Enhancing students' intrinsic motivation for radiation physics by inquiry-based learning: A quasi-experimental study of student behaviour

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This study investigated the effect of inquiry-based learning on students' intrinsic motivation and free-choice behaviour in the context of the Dutch Ionising Radiation Practical. A crossover design was used, in which 123 students (11th grade of pre-university education) performed two radiation physics experiments with different approaches: a direct instruction experiment and a guided inquiry-based experiment. Intrinsic motivation was measured using pretest and posttest questionnaires, free-choice behaviour was assessed by counting numbers of attempted optional exercises at the end of each experiment, and exit questionnaires were used to evaluate students' preferences for either approach. Results showed that there was no significant difference in students' intrinsic motivation between the two approaches, but students' perceived competence increased significantly more in the direct instruction approach than the inquiry-based approach (Cohen's $d = -0.472$). Moreover, students tried significantly more optional exercises of the direct instruction experiments than the inquiry-based experiments. 63% of the students preferred the direct instruction approach, appreciating the clarity of the experiment, whereas 36% of the students preferred the inquiry-based approach because they experienced more autonomy. These results suggest that the inquiry-based approach of the Ionising Radiation Practical positively influences students' autonomy, but it lacks sufficient support of students' competence in order to increase their intrinsic motivation.

Keywords: Intrinsic motivation, self-determination theory, free-choice behaviour, inquiry-based learning, radiation physics education, Ionising Radiation Practical

Motivation is what gets people *moving*: working, learning, and achieving. Educational practitioners have a wide spectrum of motivating measures to their disposal, e.g. praise, bonus points, or punishments, but most of these measures affect students' *extrinsic* motivation. *Intrinsic* motivation, on the other hand, emerges from within, and is believed to be the strongest and most effective form of motivation. Intrinsically motivated students are interested, show enjoyment for the subject matter, are willing to participate in learning activities, and regulate their learning process (Ryan & Deci, 2000). In addition, intrinsic motivation is the only type of motivation being positively associated with academic achievement (Taylor et al., 2014). Hence, intrinsic motivation is the key to engage students in their learning.

In science education, however, recent research points towards serious problems regarding students' intrinsic motivation. First, students' intrinsic motivation for the science subjects generally appears to decline during their school careers, especially upon the transition from elementary to secondary school (Potvin & Hasni, 2014). Second, there is an increasing need for scientists and related professionals, but numbers of students pursuing science-related careers are dropping in several European countries (EU, 2004), and intrinsic motivation could encourage students to pursue careers related to their intrinsic interests (see e.g. Jacobs, Finken, Griffin, & Wright, 1998). Third, Dutch 15-year-old students' motivation for science is among the lowest in Europe, and it has significantly decreased over the past twelve years (OECD, 2016). Altogether, these three problems demonstrate that it is essential to increase students' intrinsic motivation for science, especially in the Netherlands.

Several teaching approaches or interventions have been proposed to enhance students' intrinsic motivation for the science subjects. Inquiry-based learning (IBL) is one of these approaches. In IBL, as opposed to direct instruction by the teacher, it is the learners themselves who ask questions, collect evidence, and use this evidence to answer their questions. Schraw, Crippen and Hartley (2006) reviewed instructional intervention strategies to promote self-regulation in science

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education, and conclude that "inquiry may increase motivation because the student takes greater ownership and shares authority" (p. 119). IBL is believed to increase the learners' autonomy by giving them ownership of their learning process, to increase their feeling of competence by letting them adapt the learning tasks to their own zone of proximal development (Vygotsky, 1978), and to increase their relatedness to others by letting them explore and investigate science subjects together. Therefore, according to self-determination theory (SDT; Ryan & Deci, 2000), IBL should have the potential to increase students' intrinsic motivation for science.

Although there is increasing evidence in favour of this mechanism of interaction between IBL and motivation, the knowledge base on this topic is still narrow. Most studies investigating IBL have focussed on the effects on learning outcomes (see Furtak, Seidel, Iverson, & Briggs, 2012) or attitudes towards science (see Savelsbergh et al., 2016), and intrinsic motivation studies have mainly been correlational instead of experimental (Mabbe, Soenens, De Muynck and Vansteenkiste, 2018). However, Nooijen (2017) conducted a small-scale quasi-experimental study and found clues for a significant improvement in intrinsic motivation by implementing inquiry-based learning in a radiation physics practical, which formed the basis for this study.

In addition to the aforementioned lacuna, many intrinsic motivation studies are surveys using self-report instruments such as questionnaires, the intrinsic motivation inventory (IMI; McAuley, Duncan, & Tammen, 1989) being most frequently used. We argue, however, that student motivation should not only be studied in terms of self-report measurements, but also in terms of observed student behaviour: increased student motivation should manifest itself in students *moving* differently, i.e. students making choices showing their interest and enjoyment. Examples of this kind of student behaviour, often called 'free-choice behaviour' (e.g. Deci, Koestner, & Ryan, 1999), include watching an extra educational video on the topic at hand, voluntarily attending a demonstration or guided tour, or working on optional enrichment assignments.

This research builds on Nooijen's work (2017) by studying differences in intrinsic motivation and associated free-choice behaviour between students engaging in inquiry-based and direct instruction learning tasks. Our research question is the following:

> What is the difference in students' intrinsic motivation and associated free-choice behaviour promoted by inquiry-based and direct instruction approaches of a secondary-school radiation physics practical?

We used a quasi-experimental approach to compare students' intrinsic motivation in terms of their self-reported interest and enjoyment and their free-choice behaviour between two versions of the Ionising Radiation Laboratory ("Ioniserende Stralen Practicum", 2018): a direct instruction ('closed') version with a ready-to-use experimental setup, step-by-step instructions and maximum guidance versus an inquiry-based ('open') version, where the same experimental setup is provided to the students, but they formulate their own research question and devise a plan to answer this question using the given setup.

Theoretical Background

Self-Determination Theory and Intrinsic Motivation

Many different definitions of the concept of motivation exist. Huitt (2011) provides a brief discussion, concluding that "motivation is an *internal state or condition* (sometimes described as a need, desire, or want) that serves to activate or energize *behavior* and give it direction" (emphasis added). This definition illustrates that motivation is 'something inside the mind' of an individual, i.e. a mental state, that directs his or her behaviour. Most conceptualisations of motivation distinguish between extrinsic and intrinsic motivation: the origin of an extrinsically motivated mental state is external of the individual, whereas the mental state associated with intrinsic motivation emerges from within the individual. For example, students who want to obtain good grades at a physics test because their parents—an external source of motivation—require them to do so are said to be externally motivated, whereas students who are motivated to perform well because they are interested in the subject and enjoy working on it are intrinsically motivated.

In their self-determination theory (SDT), Ryan and Deci (2000) further refined the spectrum of types of motivation. Figure 1 shows the continuum from amotivation (no motivation) via four types of extrinsic motivation to intrinsic motivation. Different regulatory styles are associated with different types of motivation, and the perceived loci of causality illustrate that the motivation of intrinsically motivated individuals originates from internal processes, whereas extrinsically motivated individuals attribute the source of their motivation to external affairs. However, motivation may also *appear* to be internally caused if an individual identifies with or internalises an extrinsic form of motivation. This is indicated in Figure 1 by 'identified' or 'integrated regulation': although from the individual's perspective the motivation appears intrinsic, the original source of motivation is still external, hence it is a form of extrinsic motivation.

Self-determination theory identifies three basic psychological needs, defined as "nutrients that are essential for growth, integrity, and well-being" (Ryan & Deci, 2017, p. 10). These three needs are:

1. Autonomy, i.e. "the need to self-regulate one's experiences and actions" (Ryan & Deci, 2017, p. 10).
2. Competence, i.e. "our basic need to feel effectance and

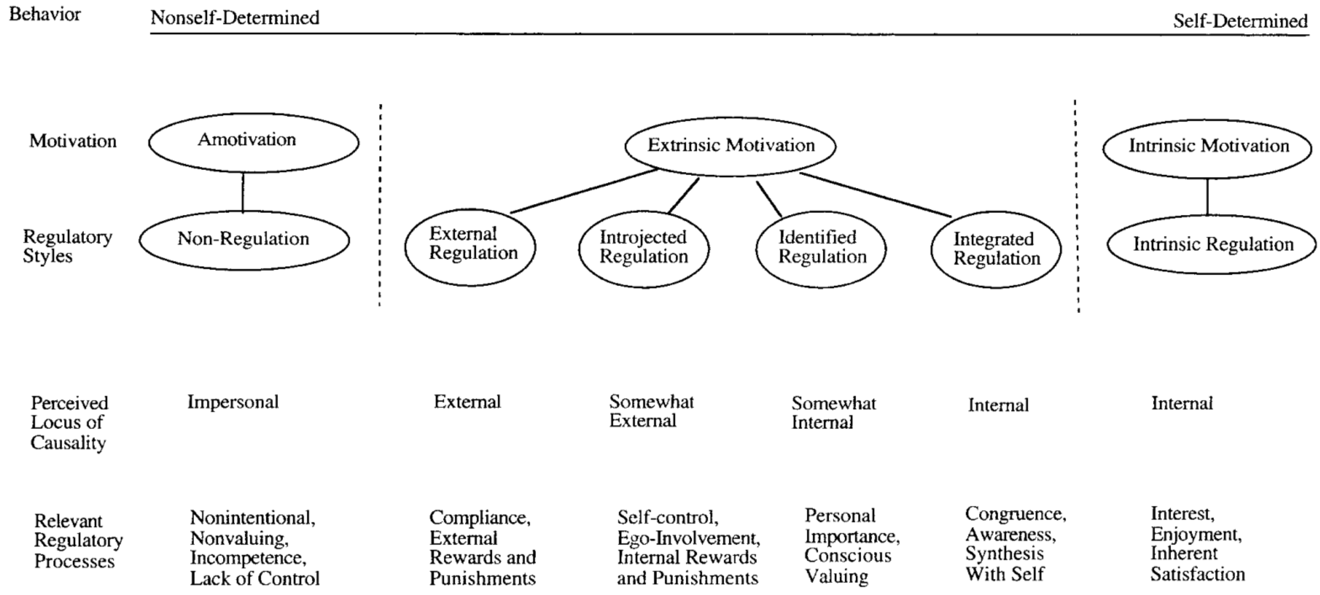

Figure 1. The Self-Determination continuum showing types of motivation with their regulatory styles, loci of causality, and corresponding processes. Reprinted from Ryan and Deci (2000).

mastery" (Ryan & Deci, 2017, p. 11). This relates closely to Vygotsky's (1978) zone of proximal development: tasks and actions should be just within reach of one's current capabilities.

