Chapter 10
Representational Competence, Understanding of Experiments, Phenomena and Basic Concepts in Geometrical Optics: A Representational Approach

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10.1 Introduction

A considerable body of empirical and theoretical research has shown the essential role of multiple representations (MRs) for science learning, on the one hand for specific aspects such as conceptual learning (Nieminen et al. 2012; Tsui and Treagust 2013, ch. 2, 5, 16) and reasoning (Tytler et al. 2013, ch. 6; Verschaffel et al. 2010), or problem solving, transfer or communication, on the other hand for expertise in general (Gilbert and Treagust 2009, ch. 12; van Someren et al. 1998, ch. 2). A theoretical account of these findings is discussed in Chap. 1 of this book in terms of models for the cognitive ("dual coding" family of models) and educational (DeFT; Ainsworth 2006) aspects of MRs. On the epistemological level, the term 'representation' is understood as a tripartite relation of a referent Rt (or object),

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its representation Rn, and the meaning M (or interpretation) of Rt, Rn and of their interaction. This relation is referred to in various ways (eg. 'Peircean triangle', or 'triangle of meaning'; see Tytler et al. 2013, ch. 6).

In the present contribution, we review the background and results of two connected studies of MRs related to experiments (Hettmannsperger et al. 2014; Hettmannsperger 2015; Scheid 2013; Scheid et al. 2014). We had chosen geometrical optics as area of investigation, because it is rich in MRs, and it is taught as one of the first subjects in many German physics curricula, so it seemed worthwhile to know if there are effective learning approaches already at that stage. The focus of investigations was on two aspects, which are considered to be essential for the learning of science in general, and of physics in particular.[1]

10.1.1 Experiments and Representational Coherence Ability

It is well known in science education, that proper understanding of and learning from experiments (or observations) requires mastery of a multiplicity of representational formats (RFs), from the "enactive" or "operational" manipulation of the experimental devices and materials (Bruner 1964; Piaget 1977) to the most abstract level of the mathematical formulation of the law(s) of nature underlying (or investigated) in a given experiment (Feynman 1990). An important consequence of the above-mentioned essential role of MRs for science (for many individual aspects and in general) is that RCA is not an isolated competence, to be distinguished from domain-specific expertise, but it is rather an integrative component of it (see Anzai 1991; van Heuvelen 1991). There is ample evidence for this crucial role of RCA especially also for experiments and observations, both from science education research (Gilbert and Treagust 2009; part II, 107 pp.; Tytler et al. 2013, in particular ch. 3, 6, 9) as well as from best practice (Marzano et al. 2001).

According to research syntheses by Höffner and Leutner (2007) and Ploetzner and Loewe (2012), the level of abstraction (or realism) is an essential feature of MRs, and we propose the idea of a "representational ladder" related to an experiment (and/or observation), see eg. Fig. 10.1 (the visual form was inspired by Leisen 1998) which is a kind of meta-representational metaphor and visualization: To use a ladder properly, one not only has to be able to stay safely on every rung, but also to easily climb up and down. In the example of Fig. 10.1, learners can do an image formation experiment or work with a photograph or realistic drawing of it according to the lowest line in the figure. The ray diagram encapsulates the optical situation in a schematic way, allowing, given the object position, to determine by geometrical construction the position and size of a sharp image. The mathematical equations in the topmost line allows to answer the same question in a purely symbolic way (its semi-quantitative textual formulation provides an intermediate step helping to interpret the quantities and the relationships in the equation). Note that Fig. 10.1 does merely propose a visualization (representation!) of different levels of abstraction, and is not a proposition of a learning progression.

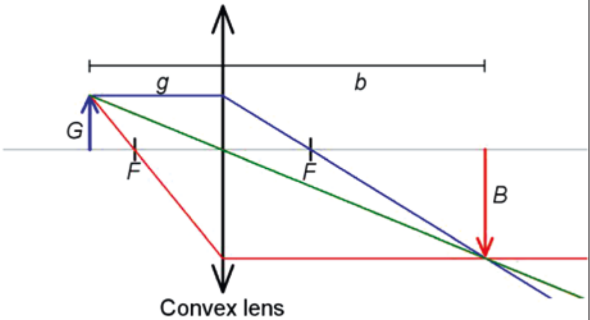
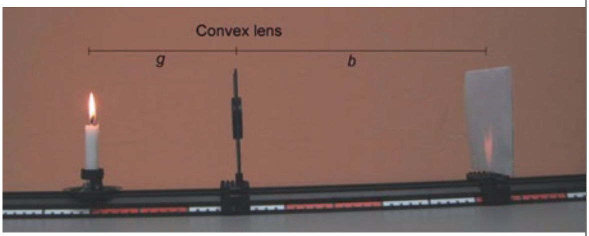
level of abstraction →		
	mathematical description	$\frac{B}{G}=\frac{b}{g}$; $\frac{1}{f}=\frac{1}{g}+\frac{1}{b}$
	semi-quantitative description	The closer the object to the focus, the larger the image distance and size
	schematic drawing (ray diagram)	
	real(istic) drawing or photography	

Fig. 10.1 "Representational ladder" of a geometrical optics experiment

10.1.2 Experiments and Representation Related Conceptual Understanding and Change (RCU/C)[2]

A growing strand of research is focusing on the representational demands of developing students' conceptual understanding and change, pointing out that students need to develop and understand multiple representations to improve their understanding of basic scientific concepts (Botzer and Reiner 2005; Hubber et al. 2010; Plötzner and Spada 1998).

