talk across different phenomena. Study 1 presents an inventory of students' observational and theoretical descriptions after they had been taught rotational motion during the previous school year; it simultaneously constitutes an inventory of students' knowing before another physics unit that presupposed knowledge of the first instructional cycle. Study 2 reports on the same students' discourse after a four-week unit on the dynamics of rotational motion. The results of Study 1 indicate that in spite of prior instruction, students' observational and theoretical descriptions of rotational phenomena were different from scientific canon and inconsistent within and across contexts. Study 2 further underscores the variations in student discourse about rotational motion within and across context and the differences with canonical discourse. More importantly, it illustrates that only a minority of students provided adequate observational and theoretical descriptions about the dynamics of rotational motion.

Introduction

There is a considerable literature on students' ways of seeing and explaining the world. Students come to school with ways of seeing and talking about natural phenomena which are frequently inconsistent with the scientific canon. Some areas such as Newtonian mechanics have been researched more extensively than others (for a review of students' ideas on motion see McDermott 1984; an extensive bibliography can be found in Pfundt and Duit 1994). One of the less researched areas in physics is students' ways of talking about rotational motion. Although rotational motion is an important aspect of today's industrial worlds, where one can find wheels, shafts, and motors that rotate, experience has shown that the physics of rotational motion provides students with considerable difficulties in learning (Searle 1985, Otto 1988).

In the past, a considerable number of studies have been devoted to determining students' 'alternative conceptions,' 'naive frameworks,' or 'preconceptions' (Gilbert and Watts 1983, diSessa 1993). This study takes a different perspective. Like an increasing number of researchers in philosophy, social studies of science, social psychology, cognitive science, and education, we understand knowledge in terms of people's competence for participating in a variety of discourses (Clark and

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Schaefer 1989, Rorty 1989, Edwards and Potter 1992, Pea 1993, Knorr-Cetina 1995). A number of science educators recently suggested that what students bring to school are not conceptions as individual properties, but ways of seeing and speaking about the world which are characteristic of the communities in which people participate (Marton 1984, Lemke 1990, Ueno 1993, Roth 1995). The form and content of these discourses are, like other human practices, a function of the particular context in which they are used to describe and explain phenomena. However, we are not aware of any single study which looked at the consistency of students' explanations within a specific context (e.g. a ball held by a string in a circular orbit) and across context (e.g. a space craft on a circular orbit).

The teacher must be aware of the discourses students bring to the classroom because these interact in important ways with the ways of talking science that students are to appropriate in the science classroom. Whether teachers use a conceptual change approach or one based on learning as the appropriation of new forms of discourse, they need to be aware of what students bring to the classroom. With this knowledge, they can design their instruction of, and interactions with, students in such a way as to bring about learning (Lemke 1990, Roth 1995). However, past research indicates that secondary school teachers are largely unaware of students' science and are not very good at predicting student-held conceptions (Watts and Zylberzstajn 1981, Osborne *et al.* 1983, Anderson and Smith 1985, Berg and Brouwer 1991).

There is some evidence that ways of seeing and talking about phenomena related to physics are contingent on specifics of the context and may not be consistent across various settings, problems, problem formats, etc. (Ueno 1993, McGinn *et al.* 1995). If such inconsistencies exist, they may lead to situations where teachers think that students understand what is prerequisite for a lesson or unit, when in fact this knowledge is only partial or even conflicting. These inconsistencies would lead to variations in the integration of new content. Teachers therefore need to understand students' prior talk about relevant phenomena not only in terms of isolated aspects, but also in terms of a holistic 'way of talking.'

This investigation was designed to investigate patterns of students' discourse about rotational motion before and after an instructional unit on rotational motion; the students had studied a related unit on uniform circular motion in the previous year. Two studies were designed. The first investigated students' talk about rotational motion, its consistency within and across situations. The second study investigated students' talk about the dynamics of rotational motion after a four-week unit on the topic.

Study design

Context of investigation

This article is part of a larger interpretive study concerning teaching and learning of rotational motion in one Year 12 physics classroom of a state high school in the suburbs of a large Australian city. Over a six-week period, an intensive data base was established that includes tests of student understanding prior and post instruction, questionnaires as to students' discourse about the nature of science, classroom learning environment and laboratory activities, a minimum of five interviews with ten students, and videotapes of all classroom activities. The database also includes the teacher's talk about the same topics, discourse about teaching, and predictions of students' physics-related discourse. A number of aspects from the larger study have already been described. These included students' learning in traditional laboratories, students' learning from demonstration, the existence of multiple views, consistency of students' and the teacher's views of the learning environment, and the teacher's and students' discourse about the nature of science and the enacted curriculum (Lucas *et al.* 1996, McRobbie *et al.* 1997, Roth *et al.* 1997a, b, 1999). The present article is concerned with students' talk about rotational motion within and across contexts, before and after instruction.

Participants

The Year 12 physics class we studied was one of two in the school and consisted of 17 boys and seven girls. Physics is taught over a two-year period in years 11 and 12, so that the students were in their second year of the subject. In this school, most students who enrol in physics are university-bound; they usually select the subject because it is either an entrance requirement or highly recommended for many science and technology-related programs at the local colleges and universities. Physics was taught by Mr. Sparks (all names in this study are pseudonyms) who held a masters degree in science education, has published in science teacher journals, and has presented workshops for teachers at national and state science teacher conferences. His peers recognize him as a very competent teacher with great skills in designing and building new and standard demonstrations or in developing computer interfaces for data collection and analysis in student laboratory experiments.

Curricular context

To set a context for students' responses during Study 1 and 2, this section describes the content of students' physics lessons in the previous year and during the present investigation. The descriptions of Mr. Sparks' teaching provide further hints as to the knowledge valued in the physics class.

During the previous school year, the unit on circular motion included the notions of angular velocity and its relationship to the period of rotation, centripetal force, centripetal acceleration and the relationship between velocity and angular velocity for an object in a circular orbit. The topics of the unit under study were angular velocity, angular momentum and angular acceleration and their vectorial nature; moment of inertia, specifically those of hollow cylinders, solid cylinders, solid spheres and bar-like objects; the parallel axis theorem; period of a pendulum with a bob that is not a point mass; and the law of conservation of angular momentum.

Physics was taught in three 70-minute lessons per week. Mr. Sparks mainly used four techniques to teach the unit on the dynamics of rotational motion: lectures, focused mostly on mathematical aspects of the topic; demonstrations, focused on illustrating concepts and generating student interest; laboratory activities, designed to give students practical experience with rotational motion phenomena; and textbook problems, done predominantly as homework assignments.

In the interviews it became quite clear that many students were formula dependent. When asked for an explanation, they tried to recall equations appropriate in the context of the question. The following excerpts from the interviews are quite typical of students' dependence on the formulas. Asked why a circling ball on a string would accelerate once the string wrapped around the stick, Christina answered:

> Because of the formula $I = MR^2$. The 'I' obviously depends on the radius. If your mass is constant - which it is because you have got the same ball - and your radius is changing, then obviously the moment of inertia is going to change. When you can sub them in, I mean it helps with the explanation I think because Mr. Sparks often says that if - he actually draws it physically - if one gets larger then the other will get smaller. Then you would have to sub it into another formula which you can use the moment of inertia as well as the angular of velocity and then see that relationship. (Christina, 0815V1)

Christina's grades in physics were close to the class average. Here, her entire explanation was in terms of formulas, subbing in and relationships expressed in formulas. Probed to explain in words why the angular velocity should increase, Christina continued the same type of discourse in terms of the formulas she had memorized:

> Back to the formula if I can use the formula, is it $L = IW$? With the momentum if that's staying the same. I mean well that will stay the same L equals I W and the I if that is changing if that's getting smaller then the W will get bigger or if it gets bigger that will get small so obviously as the ball gets closer the [stick]. (Christina, 0815V1)

Even the highest achieving students, such as Dean, responded to questions about rotational motion in terms of formulas but had trouble talking about the phenomena in their own words:

> If you use the formulae just working out what fits where in the formula and rearranging it to get the last variable. Essentially a lot of that does not require a thorough understanding of what you're doing, so I guess that's the maths of it. (Dean, 1011V1)

Such answers may not come as a surprise to experienced physics teachers, and for many such teachers may not be problematic. In many ways, the students followed the example of their teacher. On numerous occasions, where verbal descriptions in everyday language would have helped, Mr. Sparks used formula dependent language ('I'd have to do an I omega squared for the wheel').