3. Relatedness, i.e. "feeling socially connected" (Ryan & Deci, 2017, p. 11).

Studies have shown that these three psychological needs foster intrinsic motivation (Ryan & Deci, 2017; Vansteenkiste, Niemiec, & Soenens, 2010). However, autonomy and competence appear to be most closely related to intrinsic motivation, whereas the relation between relatedness and intrinsic motivation appears to be less direct.

Since intrinsic motivation is a robust and moderate to strong predictor of performance in almost any field (Cerasoli, Nicklin, & Ford, 2014) and it is intrinsic motivation that encourages students to pursue careers related to their intrinsic interests (see e.g. Jacobs, Finken, Griffin, & Wright, 1998), the aim of this study was to investigate inquiry-based learning as a tool to enhance the *intrinsic* motivation of students for radiation physics.

Free-choice behaviour

Measuring intrinsic motivation in terms of free-choice behaviour has not only been advocated by opponents of self-determination theory and conceptualisations of intrinsic motivation (e.g. Scott, 1975), but also by the pioneers of self-determination theory themselves. Deci, Koestner and Ryan (1999) write: "We believe that free-choice behavior is a more valid measure of intrinsic motivation" (p. 655), because free-choice behavioural measures are typically unobtrusive, which means that participants will generally be unaware of what is being measured during free-choice periods—or even unaware of the fact *that* their behaviour is being examined—whereas they will be aware that experimenters are going to see their answers on the self-report measure. However, Deci, Koestner and Ryan (1999) also acknowledge that free-choice behaviour could be influenced by non-intrinsic motives, and that it is fundamentally impossible to distinguish only in behavioural terms between intrinsically and extrinsically driven behaviour during free-choice periods (Ryan, Koestner, & Deci, 1991). Therefore, "the best way to ensure one is assessing intrinsic motivation is to measure both free-choice behavior and self-reported interest and to consider them intrinsic motivation only when they correlate within conditions or studies" (Deci, Koestner, & Ryan, 1999, p. 655).

Following this line of reasoning, we opted for triangulation of students' intrinsic motivation with both self-report and behavioural measures. We chose working on optional exercises as the free-choice student behaviour of interest, because this behaviour closely relates to regular student work and would be beneficial for student learning in the same way as regular exercises are.

Inquiry-based learning

Different definitions of inquiry-based learning (IBL) have been proposed, differing in the level of guidance offered to the learner. Chinn and Malhotra (2002) make a distinction between authentic inquiry, which is most similar to scientific inquiry by real scientists, and simple inquiry, in which one or more of the steps taken in authentic inquiry (e.g. asking questions, or designing experiments) are provided to the learner by the teacher or educational materials. Capps and Crawford (2013) constructed a matrix for assessing the extent to which inquiry is student- or teacher-initiated based on aspects of IBL identified by the National Research Council (2000): students should

1. be involved in science-oriented questions;
2. design and conduct an investigation;
3. determine what constitutes evidence and collect it;
4. use this evidence to develop an explanation;
5. connect their explanation to scientific knowledge;
6. communicate and justify their explanation;
7. use tools and techniques to gather, analyze, and interpret data;
8. use mathematics in all aspects of inquiry.

Capps and Crawford developed a four-point scale for each of these aspects, with 1 corresponding to mostly teacher-initiated and 4 corresponding to mostly student-initiated IBL. A score of 0 would be given to aspects of inquiry being absent, i.e. a score of 0 corresponds to purely direct instruction. This resulted in a matrix showing the aspects of doing inquiry and their variations, from student- to teacher-initiated, which can be found in Appendix A.

The aspects of IBL in Capps and Crawford's (2013) matrix combined with Ryan and Deci's (2000) SDT provide a possible mechanism how IBL might enhance students' intrinsic motivation towards science (see Figure 2). In student-initiated IBL, students are autonomous (A) in the questions they pose (aspect 1), the way they set up their investigation (aspect 2), how evidence should be collected (aspect 3), etc. Moreover, the ownership the students possess over their inquiry-based learning process would stimulate them to fit their learning process to their own level of competence (C), i.e. their zone of proximal development (Vygotsky, 1978). Finally, they would feel more related (R) to their peers or teachers when communicating and justifying their explanations (aspect 6) and discussing them together.

As touched upon earlier, there is no extensive body of knowledge on the relation between IBL and intrinsic motivation. A brief discussion can be found in Van Asseldonk (2016). Because the research field on the IBL–intrinsic motivation interaction is mostly unexplored terrain, the mechanism depicted in Figure 2 could be considered the hypothesis of this study: we hypothesised that the inquiry-based approach of the ISP experiments, as compared to the direct instruction approach, positively influences the three basic psychological needs from SDT, leading to a positive effect on students' intrinsic motivation and on the associated free-choice behaviour of doing optional exercises.

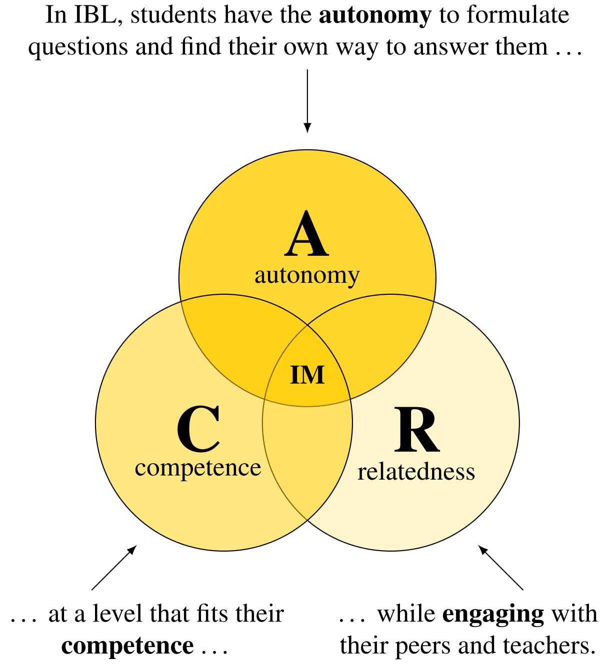

Figure 2. Hypothetical mechanism of interaction between aspects of inquiry-based learning (IBL) and intrinsic motivation (IM) in terms of the three basic psychological needs from self-determination theory (Ryan & Deci, 2000).

Methodology

We employed a quasi-experimental crossover design to study the effects of inquiry-based learning on the intrinsic motivation of upper secondary school students for radiation physics.

Context and participants

The Dutch Ionising Radiation Laboratory (ISP; "Ioniserende Stralen Practicum", 2018) provided a unique context for this study. Each year up to 20,000 upper secondary school students (grade 10 to 12 of general secondary[1] and pre-university[2] education) from schools across the Netherlands participate in the ISP to perform hands-on experiments related to ionising radiation. We decided to perform our study in the context of the ISP because of its nation-wide reach and significance, the potential sample sizes of hundreds of students, and because its practical nature facilitated implementation of inquiry-based learning.

Schools wishing to participate in the ISP can apply for a visit to the permanent lab in Utrecht, for a session organised at school by one of the three travelling labs, or for a session during the Radiation Week ("Stralende Week"). Sessions in

[1]Dutch: havo 4 en 5
[2]Dutch: vwo 4, 5 en 6

Table 1
Characteristics of the participating schools and students.

Label	Location	Size (# students)	Participants
School A	urban	1050	43 (11th grade)
School B	rural	1500	11 (11th grade)
School C	rural	1750	26 (11th grade)
School D	urban	2750	43 (11th grade)

the Radiation Week are organised in cooperation with the Central Organisation for Radioactive Waste ("Centrale Organisatie voor Radioactief Afval"; COVRA); participating schools visit COVRA for an entire day, in which students not only perform ISP experiments, but also watch a short movie about COVRA and attend a guided tour on site.

This study was performed during the Radiation Week of 2019, in which four schools participated with a total number of 123 students. Characteristics of the participating schools and students are summarised in Table 1. Several of the instruments used were piloted during school visits by the travelling labs troughout the months preceding the Radiation Week. Results of these pilots will be discussed in the Instruments section.

Study design

We used a 2 × 2 crossover design in which all participants performed two experiments with two different approaches: one inquiry-based experiment, which served as our intervention, and one direct instruction experiment, which could be considered the control. The flow diagram in Figure 3 illustrates the general design of our study. In the remainder of this thesis, inquiry-based experiments will be called 'open' experiments and denoted by ○, whereas direct instruction experiments will be called 'closed' and denoted by □.

Participants were divided into two groups in a quasi-random way, which is shown schematically in Appendix B. First, the students from schools A, C and D were asked to divide their group into two subgroups: one of these subgroups received the guided tour at COVRA before doing the ISP, whereas the other group did the ISP before receiving the tour. The students from school B all received the tour before the ISP. Then, without the students' knowledge, each subgroup was assigned to one of the two experimental groups: group 1 or group 2. Group 1 ($N = 68$) first performed an open experiment and then a closed experiment, whereas group 2 ($N = 55$) performed experiments in the reversed order. Pre- and posttest questionnaires were administered before and after each experiment, and participants were asked to fill in an exit questionnaire after completion of both experiments.

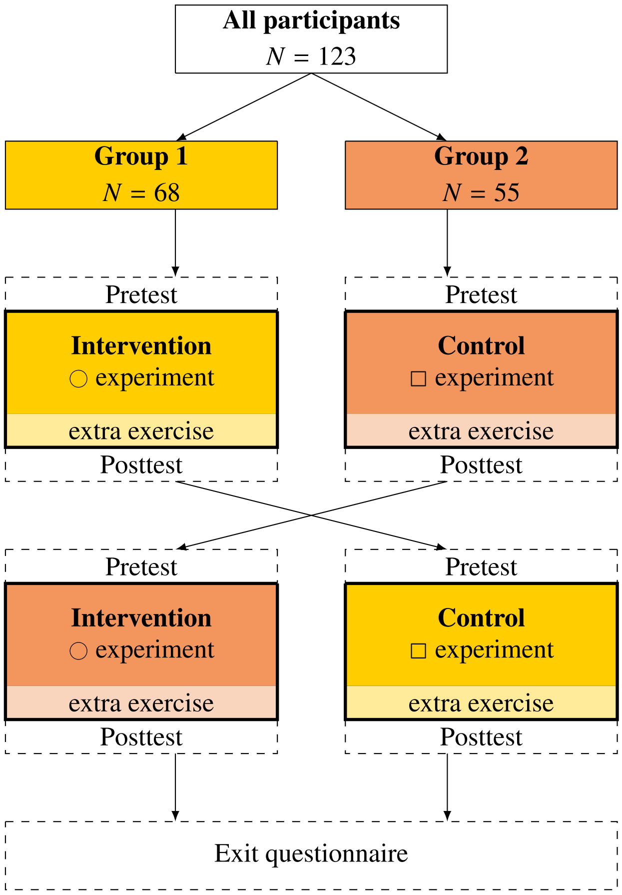

Figure 3. Flow diagram of this study.