In particular, understanding the link between scientific experiments and their conceptual basis requires the learner to deal with multiple representations at different levels of abstraction, such as describing observed phenomena by oral or written language in terms of appropriate concepts, or expressing experimental results by schematic diagrams or mathematical relations containing formal representations of these concepts. In a qualitative study of student's representations in the domain of particle models about solids, liquids, and gases, Waldrip et al. (2010) showed that student-generated representations can foster students' conceptual learning, and what teaching features offer effective support for this.

Hubber et al. (2010) confirmed the efficacy of using multiple representations in mechanics while teaching and learning the concept of force in a qualitative video study. Borrowing from other fields of science education, the importance of MRs for conceptual learning has been underlined in biology (Tsui and Treagust 2013) and chemistry (Taber 2009), in particular for the fundamental topic of the micro-macro level connection (Cheng and Gilbert 2009), and also in geoscience (Sell et al. 2006). A classical example where a domain specific representation supposed to be a tool turns into an obstacle specific for the learning topic of this study, ray optics, is the idea that the image disappears, when the principal rays used for image construction are blocked (s. Goldberg and McDermott 1987).

Regarding conceptual learning from and about experiments, cognitive conflict with discrepant events has been discussed since long as a basis for conceptual understanding and change, both in the discipline (Thagard 1991), and for the individual (Thorley and Treagust 1987; Kim and Choi 2002; Lee et al. 2003; Başer 2006; Zimrot and Ashkenazy 2007). While the precise theoretical underpinnings of conceptual change are still under discussion, in particular with respect to the sometimes surprising persistence of misconceptions (Andersson and Kärrqvist 1983; Fetherstonhaugh and Treagust 1992; Langley et al. 1997; Heywood 2005), there is growing consensus that an essential element for conceptual learning is that learners deal actively with discrepant information, whether experimental or other, i.e. that learners need to use their own cognitive and representational resources (see Hubber et al. 2010). In the present context, it is thus necessary to find appropriate learning activities where students effectively undertake multi-representational reasoning about experiments, if conceptual learning and change from the latter is to occur. Note, that the aim here is specifically conceptual learning, and not laboratory work, problem solving, or any other of the possible educational benefits of MRs mentioned in above.

In the sequel, such type of learning activities will be presented, which is the study objective of this contribution.

One strategy to engage students to learn with MRs is the use of cognitively activating tasks. These kinds of tasks aim at implementing cognitively challenging learning strategies (Klauer and Leutner 2007) such as relating prior knowledge to new information, initiating cognitive conflicts, searching different ways to solve a problem, relating representations to others with equivalent or complementary meanings, as well as encouraging students to express their own thoughts, ideas, and concepts using various domain specific representations as cognitive tool (Stein and Lane 1996; Kunter and Baumert 2013).

10.1.3 Representational Activity Tasks (RATs)

In the present context, “cognitive activation” means that students think more often, more explicitly, and more deeply about experiment-related representations, express them, and draw conclusions from them as would be the case in a usual learning

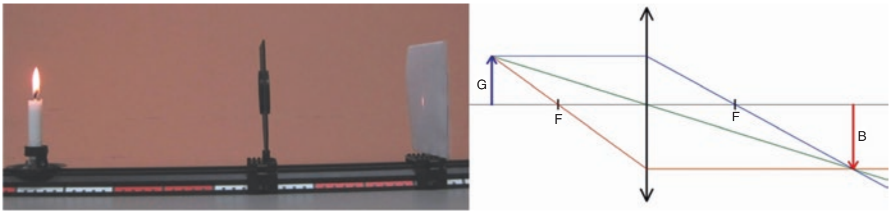


Fig. 10.2 Example of a RAT (TG) requiring mapping of two representations (showing two different imaging conditions) and a modification to achieve coherence between them (photograph as a realistic picture, ray diagram as a schematic representation) plus a short written explanation

setting, without adequate instructional means. The learning activities to achieve cognitive activation (in this sense) are a set of newly developed specific tasks, called "Representational Activity Tasks (RATs)", requiring learners to explicitly reason about and analyze various experiment related representations. Conventional tasks deal with the connections between representations most often implicitly, with a focus on content and a problem statement related to it (such as finding the optical image in a given lens arrangement), and based on the tacit assumption that the pertinent representational means to express this content and problem, and their connections (such as ray diagrams, and relating them to the experimental situation), will be used by the learner without explicitly asking for this. In contrast, RATs involve always two or more types of representations simultaneously, and explicitly ask students to elaborate on various connections between them, such as comparing, mapping, completing etc. MRs. An example of a RAT is given in Fig. 10.2, and details about the design principles will be given in 'Materials and Methods'.

