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ABSTRACT

This paper presents results from a number of trials of a new approach in assessing student conceptions in physics and changes in these conceptions over time. The goal was to explore the potential of Personal Construct Psychology and its central tool, Repertory Grid Technique, to aid in the diagnosis of learner difficulties and eventually the prescription of instructional interventions in science education. The Repertory Grid traces a portrait of the set of an individual's constructs with respect to a given set of elements. It can be used in a computerized form in which an individual identifies distinguishing elements of constructs. The feasibility of the technique in studying physics was evaluated with three subjects of varying expertise (a college student, a college teacher, and a doctoral student in physics). This preliminary study led to trying the technique with a high school student who assembled five grids to reveal concept understanding. A second trial with seven students also supported the usefulness of the approach in revealing deficits in students' conceptual understandings. (Contains 7 grid figures and 26 references.) (SLD)

The Potential of Repertory Grid Technique in the assessment of conceptual change in physics

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This paper presents the results from a number of trials of a new approach to assessing student conceptions in physics and changes in these conceptions over time. The goal was to explore the potential of Personal Construct Psychology (PCP) to aid in the diagnosis of learner difficulties and eventually the prescription of instructional interventions in science education, specifically physics. The question is, therefore, "Will Repertory Grid Technique function as a tool for the assessment of students' conceptions and their evolution?". The usefulness of such a tool will lie in its ability to aid in forming accurate diagnostic assessments of students' knowledge about given topics. The technique is described in detail, followed by examples of how it has been used and its potential for instructional and research purposes.

Student conceptions in physics

That students come to formal studies in physics with beliefs about how the world works that are resistant to change and influence the interpretation of instructional materials is now generally accepted. The implication of this is that instruction in physics should focus on students' beliefs, leading to a need for techniques for explicitly identifying what the students' conceptions are about given topics (Dykstra, Boyle & Monarch, 1992). By constructing explicit representations of students' alternate conceptual frameworks (e.g. alternate to Newtonian physics), instructional techniques can be developed and evaluated with respect to their ability not only to improve students' performance on tests, but more importantly and more challenging, to induce conceptual change. Clearly, the first step in this logical sequence is to accurately and efficiently identify the current conceptual schema of the student. However, this kind of assessment is rarely carried out due to the difficulty and time-consuming nature of the task (Fetherstonhaugh & Treagust, 1992). Methods such as interviews, sorting tasks, open-ended and multiple-choice test items, Likert-type scales, student drawings, and concept maps have all been tried, with varying degrees of success (Wallace & Mintzes, 1990). The difficulties encountered in assessing conceptual change are varied. Interviews and concept maps provide rich data, but are time-consuming to effect and analyze. Written tests may be assessing "school physics", i.e. knowledge acquired but not integrated. The portrait of the student concepts attained with any of these methods is also closely linked to the verbal abilities of the learners, and may be misleading as to their conceptual understanding, especially when students have linguistic difficulties.

In trying to find a practicable and powerful tool for assessing student conceptions in physics, specifically high school students who were almost all studying in a language in which they were not fluent, we investigated the potential of Repertory Grid Technique, the central tool in Personal Construct Psychology (PCP).

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What is Personal Construct Psychology?

In Personal Construct Psychology (Kelly, 1955) individuals each develop their own conceptual system or schema which can be expressed as a unique system of bipolar dimensions known as personal constructs. According to PCP, "Man looks at his world through transparent patterns or templets which he creates and then attempts to fit over the realities of which the world is composed." (Kelly, 1955, pp. 8-9). One implication of this is that individuals do not enter new areas as blank slates; rather they bring with them ways of looking at the world or "constructs" that have served them well in the past.

Personal Construct Theory

In order to study these "mental constructs", we looked to Personal Construct Theory (Kelly, 1955). This theory claims that each individual develops his or her own system of constructs which can be expressed by a unique set of bipolar dimensions called "personal constructs". Kelly perceived each individual as a "personal scientist" who creates personal constructs which are functionally comparable to the collective constructs used by the scientific community.