Data collection and interpretation

Written tests

Prior to instruction, all students responded to an open-ended test with four items in each of two contexts: a ball whirling in a circular orbit (students were shown this phenomenon prior to answering the following item) and a space craft orbiting the earth (see Appendix 1). The posttest consisted of two items, a spinning bicycle wheel held by the demonstrator on a rotating table at various angles and a steel ball on a string that wrapped around a coffee can (Appendix 2). Students were shown an experimental set up and asked to predict what they would observe. After the demonstration was completed, students were asked to note what they had observed (observational description), and then to explain (theoretical description) their observation.[1] In the ball-on-the-shortening-string demonstration, students were subsequently led through a series of questions that asked students to identify and explain a number of quantities such as velocity, force, or angular momentum. Details of both tests are provided with each study.

Interviews

To probe student understanding in greater depth and to gain a better understanding of their written answers, ten students whose learning (and views on a variety of issues) was followed closely throughout the unit. The selected students represented the entire spectrum of achievement levels. During the interviews, students were asked to elaborate their answers on written instruments, and the occasion was used to probe their understandings further. Stimulated recall sessions were also conducted in which student laboratory activities and teacher demonstrations were replayed to probe student discourse about circular motion-related phenomena. For the descriptions of students' observational and theoretical descriptions, we also drew on information that was collected during the interviews designed to elicit students' talk about the nature of science, classroom environment, and teaching and learning. During these interviews, students were also asked to refer to specific events (demonstrations, laboratory activities, chalkboard inscription) during the unit to elaborate their viewpoints; at the same time, these elaborations provided us with further information as to students' interpretations of phenomena and the related physics concepts. All interviews were recorded on videotape or audiotape and transcribed within a few days of being recorded.

Further data

In addition to the data collected specifically to elicit student understanding of the physics of circular motion, we drew on the videotapes collected during the entire unit and on observational field notes to make sense of students' responses on the written tests and during the interviews. The entire four-week unit was recorded with three video cameras and a cassette recorder. The cameras focused on three student groups including nine of the ten students. Mr. Sparks wore a radio microphone, the signal from which was inputted into the cassette recorder. The authors kept ethnographic field notes which were also entered into the database. All videotapes and audiotapes were transcribed within a few days of being recorded.

Data analysis

Throughout the entire six-week study (including the classroom observations during the week before and after the unit), the researchers met for daily discussion and interpretation sessions. During these sessions, preliminary analyses of students' written and verbal data were conducted. As a result of these meetings, specific video clips were taken back to the field site to get both students' and Mr. Sparks' interpretations of interesting events. The intensive collaboration throughout the study allowed the negotiation of alternate meanings as to the interpretations of student utterances, writings and practical actions.

The content-related analyses began with the characterization of student responses to questions about rotational motion with the results of prior studies (for example, Gardner 1984, Gunstone 1984, Berg and Brouwer 1991). Based on these existing typologies of student responses, and in interaction with the data, the analysis of forces in circular motion was extended to comprise all possible combinations of three types of forces (see table 1).

Study 1: method

All students provided written explanations for phenomena in two contexts; ten students were interviewed to probe their observational and theoretical descriptions in more detail (the written test is presented in Appendix 1). One item from each of the two contexts (whirling ball on a string [item 4], astronaut letting go of orbiting space ship [item 8]) were identical to questions used in other studies (McCloskey *et al*. 1980, Lambert 1981, Berg and Brouwer 1991), the others structurally equivalent to items developed by Gunstone (1984). Three pairs of items (1 and 6, 2 and 5, 3 and 7) were structurally equivalent from a canonical physics perspective, the other pair was similar (4 and 8).

The present analyses began with the assumption that reasoning is observable in the form of socially-structured and embodied activity (Garfinkel 1991, Suchman and Trigg 1993). Videotapes and transcripts were considered to be natural protocols of students' efforts in making sense of events, structuring of their physical and social environment, or communicating with the teacher. These protocols provided us with opportunities for construing the conversational and cognitive work done.

Study 1: results

Forces acting during circular motion (items 2 and 5)

Student answers. Two pretest items asked students to indicate the forces on objects in circular motion, that is for a ball on a string and a spaceship in orbit (Appendix 1, Items 2 and 5). A classification of student answers, answer frequencies, and typical answers can be found in table 1. (Some students added the gravitational force acting on the ball in a second plane; these vectors have been omitted.) Table 1 shows that, in spite of prior instruction, few students (3 and 2, respectively for ball and spaceship) offered Newtonian answers in terms of tension in the string and gravity respectively, a finding consistent with previous research involving students who already had physics instruction (Gardner 1984, Searle 1985). Among the students' answers, two other types of 'forces' appeared in ways which are predictable from the literature: a velocity and a centrifugal force.

Changes across story context. Students' answers were differently distributed across the two story contexts (ball-on-string, spacecraft), as summarized in table 1. For the spacecraft, there is a much higher preference for the solution which involves the centripetal force (g, T) and a forward, 'velocity' force (54%) than in the ball-on-string setting (29%). Half of this shift came at the expense of the answer that combined a forward with an outward force. It appears that while such an explanation was considered reasonable in the ball-on-string context, it was unreasonable for the spaceship: students realized that a spaceship had to be attracted to stay in orbit.

An analysis of all answers in terms of the presence of the three individual forces reveals contextual differences: a smaller portion of the class (54%) included a forward force in the ball-on-string than in the spacecraft story (67%); outward forces were invoked more frequently in the ball-on-string (54%) than in the spacecraft context (33%); and central forces were less frequent in the ball-on-string (79%) than in the spacecraft situation (96%).

Consistency of individual responses across story context. Although there are variations across contexts represented in the summary of responses across students (table 1), it hides the within-student variations across the two story contexts. There were only 12 students (50%) whose answers were consistent across the two problems and who used the same forces as explanatory resources in both contexts. A transition matrix[2] for the movement between the two problems shows these major trends: (a) all students (seven) who used a tension-forward force (T, v) explanation in the ball-on-string problem used the equivalent combination (g, v) in the spaceship context; (b) the (g, v)-based explanation of forces on the spaceship drew 6 new students, 'converts'; (c) the greatest losses (3 Ss) existed from the (T, c) and the (c, v) explanations in the ball-on-string explanation; (d) only one student provided the canonical response in both contexts.