Instruments

ISP experiments. The ISP consists of twenty different experiments; ten of these experiments can be performed either using a direct instruction (closed, □) or an inquiry-based (open, ○) approach. In both approaches the experimental set-ups are provided to the students, but the worksheets accompanying the set-ups are different. In the closed approach, students are provided with preset research questions with step-by-step instructions on how to take measurements using the set-up and how to analyse the obtained results. The open approach, on the other hand, requires the students to formulate their own research question, devise a plan to answer this question using the given setup, and execute this plan. This process is supported by guiding questions and suggestions.

For the inquiry-based approach of the experiments used in this study, Capps and Crawford's (2013) framework (see Appendix A) was employed to gauge the extent to which IBL was implemented in the ISP worksheets. Analyses by three members of the ISP staff yielded an overall average score of about 3 with good interrater reliability (Nooijen, 2017), which means that the inquiry-based approach could be categorized as ‘guided inquiry-based learning’.

Most students worked in pairs on the experiments, but if the number of students in a subgroup was odd, one group of three students was made or one student worked individually. All groups received an oral introduction with safety-related instructions by an ISP staff member and procedural instructions by the researcher prior to the experiments. Then, students could work on both experiments for 90 minutes, including pre- and posttest and exit questionnaires. As soon as a group had handed in their first experiment, they were assigned a new experiment while the other groups continued working. In case a group had finished early with both experiments, they were to wait until the end of the session.

Extra exercises. Both the open and closed approach experiments contained optional enrichment (‘extra’) exercises at the end of the worksheets. These exercises were designed to challenge students interested in the experiment to go beyond the prescribed tasks and further explore the topic, but students were not obliged to do them in order to finish their experiment. Students were explicitly informed of the optional nature of these exercises during the oral introductory instructions by the researcher.

The phrasing of the instructions was piloted during preceding ISP school visits by testing different phrasings. These were evaluated by brief student interviews about their thoughts on the extra exercises. Typical questions included: “What did you think about the extra exercises?”, “Did you think they were obligatory or not?”, and “Why did you decide (not) to do the extra exercises?”. The pilots not only revealed that explicit instructions about the extra exercises were necessary to avoid students thinking that they were required to do the extra exercises anyway, but also that the instructions should not bear too much emphasis in order to ensure the unobtrusive character of the free-choice behavioural measures. Therefore, we decided to use the following oral instructions:

> “At the end of the worksheet you will find an extra exercise. This exercise is optional: if you think it’s interesting, you can do the exercise, but it’s not obligatory.”

In addition, each experimental set-up was provided with an information booklet. The cover of this booklet contained ten frequently asked questions, with one the questions being the following:

> **Am I required to do the extra exercises?**
> You can decide for yourself: if you think it’s interesting, you can do the exercise, but it’s not obligatory.

ISP staff and attending teachers were provided with similar instructions beforehand and were asked to reply in similar ways to student questions along these lines.

During the pilot interviews some students replied that, despite the wording of the questions, they still felt uncertain on whether the optional exercises would be graded or not. Although the ISP sessions during the Radiation Week were not graded at all, which was also communicated with teaching staff and mentioned explicitly during the oral instructions, we still decided to put the following frequently asked question on the information booklet:

> **Will the extra exercises count towards my grade?**
> The extra exercises are never graded for any purpose whatsoever.

Pre- and posttest questionnaires. Students’ self-reported intrinsic motivation for radiation physics was measured before and after each experiment using pre- and posttest questionnaires. The Intrinsic Motivation Inventory (IMI; McAuley, Duncan, & Tammen, 1989) was used as a basis for the questionnaires. The IMI consists of seven subscales, each measuring a different aspect related to intrinsic motivation (e.g. the perceived choice subscale can be used to assess autonomy). In view of the limited time available between the sessions and the fact that the students were asked to fill in the questionnaire four times, we constructed short pre- and posttest questionnaires from IMI items belonging to two subscales: the Interest/Enjoyment subscale, which is considered to be the self-report measure of intrinsic motivation, and the Perceived Competence subscale. We included the latter subscale because our pilot studies and similar research by Nikandros (2019) suggested that there could be major differences between the two approaches in terms of the quality of guidance and experienced difficulty of the experiments.

The constructed pre- and posttest questionnaires can be found in Appendix D. Both questionnaires consisted of 8 statements to be answered on a 5-point Likert scale (*strongly disagree* to *strongly agree*). Table 2 contains all pretest items per subscale and corresponding posttest item numbers. Pretest item 2 and corresponding posttest item 1 were excluded from analysis, because these items consistently lowered reliability of the Interest/Enjoyment subscale. Exclusion of this item increased reliability (Cronbach’s α) of the Interest/Enjoyment subscale from between .790 and .840 to between .838 and .879, which indicated that the reliability of this subscale was good. The reliability (Cronbach’s α) of the Perceived Competence subscale was between .735 and .805, which is considered to be acceptable. Since there were no items with a consistent lowering effect on the reliability, we decided to continue our analysis with all four items of the Perceived Competence subscale.

Exit questionnaire. Students’ preferences for either approach of the experiments and the reasons behind their preferences were assessed using exit questionnaires (see Appendix D), which were filled in after completion of both

Table 2
Pretest items per subscale and corresponding posttest item numbers.

Pretest	English item	Posttest
Interest/Enjoyment (Cronbach's α between .838 and .879)		
1	I think this experiment will be fun to do.	8
2*	I think this experiment will not always hold my attention.	1*
4	I think this experiment is going to be boring.	2
6	I think this experiment is going to be interesting.	5
Perceived Competence (Cronbach's α between .735 and .805)		
3	I think this experiment is going to take a big effort.	7
5	I think I will do pretty well at this experiment compared to other students.	6
7	I think I am going to be pretty good at this experiment.	4
8	I feel sufficiently competent to do this experiment.	3

*Pretest item 2 and posttest item 1 were excluded from analysis.

experiments. Students were first asked to give each of the experimental approaches a rating between 1 and 10 and to explain how they came to these ratings. Then, students were asked to choose between the two approaches for a hypothetical third experiment. This experiment would take exactly 45 minutes regardless of the chosen approach or their work pace. Students were again asked to explain their choice.

The questions from the exit questionnaire enabled us to directly compare the open and the closed approaches in terms of student ratings and their self-reported behaviour in future situations. In addition, students' explanations allowed for conjectures about the reasons behind the obtained quantitative results.

Data analysis

Students' free-choice behaviour was assessed by comparing the numbers of students that did an attempt at the extra exercises. Here, any indication of students making an effort to read or solve the extra exercises (e.g. numbers or formulae written down, repetition of some words from the exercise, a single question mark, etc.) counted as 'an attempt at doing the extra exercises'. A McNemar's test (McNemar, 1947) was used to test for significant differences in numbers of attempts between the two approaches.

2×2 mixed analyses of covariance (ANCOVAs) were used to assess students' self-reported intrinsic motivation and perceived competence. Independent variables were experimental approach ($\bigcirc$ versus $\square$; within-subjects factor) and experimental order (first $\bigcirc$ then $\square$ versus first $\square$ then $\bigcirc$; between-subjects factor). The dependent variable was either posttest Interest/Enjoyment score or posttest Perceived Competence score. The differences in pretest scores were incorporated as a covariate[3], as suggested by Mehrotra (2014). Effect sizes were determined in two different ways: partial eta-squared values (η_p^2) were retrieved directly from the ANCOVAs, and Cohen's d was calculated for significant effects using the following equation (Cohen, 1992):

$$d = \frac{(M_{\bigcirc}^{\text{post}} - M_{\bigcirc}^{\text{pre}}) - (M_{\square}^{\text{post}} - M_{\square}^{\text{pre}})}{SD_{\text{pooled,pre}}}$$

where M_v^t is the mean total score for approach v ($v = \bigcirc, \square$) on pretest (t = pre) or posttest (t = post) and $SD_{\text{pooled,pre}}$ is the pooled standard deviation of the pretest scores of both approaches.

Students' preferences for the two approaches were compared by visual inspection and fitting of the rating histograms. A Wilcoxon signed-rank test (Wilcoxon, 1945) was used to test for statistical differences between the two approaches. These data were supported qualitatively by students' written explanations for their ratings and preferences.

[3]This can be understood as follows. Let M_v^t be the mean total Interest/Enjoyment score for approach v ($v = \bigcirc, \square$) on pretest (t = pre) or posttest (t = post). For the closed approach, the increase in intrinsic motivation $\Delta_{\text{pre}\to\text{post}} M_{\square}$ from pre- to posttest is given by $\Delta_{\text{pre}\to\text{post}} M_{\square} = M_{\square}^{\text{post}} - M_{\square}^{\text{pre}}$. The same holds for the open approach: $\Delta_{\text{pre}\to\text{post}} M_{\bigcirc} = M_{\bigcirc}^{\text{post}} - M_{\bigcirc}^{\text{pre}}$. Since we are interested in the effect of the open approach with respect to the closed approach, the overall quantity of interest is the *difference* between the intrinsic motivation increases caused by both approaches, $\Delta_{\square\to\bigcirc}(\Delta_{\text{pre}\to\text{post}} M)$. This quantity is given by

$$\begin{aligned}\Delta_{\square\to\bigcirc}(\Delta_{\text{pre}\to\text{post}} M) &= \Delta_{\text{pre}\to\text{post}} M_{\bigcirc} - \Delta_{\text{pre}\to\text{post}} M_{\square} \\ &= M_{\bigcirc}^{\text{post}} - M_{\bigcirc}^{\text{pre}} - (M_{\square}^{\text{post}} - M_{\square}^{\text{pre}}).\end{aligned}$$

This equation can be rearranged to yield

$$\Delta_{\square\to\bigcirc}(\Delta_{\text{pre}\to\text{post}} M) = M_{\bigcirc}^{\text{post}} - M_{\square}^{\text{post}} - (M_{\bigcirc}^{\text{pre}} - M_{\square}^{\text{pre}}),$$

which implies that the difference in pretest scores, $M_{\bigcirc}^{\text{pre}} - M_{\square}^{\text{pre}}$, can be considered a covariate for the posttest difference $M_{\bigcirc}^{\text{post}} - M_{\square}^{\text{post}}$. The same reasoning applies to the Perceived Competence scores.