> Constructs are used for predictions of things to come, and the world keeps on rolling on and revealing these predictions to be either correct or misleading. This fact provides the basis for the revision of constructs and, eventually, of whole construct systems. (p.14)

The parallel between personal constructs and scientific hypotheses makes Personal Construct Theory seemingly appropriate to studying concepts in science, a pertinence which has been previously noted, but not developed (Duit, 1991). In 1979, the British Association for Science Education explicitly suggested that the applicability of psychology models such as Kelly's should be investigated for their applicability to science education. The Personal Construction of Knowledge Group underscored the importance for science educators of paying attention to the personal meanings of their students and recognizing students' existing constructs as the basis for future learning (Pope & Gilbert, 1985). It would seem, then, that Personal Construct Psychology shows theoretical promise as a tool to facilitate the accurate portrayal of students' conceptions about scientific phenomena.

Repertory Grid Technique

The main tool for studying constructs is the Repertory Grid which traces a portrait of the set of an individual's constructs with respect to a given set of elements (Fransella & Bannister, 1977; Shaw, 1980, 1994; Shaw & Gaines, 1993). Although its origins are in clinical psychology and it was originally developed to be used in clinical interviews, it can now be used in a computerized form, such as RepGrid2 (Centre for Person-Computer Studies, 1991), which facilitates both obtaining the constructs and analyzing the resulting grids. In its computerized form, the user is presented with three elements randomly chosen from a list of elements pertinent to the context being explored. The elements can be people, places, problems to solve, objects, etc. They should form a set with some kind of overall coherence; for example, people at work, potential places to live in or problems involving fractions. Only one such set is used at a time. The user is then asked to identify one element which can be distinguished from the other two, and to provide labels for the poles of this construct. Each element is rated on this construct. Elements can be added to help clarify seemingly similar constructs. The procedure is repeated until no new constructs can be extracted. The set of constructs can then be examined or analyzed using techniques of cluster analysis and principal components analysis. Grids obtained from different individuals can be compared using an integrated analysis tool.

For example, if books are the topic selected, the user might input *Moby Dick, 2001: A Space Odyssey, Dune, The Color Purple, The Apprenticeship of Duddy Kravitz,* and *Macbeth.* The first triad presented could be *Moby Dick, 2001,* and *Dune,* and the user would be asked to think about which one of the three was different from the other two. When the user identified one, *Moby Dick* for example, the next step would be to provide labels for the two ends of the construct. The user could identify one pole as "futuristic" and the other as "historical". The program assigns provisional values of 1 (i.e. futuristic) to *2001* and *Dune* and 7 (i.e. historical) to *Moby Dick.* The user then places the other elements on the construct continuum, and rearranges all of them until the relative ranking of the elements is satisfactory. The pole names can be edited to reflect more accurately the construct invoked.

Examples of Repertory Grid Technique applications

There are numerous examples of the Repertory Grid approach being used to explore personal constructs in different domains: the perceptions of pre-service teachers towards their role as teachers (Shapiro, 1991), second language teaching (Zuber-Skerritt, 1988), teaching of psychology (Tobacyk, 1987), and knowledge engineering for expert systems (Gaines & Shaw, 1989). In one example of a study of primary school teachers' and fractions, the personal construct approach was used to trace a portrait of the whole of their constructs, including both content (fractions) as well as pedagogy (Lehrer & Franke, 1992). This approach proved to be useful in reflecting the complexity and the richness of teachers' constructs.

Constructs, like the concepts which they reflect, represent a dynamic system which provide a portrait of conceptual changes of an individual (Shaw & Gaines, 1993). This approach represents a promising avenue for studying student conceptions and conceptual change, addressing both nomothetic and idiographic concerns (Wandersee, Mintzes & Novak, 1994). Using an approach based on Repertory Grid Technique could provide a means to assess the evolution of an individual's conceptual framework with respect to a given domain. This could then be used to gain insights into the impact of instructional interventions on a students' conceptual framework.

Winer (1986) used Repertory Grid Technique to construct assessment instruments to explore the changes in teacher attitudes towards educational applications of computers following different in-service training courses. The study examined the changes seen in a group as defined by membership in a given class rather than focusing on specific individuals. The technique was developed in order to overcome the reliance on the "good judgement" of the researcher typical in the development of attitude assessment instruments. The difficulties encountered were largely due to limitations in the computational power available at the time, limitations which have now long been overcome.

The only study found which deals with students' concepts in science is Fetherstonaugh (1994). He used a paper and pencil version of the Repertory Grid Technique to explore high school students' ideas about nine different kinds of energy as identified by verbal labels (e.g. solar, nuclear, energy in a moving bullet). He found the method to be successful in revealing the breadth and depth of ideas as well as the links between them. He stressed the importance of eliciting each individual's constructions rather than constructing a group measure so as to create a portrait of the whole range of student constructs and not just the middle range. This has important implications for teaching methods which are attempting to deal with topics, such as energy, about which students have idiosyncratic views.