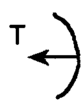
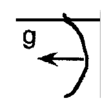
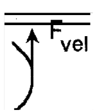
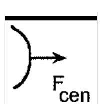
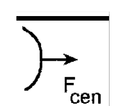
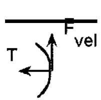
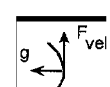
Acceleration of bodies in circular motion (items 3 and 7)

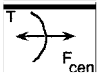
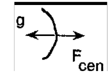
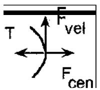
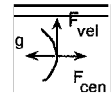
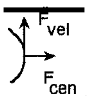
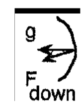
Student responses. Two pretest items asked students to discuss the acceleration experienced by objects in circular motion, that is by a ball on a string and a spacecraft in orbit (Appendix 1, items 3 and 7). In both contexts, there were 15 (63%) responses with acceleration vectors to the centre of the orbit, the highest proportion of canonical responses recorded in this study. Six students (25%) indicated zero acceleration in the ball-on-string; five such responses (21%) were provided in the spacecraft context. However, even students with very high achievement talked about acceleration keeping the ball on the circular orbit ('a is the force pulling the ball in') rather than the acceleration being the consequence of a force (tension of the string) as Newtonian discourse would have it.

Student written and verbal answers were very stereotypical (varied little between students) and appeared to have been given as an automatic response to a known stimulus. In questions about velocity and acceleration in circular motion, answers such as, 'velocity always goes to the tangent, in the direction, and the acceleration always inward, towards the centre' (Sean 0718V5) and 'The velocity is always tangential to the direction of the string and the centrifugal acceleration is always towards the centre of the circle' (Andy 0721V2), were received. When probed, the same very high achieving students frequently began to hesitate, no longer sure about their answer, 'I thought it would move towards the centre, that's what I remember from last year, circular motion theories. I think mainly the acceleration is in the middle, towards the middle' (Sean 0718V5).

Consistency of answers across contexts. The transition matrix for the accelerations from the ball-on-string to space problem shows these trends: (a) 19 students (79%) provided consistent responses in both story contexts; (b) 14 responses (58%) were consistently canonical, and four responses (17%) indicated zero acceleration; and (c) the greatest gain was recorded for a forward acceleration (2 Ss).

Table 1. Students' explanations for the forces acting on a revolving object ($n = 24$)

String Problem (*item 2*)			*Spacecraft* (*item 5*)		
Answer	*Sample explanation*	*Count (%)*	*Answer*	*Sample*	*Count (%)*
	The ball is constantly changing direction When an object changes direction, it also experiences acceleration towards the centre of the circle. (Jon)	3 (13) (11)[1]		Because the acceleration is toward the centre of the circle (orbit), so too will be the force acting upon it. (Quentin)	2 (8)
					
	A centrifugal force is pushing the ball outwards. (Matthew)	(1) (4)		The only force, if any, would be the force of motion. This would make the spaceship drift away from earth. (Ron)	1 (4)
	The tension in the string pulls the ball toward the hand. The ball wants to travel out of the circle continuing out in the motion it had at a certain point. (Ellen)	7 (29)		[F_{vel}] is the direction the ship wants to fly in a straight line; g is the gravitational pull on the ship; and then there is the resultant of the other two forces. (Carl)	13 (54)

	The hand exerts a force on the ball to keep it in the circle instead of falling off at a tangent. There is an opposite reaction force. (Quentin)	6 (25)		There would be the force of gravity pulling the spaceship towards the earth and the forces pulling it out into space. (Christina)	4 (17)
	Force of gravity pushing the ball outwards. Reaction force (tension) pulling it inwards. And there is also a force pushing it to go around, in the direction it is going. (Norm)	3 (13)		Gravity will pull at the ship; and the ship will resist against the gravity. And a force acting forward due to momentum. (Bruce)	3 (13)
	The ball is being pulled outwards from the centre of the circular path by its mass and the way it is being whirled. The force pulled the ball forwards by way of it being whirled. (Arlene)	3 (13)			
other	no forces	1 (4)		There will be a pull towards the earth, and there will also be a pull downwards. (Arlene)	1 (4)

[1] Reported by Searle (1985)

Velocity of bodies in circular motion (items 1 and 6)

Student responses. In response to the question what happened to the velocity as the ball-on-string orbits, 11 students (46%) provided explanations consistent with the Newtonian framework: the velocity changed because one of the quantities determining this vector, the angle, changed, while its magnitude, speed, remained constant (table 2). Ten students (42%) contended that there were no changes in the velocity. In the spaceship context, the response rates changed somewhat: seven students (29%) provided canonical explanations, and 11 students (46%) claimed that velocity did not change as the spaceship orbited.

Consistency of answers across context. Whereas table 2—which collapses the information of all students - appears to indicate a small loss of the canonical answer to the speed change category from the ball-on-string to spaceship contexts, the transition matrix provides evidence of considerable movement of students across response categories. Accordingly, 11 students (46%) responded consistently across the two contexts, five of which in the canonical answer category. The major shifts from the canonical answer in the first context occurred to the 'no change in velocity' (3 Ss) and 'decrease in velocity' (2 Ss) categories of the spaceship problem.

Trajectory of bodies after being released (items 4 and 8)
Item 4 asked students to predict the path of the ball if the string was cut. Item 8 asked students to predict the trajectory of the astronaut if he let go of the spaceship. The items are not equivalent in the same way as the previous item pairs, for the central force in the former situation ceases to act on the ball, but the gravitational force continues to act on the astronaut. Answer categories and frequencies, typical student responses and data from previous studies are presented in table 3.

Student responses. In the context of the ball-on-string problem, 14 students (58%) provided a canonical answer and corresponding explanation. This frequency is of approximately the same order as those of university students in prior research (Berg and Brouwer 1991, McCloskey *et al.* 1980) but considerably higher than those of Canadian Grade 10 students (Berg and Brouwer 1991). Six students (25%) suggested a path of the ball which was outward and forward, because of the ball's 'natural tendency to continue in a circular path.' Three students (13%) suggested that the ball would fly outwards and away from the correct trajectory; they explained this path as a combination of the forward and centrifugal forces.

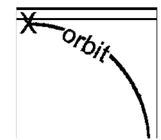
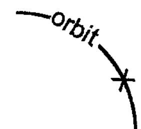
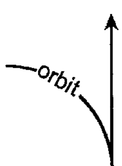
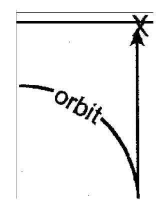
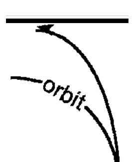
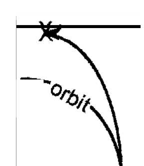
Four students (17%) provided a canonical response and explanations for the problem with the astronaut (table 3). One of these students was uncertain if the smaller mass of the astronaut should have an effect on the actual distance from the centre of the earth, 'The astronaut would basically follow the same path as the spaceship. The gravity of the earth keeps him in a circular motion. Because of the mass difference, the astronaut may be more or less distant from the earth' (Dean). Of the non-canonical responses, the most common was that the astronaut would move away from the orbit on a tangential trajectory (7 Ss).