Results

Most experiments were performed by pairs of two students. There were 3 groups consisting of three students working together, and 2 students worked individually. The 123 participating students finished 59 experiments in total. Two pairs from group 1 (see Figure 3) only finished their first experiment because they ran out of time while working on their second experiment; these pairs were excluded from the analysis. One student answered 'not applicable' to pretest item 5 and posttest item 6 (see Table 2), so this student was excluded only from the analysis of the Perceived Competence subscale.

Extra exercises

Table 3 summarises the numbers of student pairs who did or did not make an attempt at the extra exercises for the open and the closed experiments. 45 of 59 pairs (76%) did not make an attempt for both of the experiments ('○ no □ no'), whereas only 5 pairs (8%) made an attempt at both extra exercises ('○ yes □ yes'). However, the interesting groups are the pairs who showed different behaviour for the two experimental approaches: 8 pairs did the extra exercise for their closed experiment but not for their open experiment ('○ no □ yes'), whereas 1 pair did the open experiment extra exercise, but not the closed one ('○ yes □ no'). An exact McNemar's test (McNemar, 1947) determined that the difference between these two groups was statistically significant, $p = .039$. Hence, students' free-choice behaviour of doing extra exercises was promoted more by the closed experiments than by the open experiments.

Interest and Enjoyment

Table 4 shows descriptive statistics and reliabilities for the Interest and Enjoyment subscale. The Interest and Enjoyment scores met three of four assumptions in order to compare mean scores between the two experimental approaches using a 2×2 mixed analysis of covariance (ANCOVA) with experiment order as between-subjects factor. A discussion of these assumptions can be found in Appendix E.

Table 3
Numbers of student pairs who did ('yes') or did not ('no') make an attempt at the extra exercises for the open and the closed experiments.

		Closed (□)		
		Yes	No	Total
Open (○)	Yes	5	1	6
	No	8	45	53
	Total	13	46	59

Table 4
Descriptive statistics and reliabilities (Cronbach's α) for the Interest and Enjoyment subscale.

Approach	Test	N	M	SD	α
Open	pre	119	3.45	0.79	.858
	post	119	3.39	0.89	.879
Closed	pre	119	3.57	0.76	.838
	post	119	3.37	0.86	.853

Mean pre- and posttest scores are visually displayed in Figure 4. Although both approaches seemed to result in decreasing intrinsic motivation with the decrease being slightly greater for the closed approach than for the open approach, the ANCOVA revealed that this difference was in fact nonsignificant, $F(1, 116) = 0.054$, $p = .817$, $\eta_p^2 = .000$. In addition, there is no significant main effect of experiment order, $F(1, 116) = 0.000$, $p = .984$, $\eta_p^2 = .000$, and the interaction between approach and order was also nonsignificant, $F(1, 116) = 3.416$, $p = .067$, $\eta_p^2 = .029$, which implied that there is no difference in Interest and Enjoyment between the first and the second experiment performed by the students.

In conclusion, there were no differences in students' self-reported intrinsic motivation between open and closed experiments. However, as explained above, we did find a significant difference in the numbers of extra exercise attempts between the two approaches. The seemingly contradictory nature of these results supports the assertion that the results of free-choice behaviour need to be triangulated by other means, and raises several methodological questions. These questions will be addressed in the Discussion section.

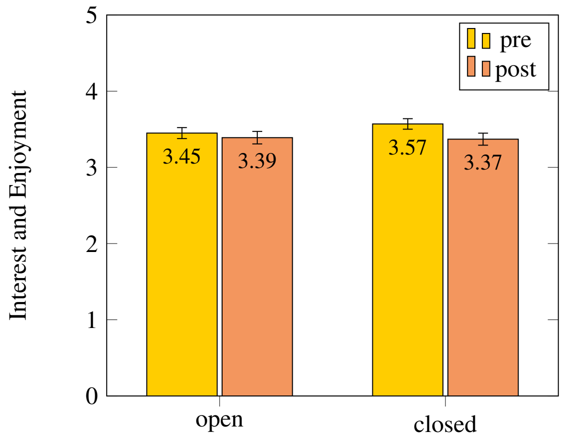

Figure 4. Mean pre- and posttest scores on the Interest and Enjoyment subscale (3 items on 5-point Likert scales) for the open and the closed experiments. Error bars represent standard errors of the means.

Perceived Competence

The Perceived Competence descriptive statistics are shown in Table 5, and mean pre- and posttest scores are visualised in Figure 5. Students' Perceived Competence increased for both approaches, but the increase was larger for the closed approach than for the open approach. An ANCOVA analoguous to the one for Interest and Enjoyment (meeting all four ANCOVA assumptions; see Appendix E) indicated that this difference between the two experimental approaches was statistically significant, $F(1, 115) = 20.426$, $p < .001$, $\eta^2_{\mathrm{p}} = .151$, Cohen's $d = -0.472$. There was no significant main effect of experiment order, $F(1, 115) = 0.372$, $p = .543$, $\eta^2_{\mathrm{p}} = .003$, and the interaction between experimental approach and order was also nonsignificant, $F(1, 115) = 3.235$, $p = .075$, $\eta^2_{\mathrm{p}} = .027$. Thus, students' perceived competence increased for both experiments, but was supported more by the closed approach than for the open approach.

Overall student ratings and preferences

Histograms of overall student ratings for the closed and the open experiments are shown in Figure 6. The closed experiment rating distribution could be fitted well by a normal distribution with mean rating $M = 7.2$ and standard deviation $SD = 0.85$. The open experiment rating distribution, however, showed a different pattern. The peculiar distribution of answers prompted us to try a fit with two normal distributions: one with $M = 7.0$ and $SD = 1.09$ and one with $M' = 4.1$ and $SD' = 0.69$. This approach leads us to believe

Table 5
Descriptive statistics and reliabilities (Cronbach's α) for the Perceived Competence subscale.

Approach	Test	N	M	SD	α
Open	pre	118	3.08	0.70	.805
	post	118	3.31	0.81	.791
Closed	pre	118	3.19	0.57	.762
	post	118	3.71	0.61	.735

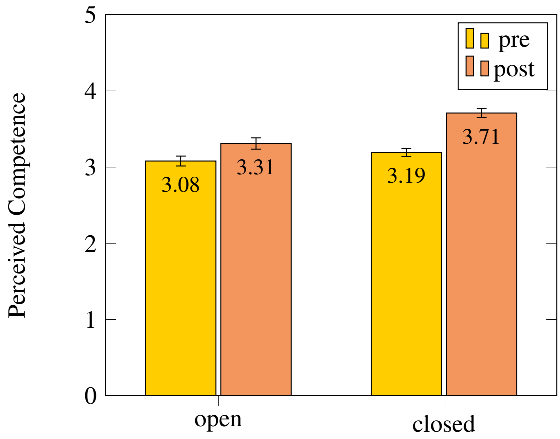

Figure 5. Mean pre- and posttest scores on the Perceived Competence subscale (4 items on 5-point Likert scales) for the open and the closed experiments. Error bars represent standard errors of the means.

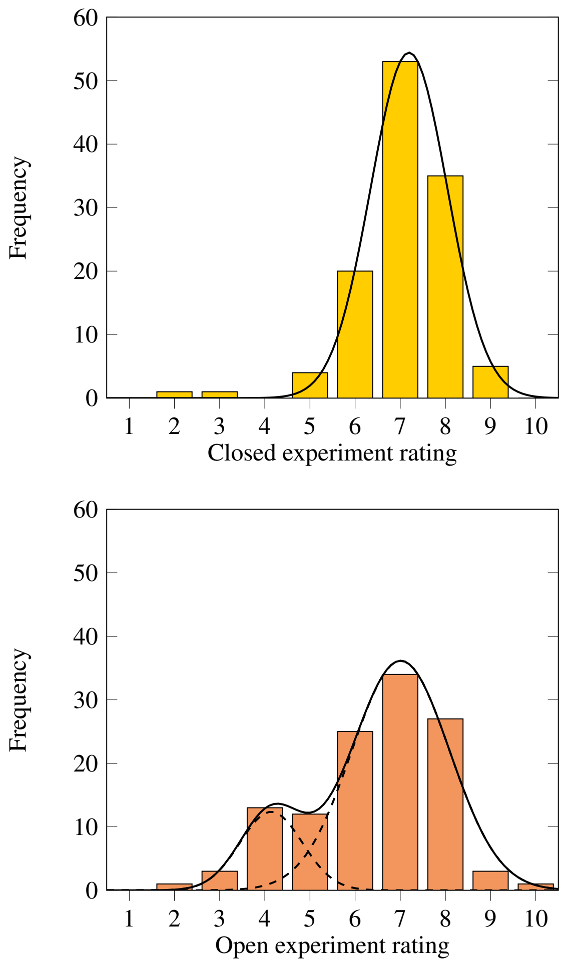

Figure 6. Histograms for closed and open experiment ratings. Fitted functions are

$$f(x) = A\exp\left(-\frac{(x-M)^2}{2 \cdot SD^2}\right),$$

i.e. a normal distribution with $M = 7.2$ and $SD = 0.85$ for the closed experiment ratings, and

$$f(x) = A\exp\left(-\frac{(x-M)^2}{2 \cdot SD^2}\right) + A'\exp\left(-\frac{(x-M')^2}{2 \cdot SD'^2}\right),$$

i.e. a double normal distribution (see dashed lines for individual distributions) with $M = 7.0$, $SD = 1.09$, $M' = 4.1$ and $SD' = 0.69$ for the open experiment ratings.

Table 6
Exemplary explanations given by the students for choosing one of the two approaches. The question answered was: "Suppose that you have to do another ISP experiment which will take you exactly 45 minutes. It does not matter whether or not you are able to finish the experiment. If you were allowed to choose between an open and a closed experiment, which would you choose and why?"