Morine-Dershimer et al. (1992) compared concept maps of effective teaching, repertory grids on teachers characteristics, and critiques of a videotaped teaching episode to evaluate the relative usefulness of each technique in measuring changes in prospective teachers' conceptions. In their study, they found concept maps to be the most useful, with repertory grid second, and the critiques third. The main problem they noted with repertory grid was the difficulty they had in interpreting the brief labels provided for each construct. They do state that "the potential of [repertory grid technique and critiques] to provide useful data on cognitions of prospective teachers should not be dismissed on the basis of the findings reported here. Alternative data collection and analysis procedures should be explored in order to identify the most productive uses of these tasks." (p. 482) We felt that the difficulties encountered by Morine-Dershimer et al. would be significantly reduced due to the inherently different nature of the element sets involved in physics as compared to teacher characteristics.

Proof of concept

In order to evaluate the practicability of using a Personal Construct Psychology-based approach to accurately portray student conceptions in science, a preliminary study was undertaken to demonstrate "proof of concept". In other words, is it possible to elicit grids from a high school student using given sets of elements so as to permit a pedagogically useful diagnostic to be established. The potential contribution of a systematized, computer-based technique for understanding student conceptions about given phenomena to the improvement of science teaching cannot be overestimated. It is received wisdom that effective teaching must begin where the student is and tailor instructional interventions to students' existing conceptual frameworks. The challenge has been the accurate assessment of student conceptions.

Choice of domain and elements

For the study, the domain chosen was physics, specifically concepts in mechanics. There were several reasons underlying this choice. First, this is a topic which is studied in high school physics courses. Second, this is an area which has received considerable attention from traditional methods of assessing students conceptions, providing points of comparison to evaluate our method. It has also been suggested that student beliefs in introductory mechanics are among the most resistant to change (Gunstone & Watts, 1985). Third, this area is one which is dealt with by microcomputer-based laboratories (such as PSL from IBM, 1989), and one long-term goal of our research is to assess the impact of such laboratories (Vázquez-Abad, Dassa & René de Cotret, 1993).

The choice of what *kind* of elements to use was one which provoked considerable thought and discussion. Our initial reaction was to use the kinds of problems which are traditionally given to students to solve on paper-and-pencil tests. However, we quickly rejected this option for several reasons. Although it would be interesting to see what constructs students felt were relevant to different problem-solving situations, it seemed to us that the risk of unduly biasing students by providing them with semantic labels in the verbal problems outweighed the interest of this kind of element. This consideration was combined with that of trying to distinguish between students' conceptual understanding of scientific concepts and their fluency or lack thereof with accepted terminology. Another drawback of this kind of element is that the use of "traditional" test items may trigger an association with "School Science" and result in formulaic answers rather than an indication of how the individual analyzes the "real world" (Gunstone & Watts, 1985). When one adds to these considerations the fact that a high percentage of students enrolled in our local school system (Montréal, Québec) lack fluency in the language of instruction, we felt strongly that avoiding written descriptions as elements for eliciting constructs was important.

Our second thought was to use the kinds of graphs that are displayed in microcomputer-based laboratories such as Personal Science Laboratory (IBM, 1989) to represent the real-time relationship between various phenomena; for example, velocity and time, velocity and acceleration. Cursory tryouts showed this approach to be unproductive. Unless the graphs were labeled, the only constructs which were elicited dealt with the superficial nature of the curve—straight line, parabola, etc. However, when the graphs were labeled, we were again providing at least some semantic labels, an approach which we rejected above. In neither case were the situations or phenomena which produced the graphs being tapped to elicit constructs which touched on relevant concepts.

Analysis of the reasons for rejecting both paper-and-pencil test items and graphs led to the consideration of drawings of different physical phenomena in sufficient context so that no verbal labels were necessary. Five sets of six drawings each were produced; four of the sets grouped elements which dealt with similar phenomena [acceleration, harmonic motion, circular motion, force) and the fifth was a collection of drawings dealing with diverse physical phenomena.