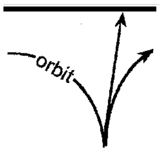
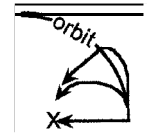
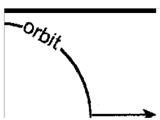
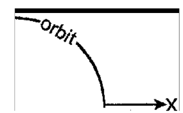
Relationship across context. Table 3 indicates a considerable shift in the frequency of canonically correct responses. A transition matrix reveals that only four of the students with correct answers and explanations for the ball's trajectory also pro-

Table 2. Velocity of an object on a circular orbit (N=24)

String Problem (item 1)			*Spacecraft (item 6)*		
Answer	*Sample explanation*	*Count (%)*	*Answer*	*Sample explanation*	*Count (%)*
No change in velocity. ($dv = 0$)	Velocity is constant because there is no other horizontal acceleration acting on the ball. (Norm)	10 (42)	No change in velocity. ($dv = 0$)	No changes. Gravity is constant at a certain distance from the centre of the earth. If the velocity of the craft changed, the craft will no longer oribt correctly. (Andy)	11 (46)
No change in velocity; changing angle. ($dv = 0$; $d\theta \neq 0$)	The velocity would remain constant, because although a vector quantity with both direction and magnitude, only the direction component would change. (Jon)	3 (13)			
Changing velocity; changing angle. ($dv \neq 0; d\theta \neq 0$)	The velocity changed as ball moves around, because the direction is changing. The speed is constant (Allison)	11 (46)	Changing angle; $\therefore$ changing velocity	The velocity vector would not change in magnitude, but would change in direction every instant. (Quentin)	7 (29)
			Change in speed ($d\lvert v\rvert \neq 0$)	It would get faster as the pole gets closer, as the pole attracts it. (Dorian)	3 (13)
			Other or none.		3 (13)

Table 3. Trajectory of an object after being released (*n*=24)

String Problem (item 4)			*Spaceship (item 8)*		
Answer	*Sample explanation*	*Frequency*[1]	*Answer*	*Sample explanation*	*Frequency*[1]
				The astronaut has his own velocity (he won't slow down because no air resistance), and he also experiences acceleration due to gravity. So he will orbit at a set distance from the earth. (Andy)	**4** **(17)**
				The astronaut's velocity compared with the spaceship would be smaller. But since his mass was smaller, he would have a smaller gravitational pull, therefore he probably would stay in orbit. (Jim)	**2** **(8)**
	The path of flight is in the direction of the instantaneous velocity of the ball at the time it is cut. Normally, the ball undergoes acceleration which keeps it in a circular path. When the string is cut, there is no acceleration holding it in orbit, and so it flies off in the direction of its orbit. (Andy)	**14** **(58)** (50) *(53)*		The astronaut would have the same velocity magnitude as the craft,and would keep moving at a tangent to the circle of orbit. He will travel the same distance as the spacecraft. (Quentin)	**7** **(29)**
	As the ball is released, while still having the tendency to continue in a circular motion and also wanting to travel straight out in the direction, it is headed at that particular point, and it will take the resultant pathway. (Ellen)	**6** **(25)** (28) *(30)*		The astronaut, when letting go of the ship, would want to go out; but it would also be attracted to the earth because of gravity. (Jon)	**3** **(13)**

 2 alternate solutions	When the ball is released, it has motion in direction of the circle, and also has a force pushing the ball outward. ∴ The ball's direction is [as indicated]. (Norm)	**3** **(13)** (6) *(6)*	 3 alternate solutions	While he briefly continues to move parallel to the tangent, as he cannot maintain speed, the gravitational force will eventually grab him and send him towards the centre of the earth. (Sean)	**6** **(25)**
	The ball will fly directly away from the centre of the circle because of the force acting outwards. (Jim)	1 (6) *(6)*		The astronaut is in the path of the spaceship, but then dirfts straight out due to no gravitational forces acting upon it. (Christina)	**1** **(4)**
			Drift in space	The astronaut has no acceleration and no force to move him. So once he lets go, he will only drift. (Dorian)	**1** **(4)**

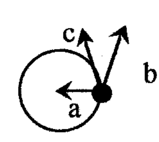
[1]: Number of students, this study.
(bold): Frequency (%), this study.
Underlined: University students (Berg and Brewer, 1991)
Underlined italicised: University students (McCloskey *et al.* 1981)

vided canonical answers for the astronaut. Five students (21%) inappropriately extended the direction of velocity argument to the astronaut that had been successful for the ball; four others suggested that the astronaut would drop to the earth's surface. Of the six students who had suggested forward inward-bent solutions for the ball, four again suggested bent solutions—two forward, but away from the earth, the other two dropping to the ground.

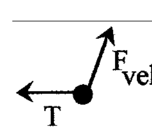
Inconsistencies of responses within contexts. The comparison of students' responses as to the forces acting on an orbiting object and the acceleration it experiences reveals large discrepancies. Although 14 students had correctly indicated the acceleration of the ball, none provided a description and explanation of the forces acting that would have been consistent according to Newton's second law—only one student's responses to the two items were consistent, but incorrect ($F = 0$, $a = 0$). However, the inconsistencies with respect to the relationship between velocity and acceleration were much smaller. Six students predicted constant velocity, while at the same time maintaining that there was a centripetal acceleration. The discrepancies in the context of the spaceship were of the same order. In twenty cases (83%), students indicated accelerations that did not correspond to their answers to the acting forces. Nine students (including all six from the corresponding problem in the ball problem) provided answers in which the velocity was constant although they had indicated the existence of an acceleration.

A typical example of inconsistencies within a context is presented in the answers by Rhonda, a student who achieved average physics grades (figure 1). The three answers pertain to the same ball on a circular orbit. In her first answer, Rhonda indicated that the velocity remains constant. On the other hand, her second drawing suggests that there are two forces, the tension of the string tugging the ball inwards and a velocity force pulling the ball forwards. Finally, she indicated that there is an acceleration tugging the ball inwards. Here, there is an inconsistency between answers (a) and (c), a constant velocity in spite of an acceleration. Second, the acceleration experienced by the ball is inconsistent with the forces indicated in answer (b). It is typical for students' answers that the 'velocity

a. The velocity remains constant. The resultant force c of the components a, b of the ball indicates the velocity of travel of the ball. As these two components remain the same, the resultant is the same.



b. The force of the string 'pulling' against the ball. The force is pulling away from the ball.



c. The acceleration experienced by the ball is towards the centre.

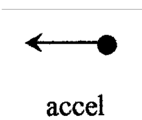


Figure 1. A typical example of student's responses that show inconsistencies within a context.

force' was rarely related to the ball's acceleration. On the other hand, Rhonda incorrectly described the ball's direction of travel as being the 'resultant' of the two forces acting on it.

Discussion

The results presented here show considerable variations in: students' observational and theoretical descriptions within contexts; in students' science observational and theoretical descriptions across contexts; and (in part) in answer frequencies compared to previous studies. Such variation is not particularly surprising given that rotational motion is a topic of considerable conceptual complexity and the teacher had adopted a traditional formula based teaching strategy. Furthermore, the structural equivalence of the pairs of items was camouflaged from the students by the surface or contextual elements upon which they drew in order to frame their responses.

Following recent conceptualizations in social psychology and sociology, it is assumed that respondents do not have fixed frameworks, but generate situated answers (Edwards and Potter 1992, Latour 1992, Edwards 1993, Gilbert and Mulkay 1984, Pollner 1987). These answers, when viewed by more traditional analysts, appear to be inconsistent and often contradictory—but this may be artefacts of the researchers' interpretations. In the proposed approach, respondents' answers arise from an interaction of the speaker's interpretations of the physical, social and conversational setting, and his/her own resources for making sense including subjective experience, discourse (fragments), and visual images. With changing contexts, the plausibility of making certain observational or theoretical descriptions changes, and with it, the answers the researcher receives.

From this perspective, students' 'alternative frameworks' or 'misconceptions' are then plausible inferences with local explanatory power—although they are not consistent within and across contexts, or with a scientific way of structuring an explanation. For example, it is not farfetched to assume that students have seen TV images of astronauts working under 'weightlessness' in their spaceships, though only a few hundred kilometers above the surface of the earth. To make their explanations plausible, they need to argue for force that opposes gravity so that the astronauts can experience 'weightlessness.' One does not need to assume a conceptual framework for students, rather that they use a discourse element remembered from previous physics classes to produce the balanced force pairs.