Note that, while there are good reasons for potential benefits of MR based learning in the above sense, it creates also complex demands and increased cognitive load for learners (van Someren, ch. 12; see Ainsworth 2006, and literature cited therein). It is therefore a highly relevant question, whether an approach like RATs can indeed improve RCA and RCU/C in spite of these demands. On the basis of the above research background, the following general research questions are treated in the present contribution: What is the impact of RATs on (a) representational coherence (b) conceptual understanding when learning with experiments in ray optics?

Within the framework of a general overview and discussion of MRs in physics education in this volume, the focus of the present contribution is on results about these research questions and their interpretation, while detailed descriptions of the methodology of the pair study on RCA and RCC/U are given elsewhere.

10.2 Materials and Methods

10.2.1 Instructional Material and Intervention

In view of the background given above, the learning tasks aiming at representational coherence (RCA) and representation related conceptual understanding/change (RCU/C) require the following cognitive activities:

10.2.1.1 Representational Coherence Ability

Learners are required to carry out one of the following four different tasks formats requiring coherence between different representations ("coherence tasks"):

- compare and map representations
- complete/modify representations (in order to establish consistency between different RFs)
- find and correct errors in representations (based on information from different RFs)
- describe and explain their reasoning during the above activities.

Figure 10.2 shows an example of a RAT which involves mapping and modifying multiple representations. This RAT consists of two similar experimental settings containing a convergent lens, but with two different cases of image formation, viz. reduction (left) and magnification (right) of the object size (as determined by different relative values of object distance and focal length). These two settings are not expressed by the same type of representation, but by a photograph and a schematic drawing (ray diagram), and students are asked (i) to mark the differences between the arrangement of optical elements (ii) to adapt the schematic drawing, in order to establish coherence with the realistic representation, and (iii) to describe and justify their modification in a short written text. The task thus explicitly requires to link three different types of representations (realistic and schematic image, text). In contrast, the conventional task related to the same content asks to work with only one representational format, eg. to complete the image construction with principle rays (schematic image, see Fig. 10.3).

Note that in this and some other cases the CG tasks were just conventional applications of the ray model, and the requirements (as well as the written task formulation) were more difficult for the treatment group (TG) than for the CG. The comparison is not between tasks of equal difficulty, but between equal learning time, where a part of the conventional tasks has been replaced by the more demanding RATs.

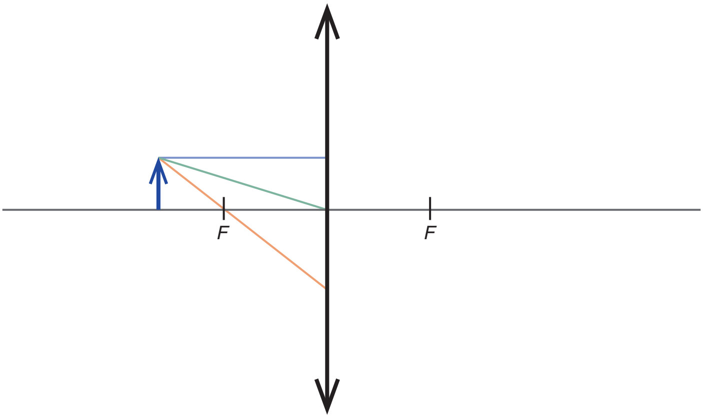


Fig. 10.3 Example of a traditional task (control group, CG) that focuses on only one type of representation, requiring to complete the image construction with principle rays (a typical type of task in the teaching of geometrical optics in the classroom setting of the target sample below)

Table 10.1 Conceptual difficulties treated in the RCC/U study (all taken from existing research, see text)

Relation between light propagation, scattering, and perception
Relation between light rays (model) and light beams (phenomenon)
Role of principal rays
Formation of real images (intersection of outgoing rays)
Formation of virtual images (intersection of prolonged outgoing rays)
Effect of covering parts of a lens
Aerial image

10.2.1.2 Representation Related Conceptual Understanding/Change

The learning tasks to foster this aspect of science learning required use of different representational formats for reasoning about common conceptual difficulties (see Table 10.1), all of which were taken from existing research in this domain (Goldberg and McDermott 1987; Wiesner 1986; Reiner et al. 2000). The TG students received specific MR based cognitive activation measures, mainly self-generation of MRs (in line with the findings of Waldrip et al. 2010), in some cases also completion of partially given MRs. An example is the visibility of the real image formed by a

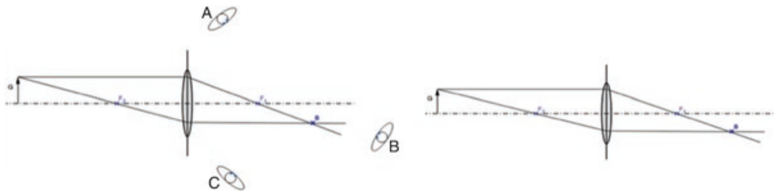


Fig. 10.4 Example of a RAT requiring analysis/reasoning concerning a conceptual difficulty related to the formation and visibility of real image by a converging lens. Learners are requested to reason on the basis of the ray diagram in order to explain which of the observers (*A*–*C*) could see the image with a transparent/opaque/no screen at point S