To test the feasibility of using this kind of drawing, three subjects worked through RepGrid 2 using the element sets. Each person represented a different level of content knowledge: a first year university student in chemistry who had taken high school and pre-university level physics courses; a professor in science education with a B.Sc. in physics; and a doctoral student in physics. The results indicated that useful grids could be produced using these element sets, although the set of diverse elements was perceived as less though-provoking than the others. The subjects all felt that the constructs elicited and the subsequent relationship among the elements accurately represented their understanding of and concepts about the physical phenomena illustrated. The level of language used (as well as the language itself) varied, both between and within individuals. Both technical and colloquial terms could be used with ease, a consideration that was very important as our target population of high school students had less content knowledge than any of these individuals. Evidence of different conceptualizations (and of misconceptions) was obtained as well.

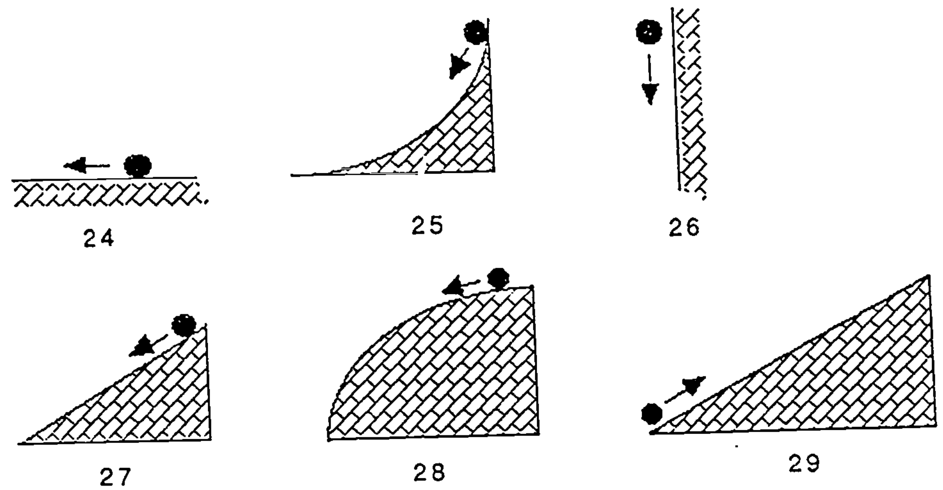
Target population trial

The results from the preliminary tryouts led us to believe that the element sets were sufficiently rich to warrant trial with a representative of the target population. As mentioned earlier, the thrust of the research project is to explore whether Repertory Grid Technique can be used as a diagnostic tool to help identify conceptual (mis)understandings or lacunae with respect to given scientific concepts, specifically at the high school level. In order to test this, we needed to determine if a high school student would be able to master the technique and produce grids which would provide sufficient insight into his or her understanding of the physical phenomena to allow for a diagnostic to be made.

Joanne, a 16 year old girl in her last year in high school, was asked to participate. This was done in May, as she was finishing the physics course. It was explained to her that the purpose of the study was to develop a tool to help in understanding what students thought about different concepts in physics. No indications were given about what concepts were being addressed by each set of elements. It was stressed that there were no right or wrong answers, and that no information from her work would go back to her teacher. A first grid was elicited on the topic of movies to familiarize her with the technique; when she expressed comfort with the technique, she was given the five element sets to work through. It took her approximately 30 minutes to produce each grid, and she said that it became easier as she became more familiar with both the software and the technique.

The five grids, preceded by the element set from which they were elicited, are presented below exactly as produced. Following each one is a brief analysis; a global diagnostic follows the final grid.

Element set #2



Grid #2

Constructs		Elements 24	25	26	27	28	29		
opposite	1	4	7	1	1	1	7	1	velocity of movement at the beginning is bigger than at th
exterior force	2	1	7	7	7	7	1	2	gravity force
2 movements	3	7	1	7	1	7	1	3	one movement
2 opposite movements	4		7		7		1	4	2 different movements
surface is straight	5	1	7		1	7	1	5	surface is curbed