What has been described here as Rhonda's within-context inconsistencies are also reasonable within the proposed framework (figure 1). Here, she bases her answer to the question about the acceleration experienced by the ball-on-the-string, on prior experience in the physics class where she had understood that 'acceleration is always toward the centre.' For the other question, she drew on the everyday experience that to maintain speed (velocity), one needs a force. In this new context, she was little concerned with the theoretician' s desire for consistency across contexts, but more with practical reasoning concerns for a plausible explanation of the immediately present context (Pollner 1987, Bourdieu 1990).

This new framework provides a good model for students' answers to a variety of 'scientific' phenomena. Its fruitfulness will become evident in the context of Study 2 which concerns students' observational and theoretical descriptions of phenomena for which physicists invoke the law of conservation of angular momentum. The notion of *the mangle* - a notion similar to Rorty's (1989) 'muddle'—will be introduced to account for some peculiar features of students' talk.

Study 2: method

A number of students' resources for providing observational and theoretical descriptions about rotational motion were identified in Study 1. These descriptions set the context for students' learning during the four weeks that the unit on rotational motion was taught. Study 2 is concerned with students' descriptions of phenomena that, within canonical science, are modelled with the notion of conservation of angular momentum.

Students' observational and theoretical descriptions were assessed using two events: A ball that was whirled such that its string wrapped around a coffee can and a demonstration in which a rapidly spinning bicycle wheel was held such that its axis was first held perpendicular then parallel to that of the experimenter on a rotating table (Appendix 2). Both problems followed the same structure surrounding a phenomenon demonstrated by one of the investigators and re-presented in the test booklet: (a) before demonstrating, the investigator asked students to predict what they would see; (b) after the demonstration, students noted what they had observed; and (c) students were asked to explain their observations.

Twenty-three students took part in the written part of Study 2. The same ten students interviewed in Study 1 were also interviewed in Study 2.

The ball-on-shortening-string problem (the string was shortened as the ball orbited, but no longer in a circular fashion) allowed us to link students' discourses illustrated on the pretest concerned with quantities of linear motion to that representing rotational motion. Students were asked to predict, observe and explain the motion of the ball. Subsequently, a series of written questions asked students to identify linear and angular equivalents of velocity, momentum and acceleration and the force(s) acting on the ball. This problem has both surface and structural similarities with one of Mr. Sparks' demonstrations (he sat on a revolving chair and moved his hands, each holding a brick, to and away from his body causing him to change the rate of rotation) and the description of several other situations in which the rate of rotation changed (e.g. diver tugging in, ice skater pulling in arms). Students also had done a quantitative investigation of acceleration of a wheel as a function of the distance from the centre of attached masses.

The bicycle wheel problem was constituted by a classic demonstration also used by the teacher during the unit: an experimenter standing/sitting on a rotating base moves a fast spinning bicycle wheel. Depending on the position of the wheel's axis relative to the axis of the base (perpendicular, parallel clockwise, parallel anti-clockwise), the experimenter on the base remains stationary, turned clockwise, or turned anti-clockwise. This item was designed to probe students' conservation of angular momentum-related discourse. Canonical answers to this question are based on the conservation of angular momentum in the vertical direction of the entire system (base/person *cum* bicycle wheel). This angular momentum is zero at the outset, and remains thus throughout the demonstration, $L_{z,\,\text{system}} = 0$. When the two relevant axes are perpendicular, the angular momentum of the wheel in the vertical direction is zero and the base *cum* person does not turn. If the two axes are not perpendicular, then the bicycle wheel has a vertical angular momentum not equal to zero, $L_{\text{z},\,\text{wheel}} \neq 0$, so that the system has to turn in a direction opposite to the wheel so that the sum of angular momentum remains zero ($L_{z,\text{ system}} = 0 = L_{z,\text{ wheel}} + L_{z,}\text{base}$).

Study 2: results

This section compares students' post-instruction discourse to that on the pretest. The results indicate variations from pretest to posttest and inconsistencies within the context of a similar nature as reported in Study 1.

Forces on the ball-on-shortening-string

Student answers. A classification of students' answers according to the categories in Study 1 revealed some shifts over the class as a whole. Seven students (30%) identified tension as the only force acting on the ball (up from 13%); seven students (30%) suggested the existence of tension and a 'velocity' force (previously 29%), one of whom used this latter force to account for the increase in speed as the length of the string shortened; and five students (22%) used a combination of three forces to explain the ball's motion (up from 13%), again one explaining the use of a forward force to account for the acceleration of the ball. One response each (4%) was received in the categories forward force only and no forces (down from 25%), and two responses (8%) included tension and centrifugal force.

Consistency with answers in Study 1. While the class data hint at some shifts in students' responses, the full extent of the changes is revealed by a transition matrix that maps students' use of forces in the two tests. Only eight students (35%) explained the motion of the ball-on-a-string with the same combination of forces. The major shifts occurred to and from the categories tension-centrifugal force (t, c) and tension-velocity force (t, v). Five students left the (t, v) for the (t) (3 Ss) and (t, c, v) categories (2 Ss). However, six new students used a (t, v) combination, four of whom previously had employed (t, c).

Acceleration of ball-on-a-shortening-string

Student responses. Two students suggested a combination of centripetal and forward acceleration to account for the motion of the ball, that is, the rotational aspect and the increasing magnitude of velocity as the ball orbits (canonical answer). More than half (12 Ss, 52%) included only a centripetal component to acceleration (thereby neglecting the increase in the ball's speed). Eight students (35%, up from 13%) suggested some form of forward acceleration without a centripetal component, with accelerations parallel to the tangent (5 Ss) and trajectory (3 Ss). Two of these students included tangential acceleration explicitly to account for the increasing speed. Only one student indicated zero acceleration.

Consistency with response in Study 1. The major shifts for individuals between the two studies occurred to (3 Ss) and out of the centripetal acceleration category (4 Ss), and into the categories of tangential (5 Ss) and trajectorial acceleration (2 Ss). Eleven students (48%) provided the same answer in both contexts. Both students with a combination of forward and centripetal accelerations also had previously canonical answers.

Consistency within context. In 15 cases, students' answers as to the ball-on-a-shortening-string event indicated forces and accelerations in ways that were not consistent according to Newton's second law (which was explicitly evoked by one student only). Seven students had indicated a centripetal acceleration, although they had suggested other forces such as a tangential force (2 Ss), centrifugal force (2 Ss), centrifugal and tangential (1 S), or other responses (2 Ss). Two students combined tangential and centripetal forces with an acceleration along the trajectory.

Velocity and momentum of the ball-on-shortening-string

Student responses. Fourteen students (61%) described the velocity as a vectorial quantity the direction of which was parallel to the tangent to the trajectory of the ball; eight students (35%) chose directions along the trajectory; and one student had drawn a velocity vector that was the resultant of a 'velocity' force and the tension. Eight students (35%, all from the group of 14) also described linear momentum as a vectorial quantity parallel to the tangent; four of these did so on the basis of the relationship between velocity, v, mass, m, and momentum, p, according to $p = mv$. Five students (22%) described momentum as following the trajectory (path); one student each responded with directions straight out and orthogonal to the orbit's plane. Seven students (30%) did not know where to put momentum.

Many students linked the velocity of the ball directly to the action of the forces. Two such answers were:

> For ball 'A', the 'pull from the string' is not as strong as B. This is because it is shorter, making the force have to cover a larger distance. This makes the ball's velocity less than B. For B, the string is shorter, making the force cover only a small distance. This makes the force on the ball stronger, thus making the velocity greater. (Rhonda, post-test)

> The ball's velocity [pointing inward of trajectory] is the vector product of the two forces, tangential and centripetal. (Brett, post-test)

Rhonda ascribed the increase in the velocity's magnitude to the increasing force due to the smaller distance from the centre. She further suggested that although the central force remained about the same, it was distributed over a shorter string, and therefore 'the force can be greater on each section [of the string].' Brett, whose physics grades were close to the class average, described velocity as a resultant of the two forces in his explanation rather than attributing an acceleration to his two forces (according to Newton's second law, $a = F/m$).