Table 10.2 Schedule of the unit on converging lenses and image formation (common for CG and TG)

Lesson	Content
1	Teacher experiment on converging lens: refraction, focus, principal rays, image construction
2	Students experiment about same content: variation of parameters, protocol, discussion
3, 4	Working sheets: image construction, different imaging cases
5, 6	Working sheets: lens formula, revision of unit

converging lens when a transparent/opaque/no screen is present (aerial image). A widespread conceptual difficulty is that the screen is necessary for (diffuse) reflection of the image, while it is not conceived that it would still be possible to see the image if the observer's eyes were located in the position of the screen (Goldberg and McDermott 1987). Figure 10.4 shows the related RAT (TG, left side), which asks to work with the ray diagram (schematic representation) in order to explain which of the observers (A – C) could see the image with a transparent/opaque/no screen at point S. The CG was merely asked to where the image would form, and from where it would be visible (not referring to the ray diagram). Hence, in the latter task the same conceptual difficulty was addressed, but it did not require to operate on the ray diagram.

The interventions for RCA and RCU/C were embedded in the regular curriculum and started when the topic of converging lenses and image formation had to be taught according to the official schedule. The teachers in all conditions implemented a detailed lesson plan, which was discussed and adapted according to their feedback before the intervention began. The lesson plan followed a well-established teaching sequence for the given subject matter.

The total length of the intervention was 6 lesson hours, see Table 10.2 for an overview (6 × 45 min, grouped in 3 double lessons of 90 min, a standard format for science teaching in Germany). The pretest for covariates and initial values of dependent variables and the post-test for the values of the latter after the intervention were administered in separate lesson before and after the learning unit. After having seen and interpreted a teacher experiment demonstrating the basic principles (1st lesson), students carried out and analyzed an experiment (2nd lesson) of their own, exploring further the basic content of the teacher experiment. They then worked on tasks about various aspects of the topic during a sequence of (4 × 45 min, 3th to 6th lesson). Student work was carried out in pairs.

While time-on-task and core learning content were identical in control and treatment groups (see Table 10.2), the learning tasks were differentiated according to the learning objectives of the two studies as explained above. For the RCA study, the TG1 instruction was enhanced by RATs focusing on representational coherence, i.e. with one of the four types of "coherence tasks" presented above; CG1 worked on additional conventional practice tasks instead. As an indication intervention strength, the number of representational formats N_{RF} necessary for a successful solution is 1½ times higher in the TG1 than in the CG1; the averages per item are 2.2 (≥2 per construction) and 1.5, respectively (the latter value is slightly higher than the average of 1.2/item obtained from an analysis of roughly 800 conventional textbook task, see Scheid 2013). For the RCU/C study, both groups followed also the content summarized in Table 10.2, TG2 using different representational formats for reasoning about common conceptual difficulties, also treated in the CG2 learning tasks, but without representational reasoning as cognitive activation measure. Note that CG2 is a control group only with respect to the use of RATs, but that a treatment takes place with respect to conceptual difficulties. As an indication intervention strength, the number of self-generated MRs related to conceptual difficulties/misconceptions is four times higher in the TG than in CG.

10.3 Design, Instruments and Analysis

A quasi-experimental pre-post design was used, for both the study on RCA and on RCU/C. Together, there were four groups in the two partial studies, see Table 10.3 (all based on the standard lesson plan for geometrical optics, see above). There were two types of treatment groups with an instruction enhanced by RATs (as explained in the preceding section) focusing on representational coherence (TG1), and on conceptual difficulties and conceptual change (TG2). The control groups (CGs) did not learn with RATs, the first with conventional learning tasks instead (CG1), the second with learning tasks dealing with the same set of conceptual difficulties, but not requiring explicitly to operate on a given representation, e.g. a ray diagram (CG2). This design allows for the following comparisons: TG1 and CG1 will be compared in order to know whether RCA can be fostered by the RAT approach;

Table 10.3 Design table of the two interventions: Without/with RAT intervention × without/with conceptual change (CC) intervention (no/yes)

		RAT	
		n	y
CC	n	CG1	TG1
	y	CG2	TG2

TG2 will be compared to CG2 and CG1 in order to know, whether RCU/C can be fostered by RATs as well as by learning tasks targeted at the same conceptual difficulties without a representational focus (comparison with CG2), and whether there is any appreciable advantage at all compared to learning without addressing difficulties (comparison with CG1). Up to the intervention, TGs and CGs were identical in their content, lesson plans, number of learning tasks, and duration of the learning sequence (6 weeks); moreover, corresponding TG and CG classes at the same school were taught by the same teacher.