Figure 1: Joanne's grid for element set 2

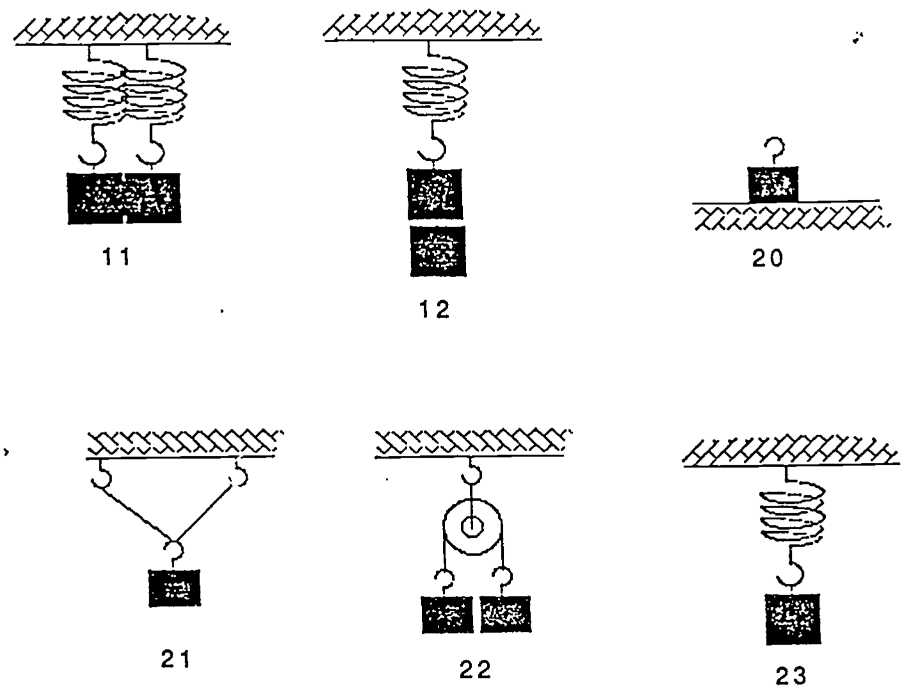
Construct 1: This construct, the comparison of velocities at the beginning and end of the movement, is well-chosen for the element set but element 25 is rated incorrectly. There appears to be a confusion between acceleration and speed for this element.

Construct 3: This construct, concerned with the number of different movements involved, requires clarification. It appears that Joanne used the term "movement" to represent the colloquial concept of direction, rather than the more technical one of a movement in two dimensions having vertical and horizontal components. If this is the case, then the presence of friction has to be clarified, as there is a conflict between the ratings of elements 24 and 29.

Construct 4: This does not appear to be a particularly useful construct; only 3 elements can be rated on it. It is not clear why element 25 is not rated the same as element 28.

There are incoherences between constructs 3 and 4, and 1 and 2 (notably element 24).

Element set #3



Grid #3

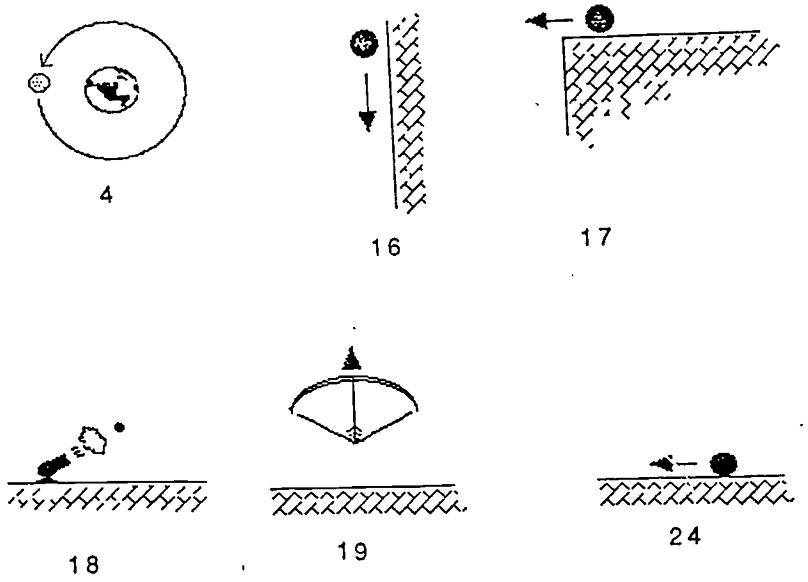
Constructs		11	12	20	21	22	23		
short movement	1	5	4			7	5	1	with a push
presence of 2 weights	2	1	1	7	7	1	7	2	presence of 1 weight
weight resting on surface	3	7	7	1	7	7	7	3	weight in suspension
movement due to a balance	4	7	7			1	7	4	movement due to a spring
weight is in instable position	5	1	1	7	7	1	1	5	weight is in a stable position

Figure 2: Joanne's grid for element set 3

Construct 1: The construct is unclear.
Construct 5: The terms "stable" and "unstable" are used imprecisely.