Consistency with responses in Study 1. Here, students' Study 1 responses to the trajectory of a ball when cut loose from the string were compared to their velocity's direction in Study 2. Twelve of the students who initially provided a canonical answer also did so during Study 2. Of the nine students who initially answered and explained other than the canonical trajectories, seven indicated velocities that were not tangential. These results indicate rather consistent responses across context and time of test.

Consistency within context. In three cases, the representations of acceleration and velocity were consistently connected (according to Newton's second law), two of which were representations of circular motion rather than the motion observed here. Two students included a forward component to account for the increase in speed, but did not have the centripetal acceleration to explain the circular aspect of the motion. The remaining 18 students produced descriptions that were not consistent. The most frequent inconsistencies pertained to forward accelerations due to the 'velocity' force that would not produce the concurrent tangential velocities, centripetal accelerations that do not account for the increase in speed, and accelerations along the path that do not account for tangential velocities.

Dynamics of rotational motion

This section reports on students' understanding of the new concepts that they were to learn in this four week (12 lessons) unit: angular velocity, moment of inertia and angular momentum. Mr. Sparks used lectures and demonstrations, and students conducted several qualitative and quantitative investigations in the laboratory. To introduce the topic of angular momentum, Mr. Sparks drew an analogy with linear momentum, $p = mv$, pointed out the structural equivalence with the equation of angular momentum, $L = Iw$, and suggested that this equivalence suggested a deeper theoretical linkage. Throughout the unit, he performed many demonstrations and talked about other situations in which the events could be conceptualized in terms of a conservation principle, the law of conservation of momentum. He used the right-hand screw rule to illustrate how a rotating object is represented by a vector perpendicular to the rotational plane and parallel to the axis of rotation.

Representations of angular velocity and angular momentum

Student answers. In the context of the ball-on-shortening-string problem, students were asked about the direction of angular velocity and angular momentum. Eleven students (48%) suggested angular velocity to be parallel to velocity; four students drew arrows along the path; one student provided the canonical representation, an arrow perpendicular to the plane of rotation; one student suggested that it was along the radial axis, and six students did not provide an answer.

Students' explanations of rotational motion phenomena

The mangle. In trying to explain their observations of the demonstrations, students drew on a variety of discursive resources, many of which were not compatible with canonical physics. In many ways, bits of students' talk were recognizable as aspects of Mr. Sparks' previous lectures and demonstrations. What seemed to have happened is that students, to comply with our request to provide explanations, constructed these situationally, on the basis of their observation (an interpretation) with the resources available to them, that is, the pieces of descriptions and images they remembered from other circumstances. From a physicist's perspective, students mangled scientific discourse by combining bits and pieces they picked up from their environment, and did so without maliciousness.[3] This local construction of an explanation—rather than a reading out of a conception—was made very explicit by Dean:

> I took it from what Mr. Sparks was saying that if you've got three. If something is spinning around two, it'll spin around a third. From that I figured that the bicycle wheel was only spinning around one axis. It was still on the other two planes so nothing else would happen. It was just almost a wild guess. I didn't really know what would happen. Just using what I heard Mr. Sparks say from that is what should happen. (Dean 0815V3)

Dean indicated that he did not remember something memorized or well understood ('wild guess'), but remembered something about changing number of axes. Using this and other pieces he recalled, he constructed his response on the post-test and during the subsequent interview. Dean and his peers have had no experiences in practising their science talk that would have allowed them to generate discursive competence, a point explicitly made in an earlier study (Gunstone and White 1981). The following example constitutes a more extreme case of mangling. To explain the phenomenon of the ball-on-the-shortening-string, Andy argued:

> $I = 2\pi\sqrt{\mathrm{m}}\, vk$. As the string shortened, k decreased. I remained the same throughout the experiment so v increased to keep I constant. I proportional to vk. Shorter string, smaller k, therefore v must be proportionally larger to keep I constant. (Andy post-test)

For those who had participated, Andy's talk had some surface similarities with things actually said or written on the chalkboard. But his phrases were not meaningful within a physics context. There was indeed an equation involving an 'I' and 'k,' moment of inertia, but this was not a conserved quantity, nor did k change as a function of radius, but was a function of the shape of the material (sphere, solid and hollow cylinder). Angular momentum was conserved (constant) and involved a velocity, but it was angular velocity. If Andy had not been one of the very high achieving students, who always made genuine efforts to learn, one might have easily discarded his answer. Rather than giving evidence for students' conceptions, the results of this study may therefore be interpreted more fruitfully in terms of students' attempts to construct local explanations.

Explaining the bicycle experiment. Students' explanations were clustered into three major types (besides no response and other) depending on the resources used: there were answers invoking the conservation of angular momentum, the phenomenon of precession and Newton's third law. These three types of answers were not equally distributed across the two problems with different relative positions of the two axes.

A canonical explanation is based on the conservation of angular momentum in the vertical direction. Three students (13%) provided an answer of this type for the situation in which the axes were orthogonal, five (22%) when the axes were parallel. Sean's response was typical:

> This is an example of conservation of rotational motion. When he holds the wheel vertical, there is no momentum about the vertical axis. When he moves the wheel to the horizontal position, momentum occurs about that axis. In order to conserve momentum, the subject naturally rotates the opposite direction. (Sean post-test)

A second type of answers drew on students' experience with another demonstration: Mr. Sparks had illustrated the phenomenon of precession, by suspending a quickly spinning bicycle wheel from one side of its axle. Instead of falling, it precessed around the string that suspended it. Mr. Sparks explained the phenomenon of precession in terms the gravitational force acting on the wheel and producing a torque; this torque interacts with the angular momentum of the wheel such that it produces the precession.

For the subquestion with the axes of bicycle wheel and person on turning table perpendicular—the case which has surface similarities with the precession demonstration—nine students (39%) drew on precession explicitly or implicitly by talking about the torque. Brett was one of these students who argued based on precession on the post-test and during the interview:

> He swerved in this direction because of precession. (Brett post-test)

> It's just that when something moving with angular motion or I suppose its plane it's moving in is changed, it exerts a force . . . Because of the friction of your shoes on whatever you're standing at the time, it won't let you rotate because it's such a small force. Because you're on a little table thing it'll later move. (Brett 0815V3)

Here, Brett drew on precession for explaining how motion arises with the axes orthogonal, and included friction to account for the small magnitude of the motion he had observed. Other students, drawing on the same experience with precession, referred to Mr. Sparks' talk about torques. Andy, for example, suggested that 'The two torsional forces acting on him caused a resulting force which turned him to the left'. On the other subquestion with the axes parallel, only three students (13%) drew on the same concepts to explain their observations. Given that in this demonstration, the two axes were parallel so that the surface similarity no longer existed, it makes sense that fewer students used the precession phenomenon and the associated discourse as a resource in their own explanations.