The investigation took place within regular secondary level I physics classrooms in the German state "Rheinland-Pfalz" (N(RCA) = 167 (CG), 175 (TG) at six different schools; N(RCC) = 250 (CG), 275 (TG) at ten different schools; age group 13–15 years, average 13.5 years, 7th and 8th grades of German school system, mostly from academic track schools ("Gymnasium[3]"; Scheid 2013; Hettmannsperger 2015). Subject matter was geometrical optics (light sources, light propagation and rays, shadows, lenses, image formation), a standard topic according to the teaching program of this age group. The length of the interventions was about six lessons (6 × 45′ = 4.5 h in total). We now turn to a description of covariates and instruments used.

In order to control for possibly different factors in CG and TG, in the RCC study pre-test values, relevant school grades (mathematics, physics, and German language), gender and class-size were taken into account as covariates. Moreover, three subscales of cognitive ability related to different representational formats (word associations, numbers, and visual/spatial imagination) were considered (Liepmann et al. 2007). For the RCA study the same covariate set was considered (except class size, as classes were not distinguished in the 2-level model considered, see below). Moreover, in order to look for potential effects of the interventions on motivation, a test based on well-validated instruments taken from the literature was used (Hoffmann et al. 1997; Rheinberg and Wendland 2003; Kuhn 2010); reliability was satisfactory across all intervention groups ($\alpha_C > 0.9$).

Instrument for RCA In order to assess their representational coherence ability of learners, test items required to relate real phenomena und experiments to various types of representations and multiple representational formats to each other. Types of coherence relationships to establish were comparing and mapping MRs, as well completing and correcting given incoherent MRs; additionally, participants had to describe and explain their reasoning while resolving these questions. Thus, the test contained the same cognitive processes as the RAT intervention, but of course different tasks. Moreover, in half of the items reasoning about multiple representations was not explicitly asked for, but implicitly necessary for solving the question; this is an essential and widespread role of MRs in scientific work and thus has a high curricular validity (see Fig. 10.5 for an example of a physics "word problem" of this kind).

A pilot study was carried out in the same age group and classroom setting as the main study, improving item formulations and detecting items which did not work properly according to the desirable ranges (Ding and Beichner 2009). Moreover, an

Ines would like to draw an enlarged image (20 mm) of a lady bug that originally has a size of 5 mm. To facilitate drawing, she wants to project an image of the bug onto a screen. The lady bug is located 10 mm in front of an appropriate lens.

At what distance should the screen be positioned?

Solve the task with a calculation.

Fig. 10.5 Example of an item assessing RCA indirectly (calculation with data contained in textual form)

expert rating with 11 experienced teachers (on average 15 years of teaching experience) yielded satisfactory curricular validity for the remaining items (intra-class correlation $0.5 < ICC < 0.7$). There were 15 items retained for the main study, for which we obtained the following instrument characteristics for the post-test (pre-test values cannot be expected to be in the desired ranges, as there is no consistent knowledge yet). Overall internal consistency was $\alpha_C = 0.79$ (across different validation samples), testing for exclusion of the individual items did not lead to an increase. Item difficulties were between $.2 < p < .8$, item-test correlation were $r_{it} > .3$ (up to slight deviations for a few exceptions). Thus, the test characteristics are in the desired value ranges according to the literature (Ding and Beichner 2009). A detailed report on the RCA test is available in Scheid (2013).

Instrument for RCU A concept test for geometrical optics (with focus on image formation by lenses) was developed and validated in the same way as for the RCA test, dealing with the core concepts of light propagation, scattering, formation of real and virtual images, and visual perception of optical images. In a pilot study in the same age group and classroom setting as the main study, items were tested for necessary improvements of their formulations and for item characteristics in the desirable ranges (Ding and Beichner 2009). The test was designed as multiple-choice-test with remaining 11 items (test duration 15 min), each of which had the scientifically correct answer and three distractors as answer options (see Table 10.4 for example items; Hettmannsperger 2015). Distractors were based on widespread intuitive students' concepts reported in literature (Goldberg and McDermott 1987; Wiesner 1986; Reiner et al. 2000). Instrument characteristics for the post-test (as in in the RCA study, see above) using the whole sample of both the RCA and RCC study are as follows: Item difficulties ranged between $.2 \leq P_i \leq .8$ and item discrimination indices between $.25 \leq r_{it} \leq .45$. Internal consistency attained a satisfactory level ($\alpha_C = .75$). A detailed description and analysis of the concept test is available in Hettmannsperger (2015).

In the RCA study a two-level model specifically adapted for the measurement of change (Heck et al. 2014; Göllner et al. 2010) was used (level 1: measurement times, level 2: intervention groups). It allows to analyze students' learning progress over time in a way which has several advantages when compared to repeated measurements analysis of variance (treatment of missings; less strict applicability requirements; more flexibility in the form of the temporal development; Göllner et al. 2010). In the RCU/C study with higher number of classes/schools, a three-level model was implemented (level 1: measurements times; level 2: learners;