The constructs do form a coherent set and the observations all take friction into account.

Element set #5



Grid #5

Constructs		Elements 4	16	17	18	19	24		
movement will follow a circle	1	1	7	7	4	7	7	1	movement will follow a straight line.
other force	2	7	7	4	1	1	1	2	gravity force
1 movement	3	7	1	1	1	7	1	3	same movement is repeted at least 2 times
ball is projected	4	[redacted]	[redacted]	7	1	1	7	4	ball is rolled
not a cyclical movement	5	7	1	1	1	1	1	5	cyclical movement
unknown origin of movement	6	1	1	1	7	7	1	6	use of an instrument
slow movement	7	1	4	4	6	7	2	7	fast movement

Figure 3: Joanne's grid for element set 5

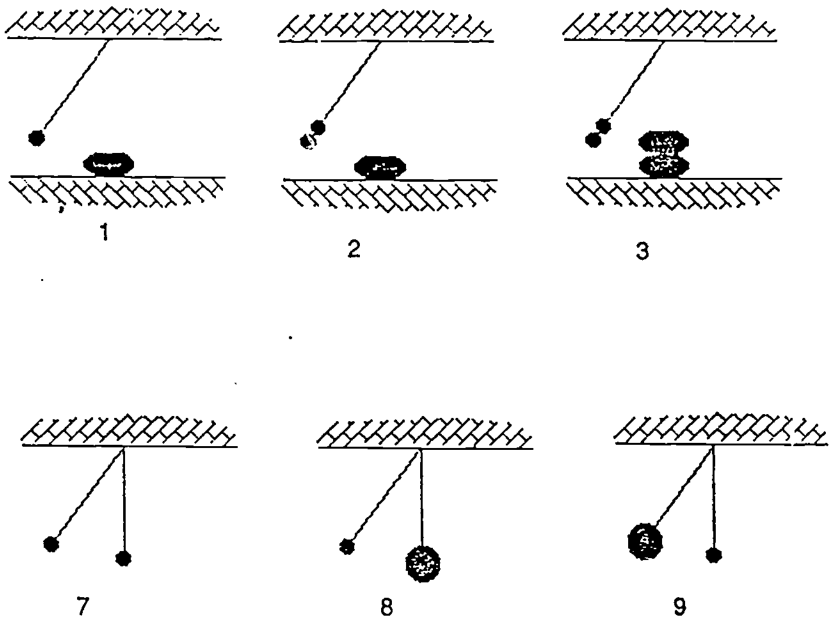
Construct 1: The rating of element 17 shows a classic error—the "Roadrunner" fall. An object is seen as proceeding in a straight line and then falling vertically, rather than following a parabolic course.

Construct 2: If we assume that the force being talked about is the force required to initiate movement, then the ratings for elements 17 and 24 should be equal. If, however, the forces considered are all forces acting upon the object, then elements 17, 18 and 19 should be rated equally.

Construct 3: Elements 18 and 19 should be rated equally.

Construct 7: The speed of the moon, element 4, is incorrectly estimated. Joanne appears to think that if there is no acceleration, the speed is slow.