The third answer category contained those responses in which students made reference to Newton's third law. Five students (21%) drew on this law when the axes where orthogonal and nine students (39%) did the same when the axes were parallel. Such a shift in response is understandable when one considers that with parallel axes, the argument of *actio* = *reactio* seems more plausible than in the case of orthogonal axes. However, because all of these students had also seen a wiggle in the latter case, a third law explanation seemed to be plausible even here. Aubrey, a sound, achieving student, provided a typical explanation:

> His body moves in the opposite direction to the spinning of the wheel. Because it is a closed system, the force of the wheel caused his body to turn. i.e., Every action has an equal and opposite reaction. . . . His body turned in the opposite direction to the spinning wheel. (Aubrey, post-test)

We categorized among 'others' all those explanations in which students inappropriately drew on conservation of momentum (2 Ss) or torque (1 S). Four students did not provide an answer or indicated 'don't know' in the case of orthogonal axes, five students in the other situation.

It was interesting to note that nine students—three in each category—drew on the same concepts in both situations (and one student provided no answer in both cases). The largest shift (5 Ss, 21%) occurred from the precession to Newton's third law, consistent with the surface similarities mentioned above. At the same time, three and four students, respectively, shifted out of and into the 'no answer' category. Students constructed a for them reasonable explanation for one context, but were aware that it was not applicable to the other.

Even very high achieving students, such as Quentin, whose answers were counted among the canonically correct ones, demonstrated mangled aspects in their science talk:

> Because the wheel is now spinning in the axis that the table turns on, the person can counteract the spinning of the wheel clockwise by rotating anti-clockwise on the table (conserve momentum). (Quentin post-test)

Here, the reference to conservation of momentum is consistent with other answers on his test that confirmed his understanding in canonical terms. However, his explanation also contains vestiges of Newton's third law. His 'the person can counteract the spinning of the wheel' is framed in terms of an agency that is usually attributed to forces. Newton's third law is frequently explicitly stated in terms of agency and counteragency, *actio = reactio*. On the other hand, the conservation of momentum normally is not stated in terms of agency, but in a passive voice as 'something that is conserved.'

Explaining the ball-on-shortening string. Structurally, this phenomenon has similarities with two phenomena presented to the class by the teacher: an ice skater pulling her arms closer to her body and Mr. Sparks on the rotating stool holding bricks in his hands that he pulled in closer. Mr. Sparks had also spent almost an entire period in demonstrating to students a computer program tracking satellites in a variety of orbits, had students calculate a variety of problems, and explained the relationship between the distance from Earth and the speed of a satellite in accordance with the conservation of momentum.

Brett indicated that he had had prior experience that helped him predict that as the ball gets closer to the hand, it will go faster ('I had something on the end of a bit of string and you've been swinging it around your finger or something and as the string gets smaller it goes faster' [0815V3]). He provided the following, canonical explanation:

> The [moment of inertia] *I* changes and as it gets smaller the inertia gets smaller because its radius is getting smaller because its mass is still the same. The other part of *I* is *R* because it's radius. The other portion of the equation for inertia is MR^2 or KMR^2 with a consonant out the front of it. I'm assuming it's a point mass because it's a ball and it will get smaller because the radius gets smaller, therefore because I is smaller and your angular momentum is remaining constant, then your angular velocity has to increase. (Brett 0815)

Other students, because of their prior experience, also predicted the motion of the ball: 'It's like tandem tennis, or something. Like when you have got a stick with a tennis ball tied to it' (Brenda). However, this was not sufficient to help them construct a canonical understanding involving the conservation of angular momentum, or even the relationship of moment of inertia and radius.

The answers of eight students had elements that could be interpreted as complete or rudimentary understanding of angular momentum as it applied to the phenomenon of the ball on the shortening string. Three students explained the phenomenon by using the conservation of angular momentum explicitly as a resource; three students did so implicitly by talking about the increase of angular velocity with decreasing moment of inertia; and two students talked about the conservation of some quantity (even using equations) but these were torque and moment of inertia. The answers of nine students (39%) could be modelled as being part of the following argument: The speed of the ball stays approximately constant, but as the radius decreases, the length of the circumference decreases and, therefore, the time for one revolution. Each of the following three post-test statements can be understood as part of this argument:

> As the string got shorter, the momentum of the sinker stayed the same and the angular velocity increased because as the string got shorter, the angle turned through got faster. (Aubrey)
>
> Each time the ball wrapped around the can, the string became shorter each time therefore decreasing its path and making the ball move around faster until it came to a stop. (Brenda)
>
> The ball spun quicker. As R got smaller, the time for one rotation got smaller. (Ron)

One student made the opposite argument that the angular velocity remained constant, and, because of the decrease in R, the velocity had to increase. Two students talked about constant forces which, with decreased radius, had a greater effect on the ball. In these explanations, the effective force, F/R, was increased, so that it led to a larger acceleration.

Discussion

The first part of Study 2 suggests that students' responses with respect to velocity, acceleration, and force acting on the ball on a string were moderately constant over the four weeks since Study 1, despite the additional teaching students received in this period. The second part of Study 2 revealed that few students could use angular momentum and angular velocity as vector quantities in their descriptions of the motion of the ball-on-the-string. Further, although the post-test demonstrations were quite similar to demonstrations shown by Mr. Sparks in the context of developing his lectures on the conservation of angular momentum, few students used either demonstrations or lectures as resources in their observational and theoretical descriptions. The descriptions included many components from physics talk that they had heard and used much earlier. Much of this talk was combined into sentences that, from a physicist' s perspective, are meaningless. The term 'the mangle' (without any negative connotations) was coined to describe the patchwork nature of students' descriptions. It is thought that this mangle can be modelled within this study's framework.

As explained above, students bring to new experiences their previously constructed discourses, interpretive horizons, images and subjective experiences. Using these elements as resources, students constructed their explanations. Because of the little practice and experience in testing these new observational and theoretical descriptions, students had little opportunity for testing them for viability, consistency and fruitfulness; and they had few opportunities for developing the competence to construct such descriptions as needed. Consequently, students' descriptions appeared to be mangled. There is some historical evidence that at times, science proceeded in a similar way. Rorty (1989) suggested that the current theoretical descriptions of the solar system emerged from earlier forms of muddled and incomprehensible talk. A rather similar description was provided for the emergence of shared canonical science talk among Grade 11 physics students. The Newtonian-like science talk emerged slowly and tentatively from the 'muddle' of their earlier talk in the face of the (ontological) ambiguity of the microworld objects and events and the expressions used to denote them (Roth 1995, 1996). However, in the latter study, students had many opportunities for talking about scientific objects and representations with their peers and the teacher. In the present classroom, there were few such opportunities. So while almost all students in the earlier study appropriated canonical talk, only few students in this study did likewise.

Conclusion

The two studies reported in this article are significant for several reasons that have not been addressed in previous research. First, the analysis of students' answers to several problems and the comparison with several existing studies revealed that the frequencies of certain response types varies across samples. Second, students' observational and theoretical descriptions vary between contexts when, from a canonical science perspective, the problems are structurally equivalent. Third, students' talk does not exhibit the same degree of consistency within a problem context but across its different dimensions (e.g. velocity, acceleration, force). Fourth, students' theoretical descriptions of new phenomena appeared to be constructed as a patchwork of the explanatory resources identified in other parts of the study.

Once research has identified problems in teaching and learning, the next step in providing better instruction lies with the identification of strategies that provide feasible and fruitful solutions. Any proposed solution will necessarily be influenced by the researchers' own theoretical framework. In the present case, a discrepancy was that students described events and objects in observational and theoretical terms that were not compatible with the scientific canon, and were internally inconsistent. As the framework rests firmly in scientific practices, particularly in the linguistic practices of scientists, we see a solution to this problem in the greater provision of opportunities for students to talk about phenomena both in observational and theoretical terms. By engaging each other in conversations, students have opportunities to experience the multiple ways of seeing and talking about what they consider to be shared perceptual and cognitive objects. At the same time, as soon as students begin to discourse publicly, there are opportunities for the teacher to listen to and participate in students' conversations. That is, the teacher has opportunities to conduct a diagnosis of students' current observational and theoretical language. Such conversations permit students to test and practise their observational and theoretical descriptions of phenomena and receive feedback as to their viability, plausibility and fruitfulness; these conversations would also allow the teacher to diagnose existing patterns in students' descriptions, and, as a reflective teacher-practitioner (Schön 1987), provide situated help for students to learn. In their interactions with students, teachers' conversational contributions may sometimes be used by students to construct new types of explanations which are incompatible with those of their teachers (Roth and Roychoudhury 1992). Only through continuous interactions among students and between students and teachers will the multiplicity of descriptions emerge and become subject to diagnosis.