Table 10.4 Sample items of the concept test

Scientific concept	Sample item
Ray model	Which statement is correct?
	Light rays are something real, like thin water jets from a spray gun
	Light rays exist only in peoples' minds, e.g. like constructions in geometry
	Light rays are exactly the same as light beams
	Light beams are mental objects, for example they are used to determine the image size
Scattering and visibility	Which of the following objects/creatures can be seen in a completely dark room?
	A glowing firefly
	A white sheet of paper
	A bicycle reflector
	The eyes of a cat
Image formation	In an experimental assembly a light bulb, a converging lens and a screen are set up so that an enlarged, inverted and sharp image of the filament is formed. What will happen if the bottom half of the lens is covered?
	The upper half of the image will be cut off
	The bottom half of the image will be cut off
	The image will become darker
	The image will become brighter

level 3: classes) (Fahrmeir et al. 2009). In both studies, proper treatment of variances (eg. entering the calculation of effect sizes) for the nested structure of the samples is of course a main advantage of multilevel analysis. Due to the focus of the present study, which is a discussion synthesizing the main effects of the two related interventions and to lack of space, details about the multilevel analyses are given elsewhere (Scheid 2013; Hettmannsperger 2015).

Finally, effect sizes between CGs and TGs were computed as Cohen d (using pooled variance) according to standard procedures (Cohen 1988; Tymms 2004). Additionally, the Hake index (Hake 1998) as a measure of the learning gain was computed.

10.4 Results

The data revealed several main statements about representational coherence and conceptual understanding, best discussed on the basis of Fig. 10.6 (see Table 10.5 for numerical values):

Initial Situation (Pretest Values) Control and treatment groups started approximately at the same level for both RCA and RCU/C; there was in fact a slight but statistically not significant advantage in favor of the CG in both cases (beyond

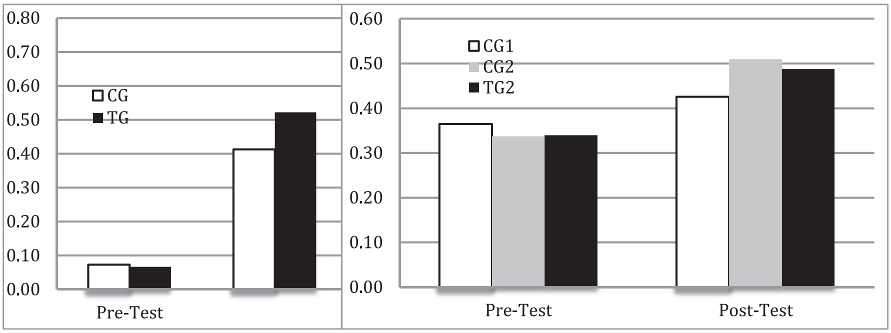


Fig. 10.6 Descriptive values of RCA (*left*) and RCU/C (*right*) in the pre- and post-test (normalized to the maximal value of the relevant test in each case; for standard deviations, see Table 10.5)

Table 10.5 Descriptive values of RCA and RCU in the pre- and post-test (normalized to the maximal value of the relevant test in each case)

		CG1	TG1	CG2	TG2
		Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Pre	RCA	0.07 (0.19)	0.07 (0.07)	n.t.	n.t.
	RCU	0.36 (0.14)	0.37 (0.14)	0.34 (0.15)	0.34 (0.15)
Post	RCA	0.41 (0.13)	0.52 (0.13)	n.t.	n.t.
	RCU	0.43 (0.17)	0.43 (0.17)	0.51 (0.24)	0.49 (0.21)

Notes: Significance level of all pre-post changes: $p < 0.001$
Significance level of group comparisons: TG1 vs. GC1 and TG2 vs. CG1 $p < 0.001$, TG2 vs. CG2: n.s. (see text for discussion)
n.t. (not tested): RCA was not investigated in study 2

visual inspection, these differences were taken account of in a more formal manner as covariates, see sec. "Design…" above).

Intervention Effects (Pre/Post and CG/TG Comparisons) After the intervention, both control and treatment improved for both variables in question. For RCA (TG1 vs. GC1), the RAT treatment led to a sizeable advantage compared to the control group ($p < 0.001$, $d = 0.6$[4]). For RCU/C, there is no significant difference between learning tasks addressing common conceptual difficulties with and without a representational focus (TG2 vs. CG2), but such a difference occurs when comparing to learning without addressing these difficulties at all (TG2 vs. CG1; $p < 0.001$, $d = 0.4$). In terms of the Hake gain index $g = (R_f - R_i)/(1-R_i)$, where $R_{i/f}$ are the initial and final score, respectively, relative to the maximal possible gain (Hake 1998), one has the following results: the RCA control and treatment group achieve a $g_{CG}(RCA) = 0.4$ and $g_{TG}(RCA) = 0.5$, respectively; for RCC the values are $g_{CG}(RCC) = 0.1$ and $g_{TG}(RCC) = 0.2$.

With regard to covariate influences, grades in mathematics (medium effect size) and physics (small effect size), as well as visual/spatial imagination abilities (small effect size) were found to have significant effects on the learning gain, but without a difference between the CG and the TG groups. For other subscales of cognitive ability, German language grades and gender (as well as class size for the RCC study) (in the RCC study, additionally class size) we did not find any significant influences. Moreover, there were no significant motivation differences between TG and CG neither in the pre- nor in the post test (see Hettmannsperger 2015; Scheid 2013).