I would choose a **closed** experiment, because...	I would choose an **open** experiment, because...
"It says exactly what you should do, which makes it easier."	"You can decide for yourself what you're going to do."
"Takes less time."	"You'll have more freedom and understand what you're doing."
"You can be sure that you're doing it right."	"More challenging."
"You'll learn more."	"You'll learn more."

that there were two subgroups of students: one group that appreciated the open experiments approximately equally well as the closed experiments, and one group that liked the open experiments much less than the closed experiments. Overall, the open experiments were rated significantly lower than the closed experiments as indicated by a Wilcoxon signed-rank test (Wilcoxon, 1945), $T = 3755.5$, $p = .001$, $r = .219$.

When asked to choose between the two experimental approaches for a hypothetical third experiment, 75 students (63%) chose the closed approach, whereas 43 students (36%) chose the open approach. One student did not respond to this question. A representative sample of the spectrum of explanations given by the students for choosing one of the two approaches is listed in Table 6. Responses for the open approach align well with the psychological need of autonomy of self-determination theory: students reported more freedom to decide for themselves what they were going to do, and they often connected this to the open experiment being more interesting. From the closed approach responses, however, we can deduce that the support of students' perceived competence of the open experiments could be improved: students mentioning "You can be sure that you're doing it right" as a positive aspect of the closed approach were essentially referring to a lack of feedback from the open approach. This is supported well by the quantitative results on students' self-reported Perceived Competence.

Interestingly, some students replied that they would learn more from a closed experiment, whereas others replied they would learn more from an open experiment. These observations could be connected to the rating distributions for both approaches, which showed that there were two subgroups of students with different appreciations of the open approach. Students who disliked the open approach could have learned more from their closed experiment—possibly because they perceived their competence as insufficient for the open experiment—whereas students who liked the open approach may have learned more from their open experiment.

Discussion

The aim of this study was to investigate the effect of inquiry-based learning on students' intrinsic motivation and associated free-choice behaviour. The research question was:

> What is the difference in students' intrinsic motivation and associated free-choice behaviour promoted by inquiry-based and direct instruction approaches of a secondary-school radiation physics practical?

A quasi-experimental crossover design with 123 participating upper secondary school students was employed to answer this question.

Results showed that there was no significant difference in students' self-reported intrinsic motivation, as assessed by pre- and posttest Interest and Enjoyment questionnaires, between the inquiry-based and direct instruction approaches of the experiments. The associated free-choice behaviour of doing extra exercises related to these experiments, however, was promoted significantly more by the direct instruction experiments than the inquiry-based experiments. One possible explanation for these seemingly contradictory results is that there may be methodological shortcomings in the use of extra exercises as a free-choice measure for intrinsic motivation. For example, the design of the extra exercises—or even the very fact that students were given an explicit exercise—might align better with the direct instruction experiments, where students were already doing closed-form exercises, than with the inquiry-based experiments, where students were free to pursue their own track through the experiment.

In addition, as pointed out by Deci, Koestner and Ryan (1999) and mentioned in the Theoretical background section, free-choice behaviour could also be influenced by extrinsic sources of motivation. As discussed in the Methodology section, during our pilot studies we conducted brief student interviews to assess the validity of doing the extra questions as a measure of intrinsic motivation. There, students' answers to questions on their motivation for (not) doing extra exercises often contained elements indicative of extrinsic motivation, e.g. "Our teacher always requires us to do everything on the worksheets." or "Although the extra exercises do not officially count towards our grades, maybe we can still get a bonus point by doing them." We tried to minimise these extrinsic influences by adapting our instruction protocols and communicating with teaching staff prior to the ISP sessions, but we were not able to validate our approach during the Radiation Week by additional student interviews.

Furthermore, students' free-choice behaviour is not only influenced by their feelings of interest and enjoyment, but also by the context in which the free-choice behaviour is provoked. In our study, students had to choose between (i) working on an extra exercise and (ii) not working on an extra exercise. However, the second option amounted to students continuing with their second experiment or being able to do anything they liked instead of working on the extra exercises. Although this situation could be considered most similar to an actual classroom situation, providing a proper, equivalent alternative to doing the extra exercises could potentially solve several of the methodological concerns raised. A recent example of such a free-choice study is Mabbe et al. (2018), who let children choose between two puzzles of different difficulty.

In addition to these methodological concerns, another possible explanation for the results on intrinsic motivation could be found by connecting these results with students' self-reported Perceived Competence, which we found to increase significantly more for the direct instruction experiments than for the inquiry-based experiments. This suggests that the inquiry-based experiments provide students with insufficient support compared to the direct instruction experiments, which could well be a reason for fewer extra exercises being done for the inquiry-based experiments. This explanation is supported by the student ratings of both approaches and the explanations given for their preferences: several mention that the direct instruction approach gives them more feedback, so that they know whether they are on the right track. The importance of sufficient quantitative and qualitative guidance in inquiry-based learning for learning outcomes has been demonstrated by previous research (see e.g. Kirschner, Sweller, & Clark, 2006; Lazonder & Hermsen, 2016) and our results point in a similar direction for intrinsic motivation.

Limitations

The findings of this study are subject to several methodological limitations. Limitations related to the free-choice behaviour measures were already discussed in the previous section. In addition, assignment of participants to the two experimental orders was done quasi-randomly as discussed in the Methodology section. However, we employed the benefits of a repeated-measures crossover design, where all participants undergo both the intervention and the control. Hence, possible bias introduced by quasi-random participant assignment would mostly affect the comparison between experimental orders, but was minimised for the comparison between approaches.

Furthermore, the context of the Radiation Week during which this study took place is rather unique. This needs to be taken into account when proposing a generalisation of the results to a broader range of learning tasks or environments. Several factors are in play here. First, two of the four participating schools intentionally applied for the special programme offered at COVRA during the Radiation Week, and one of these schools allowed students to choose whether or not they were going to take part in the programme. This implies that the sample of 123 participants will most likely not be representative of a broader population of Dutch upper secondary-school students. Second, additional features of the programme besides the ISP, i.e. the COVRA video, the guided tour and the 'visitor experience' as a whole, could have influenced our results and are not representative of a regular school setting.

Finally, the experiments of the Ionising Radiation Practical have unique features as well, which are also hardly generalisable to regular school experiments. Students are allowed to use radioactive materials for their experiments, which students themselves indicate as being thrilling or exciting in itself. In addition, the measuring equipment used in the experiments (e.g. Geiger–Müller counters, Lorentz coils, etc.) is relatively advanced compared to the usual school equipment.

Implications

Altogether, we have found that the inquiry-based approach implemented in the Ionising Radiation Practical positively influences students' autonomy, but it lacks sufficient support of students' competence in order to increase their intrinsic motivation. Thus, we can conlude that, in order for an inquiry-based learning practical to support intrinsic motivation and associated free-choice behaviour, two necessary (but not sufficient) conditions should be satisfied: (i) the inquiry-based approach should provide the students with sufficient guidance and competence support, for example by giving students feedback on intermediate steps of their inquiry, and (ii) contextual factors such as time constraints and alternatives should be controlled in order to promote the desired free-choice behaviour.

Although these findings do not directly confirm our hypothesised mechanism of interaction between inquiry-based learning and intrinsic motivation as discussed in the Theoretical background section, they put forward valuable implications both for future research and for educational practice. Our results direct future research towards investigating the amount (quantitative) and type (qualitative) of feedback needed to support students' perceived competence and to reinforce the potential of the inquiry-based approach to promote students' intrinsic motivation. Given the significant increase of students' perceived competence for the direct instruction approach, an explorative case study of students working on direct instruction experiments could shed light on the elements needed for the inquiry-based approach. An experimental study of the effect of multiple inquiry-based ISP versions with varying levels or modalities of feedback on students' intrinsic motivation would be an interesting extension to this study, while a design study could be useful to improve the current inquiry-based experiments.

It would also be interesting to explore students' attitudes towards the inquiry-based experiments of the Ionising Radiation Practical. Some students expressed the need to know whether they are on the right track during the experiment, but students doing inquiry-based experiments are essentially free to decide what 'the right track' is for their experiment, so their thoughts on how the inquiry-based experiments 'should' be done might hinder them in fully engaging with the inquiry-based approach.

The limitations discussed in previous sections could also be good starting points for future research. A methodological study on measuring students' free-choice behaviour using the extra exercises would be essential to validate the behavioural findings of this study, whereafter this study could be replicated on a larger scale with the regular Ionising Radiation Practical outside the Radiation Week. In addition, a similar research approach could be taken for investigating inquiry-based experiments on different physics topics, e.g. classical mechanics or electricity, which would allow for better generalisation of the results.

This study has demonstrated that inquiry-based learning per se is not sufficient to promote students' intrinsic motivation; not only autonomy but also support of competence is indispensable. Thus, in order to get students *moving*, it is important not only that they have space to move, but also that they have a suitable sense of direction in which they can move.

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Appendix A
Matrix for evaluation of inquiry-based learning tasks

Table A1 shows Capps and Crawford's (2013) matrix of the aspects of doing inquiry and their variations, from student- to teacher-iniated.

Table A1
Matrix of the aspects of doing inquiry and their variations, from student- to teacher-iniated. Reprinted from Capps and Crawford (2013).

Doing inquiry (D)	4 pts	3 pts	2 pts	1 pt
D1—Involved in sci-oriented question (EF1, A1)	Student poses a question	Student guided in posing their own question	Student selects among questions, poses new questions	Student engages in question provided by teacher, materials, or other source
D2—Design an conduct investigation (A2)	Student designs and conducts investigation	Student guided in designing and conducting an investigation	Student selects from possible investigative designs	Student given an investigative plan to conduct
D3—Priority to evidence in resp. to a problem: observe, describe, record, graph (EF2)	Student determines what constitutes evidence and collects it	Student directed to collect certain data	Student given data and asked to analyze	Student given data and told how to analyze
D4—Uses evidence to develop an explanation (EF3, A4)	Student formulates explanation after summarizing evidence	Student guided in process of formulating explanations from evidence	Student given possible ways to use evidence to formulate explanation	Student provided with evidence
D5—Connects explanation to scientific knowledge: does evidence support explanation? Evaluate explain in light of alt exp., account for anomalies (EF4, A5, A6)	Student determines how evidence supports explanation or independently examines other resources or explanations	Student guided in determining how evidence supports explanation or guided to other resources or alt explanations	Student selects from possible evidence supporting explanation or given resources or possible alt explanations	Student told how evidence supports explanation or told about alternative explanations
D6—Communicates and justifies (EF5, A7)	Student forms reasonable and logical argument to communicate explanation	Student guided in development of communication	Student selects from possible ways to communicate explanation	Student given steps for how to communicate explanation
D7—Use of tools and techniques to gather, analyze, and interpret data (A3)	Student determines tools and techniques needed to conduct the investigation	Student guided in determining the tools and techniques needed	Students select from tools and techniques needed	Student given tools and techniques needed
D8—Use of mathematics in all aspects of inquiry (A8)	Student uses math skills to answer a scientific question	Student guided in using math skills to answer a scientific question	Student given math problems related to a scientific question	Math was used
	⟵ Student initiated	Who initiated aspects of inquiry?		⟶ Teacher initiated

Appendix B

Participant division

Division of participants from the four participating schools over two experimental orders is schematically displayed in Figure B1.