We do not think that establishing classrooms as discourse communities will make all students conversant with Newtonian physics. This is not the intent and would be contrary to the democratic ideals in many countries that reject any form of indoctrination and allow a multiplicity of discourses. However, classroom discourse communities would provide forums (a) where students were faced with different ways of seeing and talking about a variety of phenomena and (b) where they could test and negotiate new ways of talking, and experience the fruitfulness of some but not other ways of describing and explaining phenomena. As with the learning of any discourse, this takes time and many opportunities for participating in them. Future studies will have to show the extent to which the metaphor of science as discourse will be fruitful in planning and enacting science curricula that produce more conceptual talk about conceptually challenging topics such as the mechanics and dynamics of rotational phenomena.

Notes

1. Because all observation is theory-laden and done in terms of the currently accepted idiom of a community, we follow the approach taken by some philosophers (e.g. Rorty 1989) and science educators (e.g. Langensiepen 1995) and use one category, description, to bring together 'observation' and 'explanation'. These are then distinguished as 'observational' and 'theoretical' descriptions, respectively.
2. A transition matrix maps students' answers in two contexts. Each matrix element is given by a student's answer in the first (vertical dimension) and second context (horizontal dimension). When a student does not change, his/her answer would be recorded in the main diagonal (consistency). All shifts are recorded in off-diagonal matrix elements. Such a matrix, while too space consuming for an article, permits researchers to track the inconsistencies of student answers.
3. Mangle: to disfigure or mutilate by battering, hacking, cutting, or tearing. Webster's II New Riverside.

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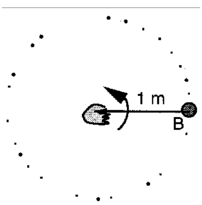
Appendix 1

Pre-test 'Motion in a Circle'

(Note that the appropriate Figure and space for student answers were provided for each question, but deleted here due to space constraints.)

Please answer the following questions to the best of your knowledge. We are intererested in your ideas AND reasoning behind those ideas.

Questions 1-4 relate to the Figure shown on the right. A student whirls ball B on a one-metre long string above her head, her hand being just above her head. The figure gives you a top view. The dotted circle represents the path of the ball and the arrow the direction of the whirling motion. The ball is moving at a constant speed.



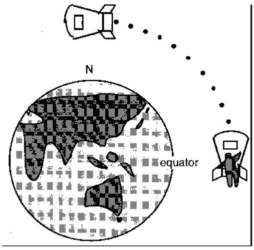
Q1. Does velocity remain constant, or how does it change as the ball whilrs around? Explain your answer.

Q2. Use arrows to draw on the figure, all the forces acting on the ball. Explain, in writing, the nature of each force.

Q3. Does the ball experience any acceleration as it whirls around? If so, draw an arrow in the figure to indicate the direction of the acceleration, label this arrow 'a'. Please explain why you think the ball experiences an acceleration in this direction. If the ball does not experience an acceleration, please explain your reasoning.

Q4. The string is cut by another student when the ball is at the position shown in the figure. On the figure, draw the flight path of the ball after the string has been cut. Explain the shape of the flight path you drew.

Questions 5-8 relate to the figure shown on the right. A spaceship moves at a constant speed on a circular polar orbit around the earth. An astronaut is making repairs to the spaceship and is attached to it. The drawing to the rights shows the spaceship above the equator and above the North pole. The dotted trace indicates the spaceship's circular flight path as it moved from above the equator to above the North pole.



Q5. Indicate the forces acting on the spaceship in each position by drawing arrows on the figure to show the direction of the forces. Explain the nature of these forces and their direction.

Q6. What changes, if any, would there be in the velocity of the spaceship as it travels from the equator to the pole position? Explain your reasoning.

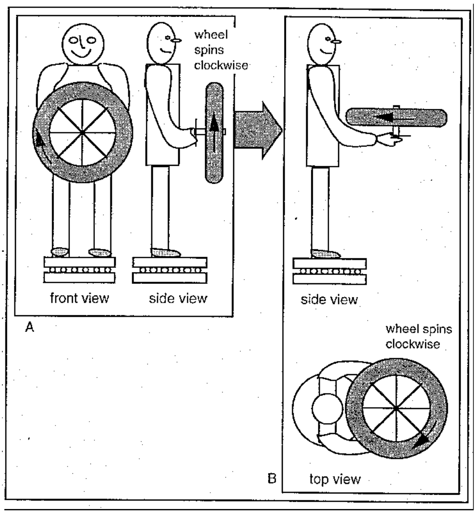
Q7. Does the spaceship experience any acceleration as it moves from the equator to the pole position? If so, draw an arrow in the figure to indicate the direction of the acceleration, label this arrow 'a'. Please explain why you think the spaceship experiences an acceleration in this direction. If the spaceship does not experience an acceleration, please explain your reasoning.

Q8. While above the equator, the astronaut lets go of the spaceship. Draw the flight path taken by the astronaut on the figure. Place an 'x' at the end point of the flight path where the astronaut would be when the spaceship is above the North pole. Explain why you drew the astronaut's flight path in the way you did.

Appendix 2

Sample items from the post-test 'Understanding Rotational Motion'

(Note that space for student answers was provided for each question, but deleted here due to space constraints.)



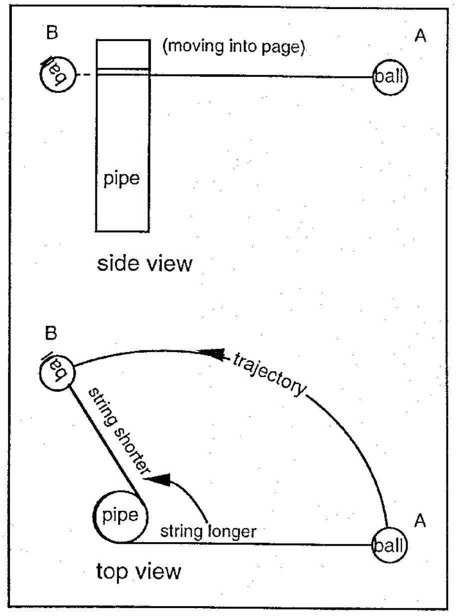
Q1.2 In the following example, the wheel will be started turning in a clockwise direction (from your perspective), holding the wheel as shown in Frame A in the drawing.

Q1.2a The person on the low friction table changes the position of the bicycle wheel into the position shown in Frame B in the drawing on the right. *Predict* what will happen and note your prediction.

Q1.2b *Observe* the demonstration, then state what you observed.

Q1.2c *Explain* your observations.

Note that as the lead ball whirled around the free part of the string *decreased* and the speed of the ball *increased*. All questions that follow are based on this observation. The drawings provided depict the ball in two positions, A and B. The string in position B is shorter than in position A. The speed of the ball is greater in position B than in position A.



Q3.3 In the drawing on the right, use labelled arrows to indicate the velocity of the ball in the two positions, A and B. In the space provided below, explain your answer.