Intervention Comparison Even though on a formally identically scale (from 0 to 1, by normalization to maximal test value), the absolute results for RCA and RCU/C cannot be directly compared. There are however two features which deserve attention: First, the pre-test values of RCA relative to the maximal score are very low (the test is related to specific physics content which had not been treated before according to the teaching program), pre-test values of RCU/C, again as compared to maximal score, are noticeably higher (it is the very idea of concept tests that its items can be understood even before formal teaching on the given subject it, in order to diagnose conceptual difficulties (and their possible change); see eg. Engelhardt (2009) for a methodological paper, and many applications of the FCI, see Coletta et al. (2007) and references therein). Second, there is a large difference in relative increase, RCA improves much more than RCU/C. In terms of the Hake gain index values just given, there is a factor of almost 4 (CG) and more than 2 (TG) for the difference in relative increase of RCA and RCU/C, a point to be discussed below.

10.5 Discussion

When comparing the two multiple representation based treatments aiming at either improvement of coherence (RCA) or at conceptual understanding/change to the control groups learning without such a representational focus (but otherwise comparable), we obtained the following results about possible influences of covariates and about the main effects of the intervention. On the lowest level of the multilevel analysis (measurement times/individuals), no influences of cognitive abilities related to two RFs (words, numbers), nor of German language grades and gender were found. Grades in mathematics and physics had a significant influence on learning gain (medium and small effect size, respectively), consistent with the famous statement by Ausubel (1978) about previous knowledge as essential predictor of learning. As geometrical optics is by definition related to geometry, and as a lot of mathematics teaching is about geometry in the age group of our sample, the somehow stronger influence of mathematics compared to physics is not completely implausible. Moreover, visual/spatial imagination abilities also had a significant effect on learning gains (small effect size). Again, it is not implausible that this component of cognitive abilities influences learning in an area which has a lot to do with geometric properties and constructions, while the abilities related to words and numbers have not. The two preceding covariate influences (math grades, visual/spatial abilities) are interesting points to be considered more in detail in the future, both for a better scientific understanding of MRs, and for classroom practice.

On the higher levels (groups), statistically very highly significant advantages with noticeable effect sizes concerning the interventions (TG versus CG) were found for both RCA and RCU/C ($d = 0.6$ and $d = 0.4$, respectively; $p < 0.001$ in both cases). Note, that these results were obtained with a series of control measures to ensure comparability (in particular same teacher, comparable initial situation, control for remaining differences by taking account of several covariates; see above). Moreover, on the level of classes in the RCU/C study, class size did not have an influence on the outcomes. Finally, none of the covariates discussed above showed a difference between the CG and the TG groups.

Thus, the beneficial effects of RATs found both for representational coherence and for conceptual understanding show a certain stability with regard to possible individual and classroom influence factors; see however, an important caveat discussed at the end of this section.

For RCA, there are at this time only few classroom interventions specifically targeted at improvement of coherence of multiple representations, and a medium effect on group level size in this state of research can be considered as satisfactory. The study provided also insight for further improvement of the approach and its analysis. First, a set of RATs dealt with the derivation of the magnification equation and turned to be slightly too difficult in its present form. Appropriate scaffolding (hints, intermediate steps) could lead to further improvement. Second, the intervention covered tasks referring to two different experiments (propagation of parallel light beams through a converging lens and image formation with a converging lens). With a longer intervention, additional experiments could be included within ray optics.

The analysis in this contribution is also restricted in the sense that the effects presented are based on the whole RCA instrument. Further analysis can focus on inter–item-differences to identify specific areas with conspicuously small learning gains, indicating potential learning obstacles, and the necessity of a more effective learning support (either by RATs or another approach), or on the contrary with high learning gains, potentially improving the understanding of the instructional features which make a RAT effective (the same holds in a similar way for the RCC study).

For RCC, the effect size is still acceptable, as the “persistence” of conceptual difficulties is well known: conceptual change is notoriously hard to achieve (see Schnotz 2006; Galili and Hazan 2000, for the subject matter of ray optics in particular), and classical strategies like inducing cognitive conflict by demonstration experiments do not automatically lead to success (Limòn 2001; Vosniadou 2013). The multiple representation based learning tasks turn out to be as effective as learning tasks addressing the same conceptual difficulties without a representational focus, and the effect size values come out at least at the threshold ($d = 0.4$) of noticeable real-world differences known from meta-analysis (“hinge point”, Hattie 2009). Note, that this is a result on the general level of the RCU instrument used, and we do not address conceptual change for specific conceptual difficulties here (this would require a discussion on the individual item level, which we do not present in this contribution).

On the one hand, the positive effects found are good news, as (multi-)representational reasoning requires an additional cognitive activity and thus creates additional cognitive load potentially harmful for learning. But as the results show, this is not the case for RATs, and as MR based reasoning is known to be essential also for other important objectives of science education, it is a promising state of affairs that appreciable positive effects on conceptual understanding are as well among the benefits of this instructional approach and can possibly be combined with these other objectives. On the other hand, in view of this very potential of representational reasoning for science learning in general one could have expected that it should be a more effective conceptual change strategy than addressing the same conceptual difficulties without a representational focus. This then leads to limitations and open questions of the present work, which will be addressed below.