Element set #6



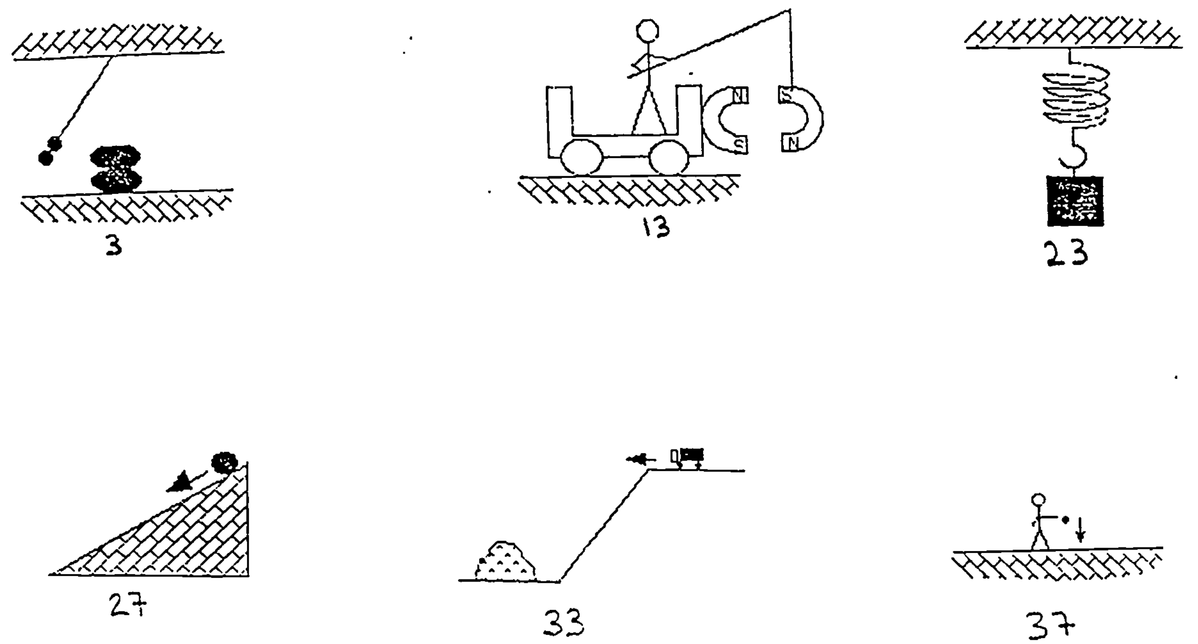
Grid #6

Constructs		Elements 1	2	3	7	8	9		
obstacle is hanging from a wire	1	7	7	7	1	1	1	1	presence of an obstacle on the ground
only one movement.	2	5	3	2	7	3	4	2	repetitive movement
not proportional	3	7	7	7	7	1	1	3	distance between 2 obstacles is proportional to
little force	4	1	4	4	1	1	7	4	big force
target is easier to move	5	4	4	7	2	3	1	5	target is hard to move (heavy)

Figure 4: Joanne's grid for element set 6

Construct 2: Element 9 is incorrectly rated, indicating a lack of understanding of the conservation of movement.
Construct 4: The concept of total energy is correctly applied.
Construct 5: Elements 7 and 9 should be equal as the targets are the same size.

Element set #7



Grid #7

Constructs		Elements 3	13	23	27	33	37		
force exterieur	1	1	1	4	7	6	7	1	force de gravité
movement caused by exterior push	2	1	7	1	7	1	7	2	attraction
man has no influence	3	4	1	5	1	7	2	3	man can control the movement
no obstacle	4	7	1	1	1	7	1	4	presence of an obstacle (to stop or slow dov movement)
one movement	5	6	1	7	1	1	3	5	repetitive movement
tension at beginning	6	3	1	2	3	7	2	6	no tension at beginning

Figure 7: Joanne's grid for element set 7

Construct 1: The contrast of exterior force to gravitational force is not very precise. However, it is similar to Construct 2 in grid 5, indicating a consistent use of the same construct.
Construct 3: It is difficult to interpret the application of this construct.
Construct 6: It is difficult to interpret how "tension" is being used.

Joanne does not see the equivalence of elements 27 and 33.

Diagnostic

In reflecting on the ensemble of five grids, we can infer three difficulties that Joanne has with respect to concepts in physics, as well as one more general analytic skill.

- She is confusing acceleration and speed; see grid 2, construct 1 and grid 5, construct 7.
- Parabolic movements are sometimes seen as one movement and sometimes as two. Different situations result in them being considered rectilinear or not. See grid 5, element 17.
- The concept of total energy appears to be acquired; see grid 6, concept 4. However, the concept of conservation of p (mv, quantity of movement) is not acquired. See grid 6, concept 5.
- Joanne also has difficulty making abstractions to see the equivalence of systems. While she did identify that in grid 3, elements 11 and 23 were equivalent, she did not see the equivalence of elements 1 and 3 in grid 6, or elements 27 and 33 in grid 7.

It is interesting to see that the diagnostic is supported by looking at both constructs across elements and elements across constructs. It is also interesting to see that some conclusions are supported by information from more than one grid.

The apparent inconsistencies in Joanne's grids are actually not surprising, despite what has been reported about the general coherence of children's ideas about science (Driver, Guesne & Tiberghien, 1985). Our judgement of incoherence merely reflects a different level of analysis:

> the student does not possess any unique model unifying a range of phenomena that the scientist considers as equivalent. Nor does the student necessarily see the need for a coherent view, since *ad hoc* interpretations and predictions about natural events may appear to work quite well in practice. (Driver, Guesne & Tiberghien, 1985, p.3)

These different levels are reflected in the diagnostic about Joanne's difficulty in making certain abstractions.