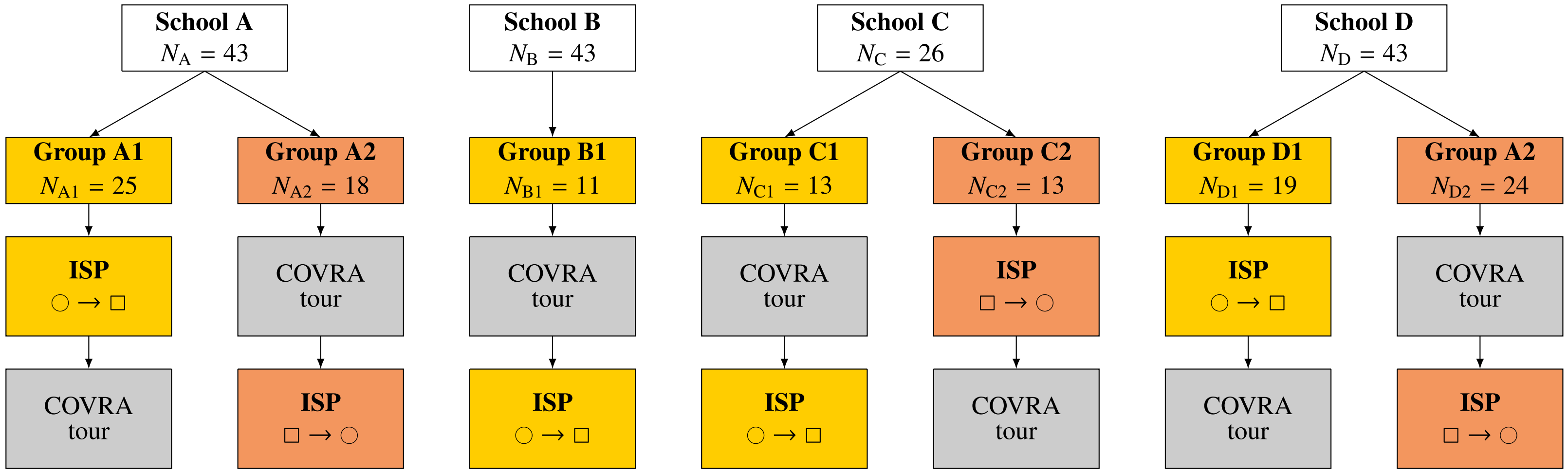

Figure B1. Division of participants over two experimental conditions.

Appendix C
ISP worksheets

Typical ISP worksheets are set up as displayed in Figure C1, Figure C2 and Figure C3.

Universiteit Utrecht

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Ioniserende Stralen Practicum

Experiment 12
Absorptie van γ-straling door lood

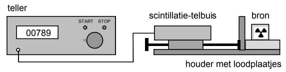
Naam: ……………………………………………..

Doel

- Meten van het verband tussen de dikte van het absorberende materiaal en de intensiteit van de doorgelaten straling.
- Bepalen van de halveringsdikte van lood voor de γ-straling uit een bron met kobalt-60.

Opstelling

De opstelling bestaat uit een scintillatie-telbuis met pulsenteller en een bron met kobalt-60 (^{60}Co). Tussen de bron en de telbuis zijn loodplaatjes van verschillende dikte in de opstelling te klemmen.



Lees eerst de inleiding over absorptie van γ-straling door materialen bij Experiment 12 in het informatieboekje *Experimenten met radioactieve bronnen en röntgenstraling*.

Metingen

1 Om de achtergrondstraling te meten, plaats de radioactieve bron op een afstand van minstens 1 m van de scintillatie-telbuis.
Meet drie keer de intensiteit I_b van de achtergrondstraling (in pulsen per 10 s) en noteer de meetresultaten in de tabel hieronder. Bereken hieruit de gemiddelde intensiteit $I_{b,gem}$ van de achtergrondstraling (in pulsen per 10 s). Noteer het resultaat in de tabel hieronder.

I_b (pulsen/10s)				$I_{b,gem}$ (pulsen/10s)	

2 Haal het deksel van de container en zet de container met de bron in de houder. Klem het loden absorptieplaatje met een dikte *d* van 0,30 cm tussen de bron en de telbuis. Meet drie keer de intensiteit *I* van de doorgelaten straling (in pulsen per 10 s) en noteer de meetresultaten in de tabel hieronder. Bereken hieruit de gemiddelde intensiteit I_{gem} (in pulsen per 10 s) en **corrigeer direct voor de achtergrondstraling**: $I_{cor} = I_{gem} - I_{b,gem}$. Noteer de resultaten in de tabel hieronder.

3 Herhaal deze metingen en berekeningen met de loodplaatjes van verschillende dikte *d* uit de tabel hieronder. Voor de met een * gemarkeerde diktes moet je twee loodplaatjes combineren.

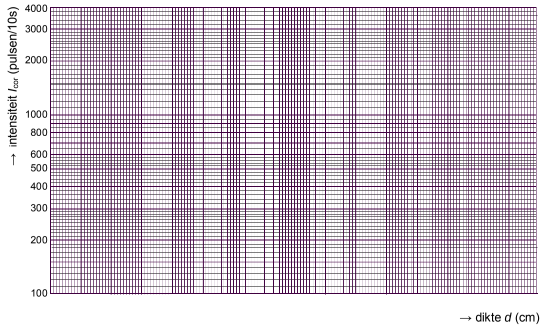
d (cm)	*I* (pulsen/10 s)			I_{cor}
0,3				
0,5				
0,6				
1,0				
1,2				

d (cm)	*I* (pulsen/10 s)			I_{cor}
* 1,5				
* 1,7				
* 1,8				
* 2,2				

4 Haal de container met bron na het uitvoeren van de metingen uit de opstelling, doe het deksel er op en zet de container op ruwweg 1 m afstand.

Uitwerking

1 Maak een grafiek van je meetresultaten op het enkellogaritmisch grafiekpapier op dit werkblad. Zie het infoboekje (bij Enkellogaritmisch grafiekpapier) voor de redenen om enkellogaritmisch grafiekpapier te gebruiken.



2 De halveringsdikte $d_{1/2}$ van een materiaal is de dikte van de laag die je van dit materiaal nodig hebt om de intensiteit van de invallende γ-straling te halveren. Bepaal uit de bij opdracht 1 getekende grafiek de halveringsdikte van lood voor de door ^{60}Co uitgezonden γ-straling.
Halveringsdikte lood: $d_{1/2}$ = ……..cm

3 Zal een even dikke laag van een materiaal met een kleinere dichtheid meer of minder γ-straling doorlaten? Vergelijk bijvoorbeeld water en lood.

………

………

4 De halveringsdikte blijkt omgekeerd evenredig te zijn met de dichtheid van het absorberend materiaal. Dat betekent: een materiaal met een tweemaal zo grote dichtheid heeft een tweemaal zo kleine halveringsdikte.
Bereken de halveringsdikte van water. Gebruik daarbij de volgende gegevens: de dichtheid van lood is 11,3 g/cm^3 en die van water is 1,0 g/cm^3. De halveringsdikte van lood heb je in opdracht 2 bepaald.
Halveringsdikte water: $d_{1/2}$ = ……… cm

5 Voor het afschermen van een γ-bron wordt vaak lood gebruikt. Een voorbeeld. Een γ-bron met een activiteit van 370 MBq geeft op 20 cm afstand in een bepaalde tijdsduur een equivalente dosis van 24 mSv. Men wil deze bron zodanig afschermen dat de equivalente dosis nog maar 1% daarvan is. Dus: 0,24 mSv.
Hoeveel halveringsdikten zijn hiervoor dan minstens nodig? En als voor het afschermen lood wordt gebruikt, hoe dik moet die afscherming dan minstens zijn?
Aantal halveringsdikten: ………
Dikte afscherming met lood: *d* = ……… cm

Extra vraag Een loodschort bevat een laagje van ongeveer 3 mm lood ter bescherming tegen straling. Waarom is een loodschort bij gammastraling met een energie van meer dan 2,0 MeV niet zinvol?
Aanwijzing: Gebruik eventueel tabel 28f van BINAS.

………

………

ISP – 2017

Figure C1. Closed approach worksheet of experiment 12.

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Ioniserende Stralen Practicum

Experiment 12

Absorptie van γ-straling door lood

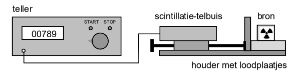
Lees eerst de inleiding over absorptie van γ-straling door materialen bij Experiment 12 in het informatieboekje *Experimenten met radioactieve bronnen en röntgenstraling*.

Doel

- Meten van het verband tussen de dikte van het absorberende materiaal en de intensiteit van de doorgelaten straling.
- Bepalen van de halveringsdikte van lood voor de γ-straling uit een bron met kobalt-60.

Meetopstelling

De opstelling bestaat uit een scintillatie-telbuis met pulsenteller en een bron met kobalt-60 (^{60}Co). De pulsenteller is in te stellen op een automatische meettijd van 10 s of op 'continu'. In dat laatste geval telt de teller na het starten door tot op de stopknop gedrukt wordt. Voor het bepalen van de meettijd is dan een stopwatch nodig.
Tussen de bron en de telbuis zijn loodplaatjes van verschillende dikte in de opstelling te klemmen. De dikte van het absorberende lood is verder nog te variëren door plaatjes van verschillende dikte te combineren.



Met deze meetopstelling is de intensiteit *I* van de doorgelaten γ-straling (in pulsen per tijdseenheid) te meten als functie van de dikte *d* van het absorberende materiaal.
De bron zendt γ-straling uit. Deze straling kan de metingen (bijvoorbeeld bij het meten van de achtergrondstraling) verstoren. Zet de bron daarom (als deze niet in gebruik is) op een afstand van ruwweg 1 m van de opstelling.