Under another perspective, the Hake gain index complements these results of an overall learning effectiveness of the two representational learning approaches. For RCA, the TG value g = 0.5 obtained is comparable to those of the treatment groups provided by other methods of cognitive activation ("interactive engagement") in the large comparison study of Hake (1998). For RCC, however, the TG value of g = 0.2 is the one of the traditional groups studies by Hake (1998). In terms of learning gain, the RCC effects do not seem satisfactory, and this leads again to the discussion of limitations and open questions, addressed in the following section.

With respect to above results, in particular the effect sizes found, we would like to point to a limitation of the present work. The investigated samples (342 students and 12 classes at 6 schools for RCA, and 525 students and 21 classes at 10 schools for RCC, respectively) are large enough to cover a considerable range of individual, class and school conditions, and thus to justify a degree of representativeness for the given classroom setting comparable to other studies in physics education. However, this setting is largely that of the German academic track schools (see), which entails the following possible consequences: First, as existing research points to an appreciable association of academic success and working memory (Gathercole et al. 2004), and as cognitive load is one of the main problems with MRs (see Sect. 10.1.3), our finding that cognitive load does not impair the positive effects of RATs has to be checked for learner groups with lower cognitive abilities. Second, in a sample including learner groups of this kind, the variance in outcomes might be larger, while the difference of averages of CG and TG might be smaller (according to the preceding argument) than in the sample analyzed here, both leading to smaller effect sizes; in this sense, effect sizes reported here belong a priori to academic track students, and generalization to other students has do be done with a caveat, or on the basis of new data.

10.6 Conclusions and Outlook

We may conclude that representational activity tasks (RATs) discussed in this contribution can foster two kinds of educational objectives related to physics experiments:

First, representational coherence ability (RCA) which deals with correctly and fluently combining, mapping and correcting multiple representational formats essential for proper understanding of and learning from experiments (or observations), from the level of "operational" or "enactive" manipulation of the experimental devices and materials to the most abstract level of the mathematical formulation of the law of nature underlying (or investigated) in a given experiment.

Second, representation related conceptual understanding and change (RCU/C^2) which deals with a link between scientific experiments and their conceptual basis and significance, with a special focus on conceptual difficulties, and requires the learner again to reason with multiple representations at different levels of abstraction as just mentioned, such as describing observed phenomena by oral or written language in terms of appropriate concepts, or expressing experimental results by schematic diagrams or mathematical relations containing formal representations of these concepts.

The focus in the case of RCA is coherence of multiple representations, in the case of RCU/C their role for conceptual understanding. Effect sizes are of medium size for the former ($d = 0.6$), and between small to medium size for the latter ($d = 0.4$). This holds for realistic teaching conditions in regular classrooms.

With regard to classroom practice, RATs thus appear as a useful element of the physics teacher's toolkit of reasonable practical relevance. The effects for RCA are stronger than those for RCC, but we found that at least (i) there was no harmful cognitive load created by the extra requirement of the MR reasoning activities, and (ii) that even for RCC the effects are as large as for learning tasks with the same conceptual obstacles, but without MRs. This then, leads to several perspectives for future research.

Subsequent investigations could look at a combined approach, which in the same time aims at conceptual learning and other objectives of (multiple) representations for the learning of science, in particular representational coherence. Is it possible to adapt the RAT instructional design in a way, where the presence of positive learning effects and the absence of harmful cognitive load, found in isolation for RCA and RCC in the present study, will be maintained in the combined approach? Another highly relevant question is whether it is possible to improve the effects of RATs on conceptual learning, found to be smaller than desirable. In view of the persistence of conceptual obstacles/misconceptions it seems reasonable to combine RATs with other forms of cognitive activation, eg. through forms of peer/group debate (confrontation) of these obstacles (see e.g. Thorley and Treagust 1987; Zimrot and Ashkenazi 2007). Finally, a more general objective is of course to investigate RATs in other domains of physics (science) rich in MRs, such as mechanics.

We hope that the two related studies presented here, with their focus on experiments on the one hand, and coherence and conceptual significance of MRs on the other, can serve as a useful and interesting contribution for the state of the discussion as presented in this volume.

10.7 Notes

1. Many statements of this contribution are formulated with respect to physics education, but could be generalized to science education; this should be kept in mind, even when it is not explicitly stated everywhere.
2. As we have to distinguish conceptual understanding (at a given stage or time) and change (between two stages or times), we use RCU and RCC, respectively, in order to distinguish the two.
3. See the "TIMSS Encyclopedia" (Mullis et al. 2008) for background about the German school system.
4. We follow the usual convention of effect size levels as small, medium and large with $0.2 < d < 0.5$, $0.5 \leq d < 0.8$ and $0.8 \leq d$, respectively (Cohen 1988).

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