Joanne's contrast between gravitational force and either exterior or other force (see Grids 5 and 7) can be seen as reflecting an Aristotelian distinction between "forced" and "natural" motion. Her assumption in Grid 5, Construct 7 that if there is no acceleration, the speed is slow, also can be seen as fitting into an Aristotelian view of the world.

Joanne's comments

After completing the five grids, Joanne was shown her grids and discussed the process of completing the grids and whether she felt they accurately represented her understanding of the different elements. As mentioned above, she found that there was a learning curve with the technique, and felt it to be easier the more she did. She said that she would be very happy to repeat the experience, and that she found herself thinking about the physics concepts illustrated in the drawings, not merely the drawings themselves. She also felt that the grids she produced accurately reflected her conceptual framework with respect to the elements.

Second trial

A second trial was then undertaken with high school students enrolled in the physics course. The students worked with an in-house French translation of RepGrid3 (Centre for Person-Computer Studies, 1994). Three groups of three students each volunteered to participate in a project which involved four consecutive lunch-time sessions. The first one was spent on RepGrid, the next two on working with IBM's PSL on physics protocols, and the final session was on RepGrid. A total of seven students (all boys) completed the process; two did not attend the second RepGrid session. They produced the grids individually and worked on PSL in groups of three.

The analysis here focused on the representation of students' conceptions and evidence of conceptual change. While clearly no dramatic "Eureka"-like experiences were expected as a result of only two sessions with PSL, the intent was to create a portrait of each student's conceptual framework and establish if changes or trends to change could be detected using RepGrid. The concept of conceptual change used was in line with Carey's (1985) distinction between weak and strong restructuring. In weak restructuring, the same concepts exist over time, but there is evidence of new relationships among them. Strong restructuring requires changes in the core concepts which make up an individual's conceptual systems. Given the extremely brief instructional intervention, strong restructuring was not expected. It was expected, however, to be able to see evidence of weak restructuring. The grid comparisons possible with RepGrid3 enable one to distinguish between the same constructs which are simply applied differently and truly new constructs, i.e. not just changes in the semantic labels.

Student reactions to RepGrid

Students were asked to comment on the RepGrid experience after completing their last set of grids. None of the students had difficulty with the technical manipulation of the software. Five of the seven students said that they found it easy to create the grids. Of the two who found it difficult, one said that the drawings were too similar; the other felt he did not know enough about the phenomena to create construct labels that were useful.

Two drawings in particular, #4 and #19, were singled out as posing difficulties in interpretation. For example, one student thought that #19, supposedly a bow and arrow, was an indicator gauge of some kind. All of the students, except for the one who felt that he didn't know enough, stated that the grids they produced accurately reflected their thoughts about the different phenomena.

Information from grids

No comparisons were made across students, although the RepGrid software permits this kind of analysis. Rather, analysis focused on within-student change. The question was whether any conceptual change could be detected as evidenced by change in repertory grids.

The students were asked if they thought about the characteristics of the drawings or if they imagined the objects in motion. All of them said that after their experience with PSL, they imagined the objects in motion. This was largely confirmed by the grids, which were much more descriptive of the drawings before PSL than after. The most dramatic example of this can be seen in one student's grids which refer to element set #3. The first grid is purely descriptive in nature (e.g. "one weight—two weights") whereas in the post-PSL grid the student is clearly trying to consider the effects of the objects in motion (e.g. "the time/distance graph is a curve—the time/distance graph is a line parallel to the abscissa").

Conclusion

While clearly the work reported here is not complete, the series of trials done with both subject-matter experts and representatives of the target population (high school students) demonstrates the potential of Repertory Grid Technique for the assessment of learners' initial states and subsequent conceptual change. The practicability of using drawings as elements, thereby avoiding any imposed verbal labels or semantic context was established.

Further work needs to be done to refine the element sets and create additional ones. Additional trials to assess the effect of simply using RepGrid on the quantity and quality of constructs elicited are also needed. Once this technique has been perfected, attention will shift to the analysis of which instructional interventions, specifically different PSL protocols, are most useful in effecting conceptual change and facilitating students' transition to "standard" conceptual frameworks for physical phenomena.

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