Onderzoeksvraag

- Formuleer een onderzoeksvraag die past bij het doel en de meetopstelling van dit experiment.

Hypothese

- Stel een beargumenteerde hypothese op over het verband tussen de intensiteit *I* van de doorgelaten γ-straling en de dikte *d* van het absorberende materiaal.
- Geef deze hypothese ook in de vorm van een schets van het verband tussen deze grootheden in een *I*,*d*-diagram.

Werkplan

- Maak een werkplan voor het experimenteel onderzoek met de gegeven meetopstelling.
- Geef in dat werkplan aan welke grootheden je op welke manier gaat variëren en meten om het wel of niet juist zijn van de opgestelde hypothese te kunnen controleren.
- Geef aan hoe je de metingen gaat corrigeren voor de achtergrondstraling.
- Maak alvast een (lege) tabel voor het noteren van de meetresultaten.
- Geef in het werkplan ook aan of het uitvoeren van het experiment een bijdrage levert aan de stralingsbelasting tijdens het practicum, en zo ja: hoe je er dan voor zorgt dat die stralingsbelasting zo laag mogelijk blijft.
- Bespreek je onderzoeksvraag, de opgestelde hypothese en het bijbehorende werkplan met je docent of de TOA.
- Stel de onderzoeksvraag, de hypothese en/of het werkplan zo nodig bij.

Onderzoek

- Voer het experimenteel onderzoek uit volgens je werkplan. Zorg bij die uitvoering voor voldoende stralingsbescherming.

z.o.z.

Verwerking

- Verwerk de meetresultaten om de opgestelde hypothese te controleren en de onderzoeksvraag te beantwoorden. In het kader hieronder staan enkele aanwijzingen voor de verwerking.

Aanwijzingen
- Geef de meetresultaten in de vorm van een diagram.

> Bepaal uit het diagram van de metingen de halveringsdikte $d_{1/2}$ van lood voor de γ-straling van ^{60}Co.
- In het informatieboekje staat informatie over het zo nauwkeurig mogelijk bepalen van grootheden uit een grafiek op enkellogaritmisch grafiekpapier.

> Vergelijk de nauwkeurigheid van het bepalen van de halveringsdikte $d_{1/2}$ van lood uit je meetresultaten in een grafiek op normaal en op enkellogaritmisch grafiekpapier.
- Met de gevonden halveringsdikte van lood is ook de halveringsdikte van andere materialen te bepalen. De halveringsdikte $d_{1/2}$ blijkt namelijk omgekeerd evenredig te zijn met de dichtheid ρ van het absorberend materiaal. Dat betekent: een materiaal met een tweemaal zo grote dichtheid heeft een tweemaal zo kleine halveringsdikte.

> Bereken de halveringsdikte van aluminium en van water met behulp van de gevonden halveringsdikte van lood.

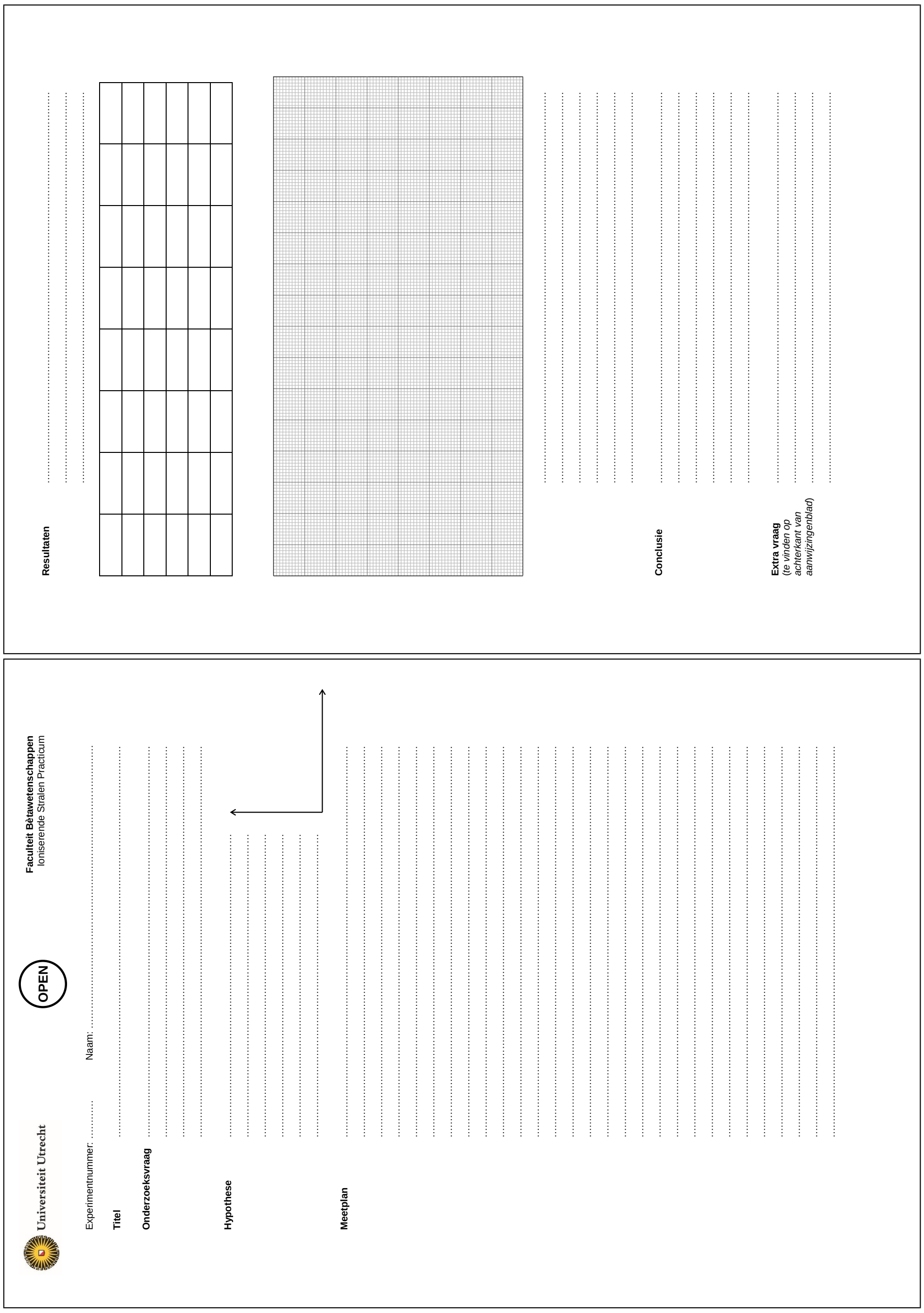
Extra vraag
Een loodschort bevat een laagje van ongeveer 3 mm lood ter bescherming tegen straling. Waarom is een loodschort bij gammastraling met een energie van meer dan 2,0 MeV niet zinvol? Aanwijzing: gebruik tabel 28f van Binas.

Verslag

- Schrijf een verslag van dit onderzoek in de vorm van een *meetrapport*. In dat meetrapport staan je *onderzoeksvraag*, de opgestelde *hypothesen*, de (verwerkte) *meetresultaten* en de daaruit getrokken *conclusies* over het al dan niet juist zijn van die hypothesen.

ISP – 2018_OV

Figure C2. Open approach suggestion sheet of experiment 12.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Experimentnummer: .... Naam: ....

Titel

Onderzoeksvraag

Hypothese

Meetplan

Resultaten

Conclusie

Extra vraag
(te vinden op achterkant van aanwijzingenblad)

Figure C3. Open approach worksheet.

Appendix D
Questionnaires

Pre- and posttest questionnaires are shown in Figure D1. The exit questionnaire is shown in Figure D2.

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Vul deze enquête in VOOR dit experiment!

Geef voor de volgende stellingen zo goed mogelijk aan in hoeverre ze voor jou van toepassing zijn op **het experiment dat je nu gaat doen**. Omcirkel slechts één antwoord. Foute antwoorden kunnen worden doorgestreept.

Stelling	**Helemaal niet mee eens**	**Een beetje oneens**	**Neutraal**	**Een beetje eens**	**Helemaal mee eens**
Dit experiment lijkt me erg leuk om te doen.	1	2	3	4	5
Ik denk dat ik tijdens dit experiment mijn aandacht er niet altijd bij kan houden.	1	2	3	4	5
Ik denk veel moeite te gaan hebben met dit experiment.	1	2	3	4	5
Dit experiment lijkt me erg saai.	1	2	3	4	5
Ik denk dat ik in vergelijking met andere leerlingen dit experiment erg goed zal doen.	1	2	3	4	5
Dit experiment lijkt me erg interessant.	1	2	3	4	5
Ik denk dat ik erg goed zal zijn in dit experiment.	1	2	3	4	5
Ik voel mij vaardig genoeg om dit experiment te gaan doen.	1	2	3	4	5

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Vul deze enquête in NA dit experiment!

Geef voor de volgende stellingen zo goed mogelijk aan in hoeverre ze voor jou van toepassing zijn op **het experiment dat je zojuist gedaan hebt**. Omcirkel slechts één antwoord. Foute antwoorden kunnen worden doorgestreept.

Stelling	**Helemaal niet mee eens**	**Een beetje oneens**	**Neutraal**	**Een beetje eens**	**Helemaal mee eens**
Tijdens dit experiment kon ik mijn aandacht er niet altijd bijhouden.	1	2	3	4	5
Ik vond dit experiment erg saai.	1	2	3	4	5
Ik voelde mij vaardig genoeg om dit experiment te doen.	1	2	3	4	5
Ik was erg goed in dit experiment.	1	2	3	4	5
Ik vond dit experiment erg interessant.	1	2	3	4	5
Ik denk dat ik dit experiment in vergelijking met andere leerlingen erg goed heb gedaan.	1	2	3	4	5
Ik had veel moeite met dit experiment.	1	2	3	4	5
Ik vond dit experiment erg leuk om te doen.	1	2	3	4	5

Figure D1. Pre- and posttest questionnaires.

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Vul deze enquête in als je klaar bent met TWEE experimenten!

Je hebt nu één open experiment en één gesloten experiment gedaan. Geef ieder van deze experimenten een rapportcijfer en leg kort uit hoe je tot dat cijfer gekomen bent.

GESL OTEN

Ik geef het **GESLOTEN EXPERIMENT** het rapportcijfer

1 2 3 4 5 6 7 8 9 10

omdat:

OPEN

Ik geef het **OPEN EXPERIMENT** het rapportcijfer

1 2 3 4 5 6 7 8 9 10

omdat:

Stel, je moet nóg een ISP-experiment doen waaraan je precies 45 minuten gaat werken. Het doet er niet toe of je het af krijgt of niet. Als je zou mogen kiezen tussen een open en een gesloten experiment, welke zou je dan kiezen en waarom?

Ik zou kiezen voor een **OPEN** / **GESLOTEN** experiment,
omdat:

Heel erg bedankt voor je medewerking aan mijn onderzoek! ☺

Figure D2. Exit questionnaires.

Appendix E
Assumptions of ANCOVA

The pre- and posttest scores should meet four assumptions in order to compare mean scores between the two experimental approaches using a 2×2 mixed analysis of covariance (ANCOVA). These four assumptions are:

1. The posttest scores should approximately be normally distributed.
2. The variances of the posttest scores should be equal for both experiment orders.
3. The covariate, i.e. the pretest scores, should be independent of the experimental approach and the order.
4. There should be homogeneity of regression slopes.

The first two assumptions generally apply to all analyses of variance (ANOVAs), but the third and the fourth assumption arise when including a covariate.

Interest and Enjoyment

Interest and Enjoyment posttest scores were approximately normally distributed as assessed by visual inspection of the histograms and quantile–quantile plots in Figure E1(a)–(d), so the first assumption was met.

Levene's test indicated that the variances of the Interest and Enjoyment posttest scores between the two order groups were equal for both the open approach, $F(1, 117) = 0.229$, $p = .633$, and the closed approach, $F(1, 117) = 0.712$, $p = .401$. Therefore, the second assumption was met as well.

A 2×2 mixed analysis of variance (ANOVA) showed that there is a significant main effect of the experimental approach, $F(1, 117) = 3.934$, $p = .050$, $\eta_p^2 = .033$, no significant main effect of experiment order, $F(1, 117) = 0.443$, $p = .507$, $\eta_p^2 = .004$, and a significant interaction between approach and order, $F(1, 117) = 9.845$, $p = .002$, $\eta_p^2 = .078$, on the Interest and Enjoyment pretest scores. The interaction can be interpreted as follows: students' pre-experimental Interest and Enjoyment for the first experiment they perform is significantly greater than for their second experiment. Although this violates the third assumption, i.e. independence of the covariate, we decided to continue using ANCOVA as our analysis model (see e.g. Grace-Martin, n.d.).

The interaction between the Interest and Enjoyment pretest difference scores and the experimental approach in the ANCOVA (see p. 8) was not significant, $F(1, 116) = .678$, $p = .412$, $\eta_p^2 = .006$, so the fourth assumption of homogeneity of regressions slopes was met.

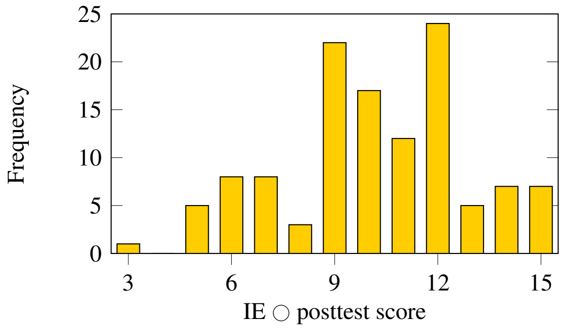
Perceived Competence

Perceived Competence posttest scores were approximately normally distributed as assessed by visual inspection of the histograms and quantile–quantile plots in Figure E1(e)–(h), so the first assumption was met.

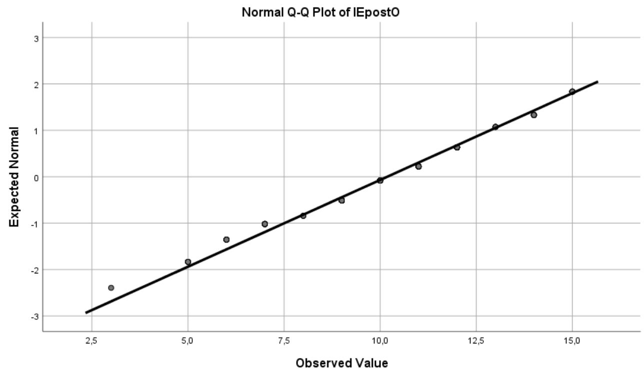
Levene's test indicated that the variances of the Perceived Competence posttest scores between the two order groups were equal for both the open approach, $F(1, 116) = 0.018$, $p = .892$, and the closed approach, $F(1, 116) = 0.767$, $p = .383$. Therefore, the second assumption was met as well.

A 2×2 mixed analysis of variance (ANOVA) showed that there is neither a significant main effect of the experimental approach, $F(1, 116) = 2.515$, $p = .115$, $\eta_p^2 = .021$, nor of experiment order, $F(1, 116) = 2.578$, $p = .111$, $\eta_p^2 = .022$, but there is a significant interaction between approach and order, $F(1, 116) = 4.157$, $p = .044$, $\eta_p^2 = .035$, on the Perceived Competence pretest scores. Interpretation of the interaction is opposite to that of the Interest and Enjoyment scores: although students' pre-experimental Interest and Enjoyment significantly decreases when going from their first to their second experiment, their initial Perceived Competence significantly increases. Since both main effects are nonsignificant, the third assumption was met as well.

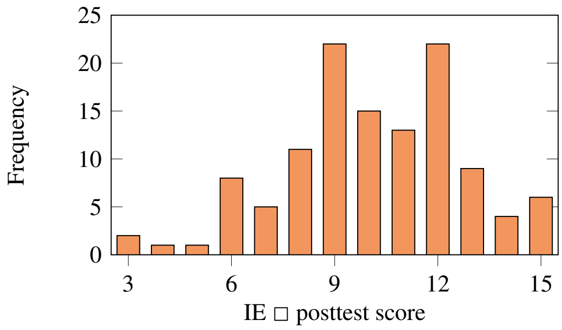
The interaction between the Perceived Competence pretest difference scores and the experimental approach in the ANCOVA (see p. 9) was not significant, $F(1, 115) = 2.841$, $p = .095$, $\eta_p^2 = .024$, so the fourth assumption of homogeneity of regressions slopes was met.



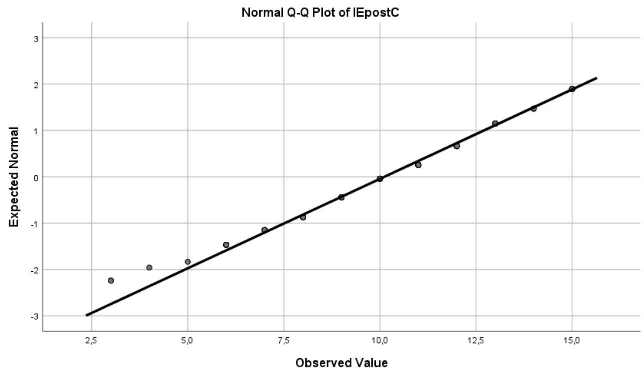
(a) Histogram of IE ○ posttest scores



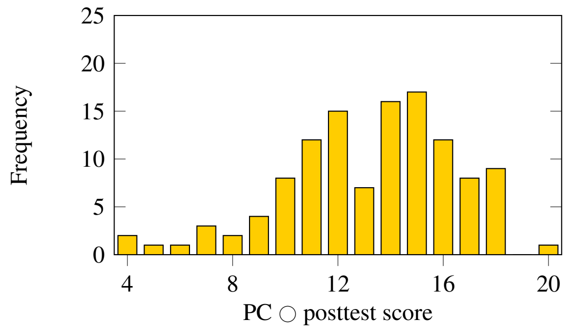
(b) Q–Q plot of IE ○ posttest scores



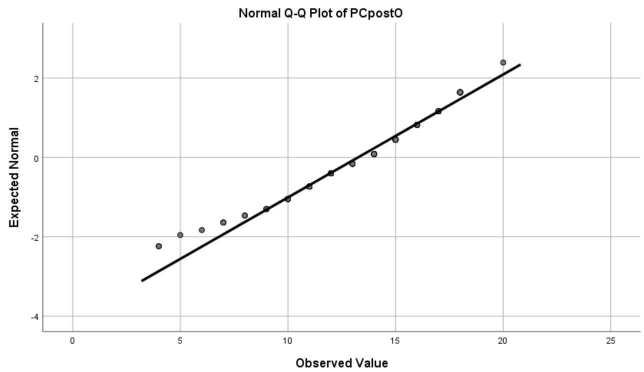
(c) Histogram of IE □ posttest scores



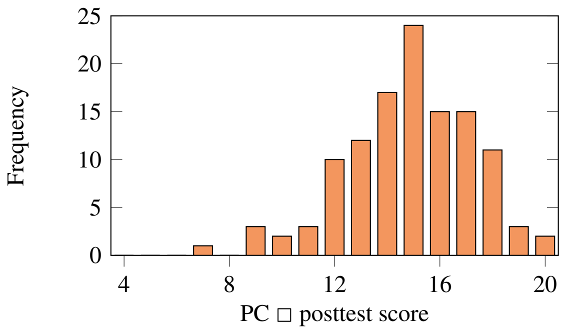
(d) Q–Q plot of IE □ posttest scores



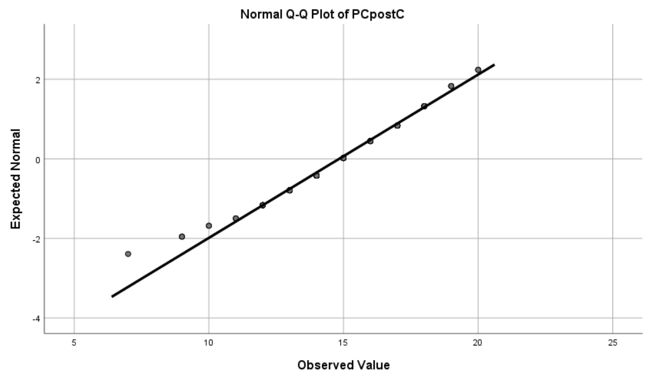
(e) Histogram of PC ○ posttest scores



(f) Q–Q plot of PC ○ posttest scores



(g) Histogram of PC □ posttest scores



(h) Q–Q plot of PC □ posttest scores

Figure E1. Histograms and quantile–quantile (Q–Q) plots of Interest and Enjoyment (IE) and Perceived Competence (PC) posttest scores for the open (○) and the closed (□) approach.