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Fostering Secondary School Science Students' Intrinsic Motivation by Inquiry-based Learning

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Abstract

Background Intrinsic motivation plays a unique mediating role in student academic performance. An inquiry-based learning (IBL) physics practical is studied in terms of effects on secondary school students' intrinsic motivation towards performing science practicals.
Results After performing IBL experiments on ionizing radiation, 38 secondary school physics students were interviewed and expressed their need for support in two main areas: the inquiry process and non-salient tasks, i.e., operating the equipment. The IBL experiments were revised accordingly, providing scaffolding through revised worksheets and videos on the use of the equipment. Subsequently, a quasi-experiment was carried out. One experimental group received both a revised worksheet and a video ($N=88$), the other only received the worksheet ($N=67$). Students performing the same practical on the basis of a step-by-step instruction sheet were used as a control group ($N=87$). Five subscales of the intrinsic motivation inventory were used as a pre- and post-test for all three groups. Results show significant gains in the Interest/Enjoyment as well as Effort/Importance subscales favouring both IBL groups. With an instructional video, all five subscales show a significant increase as compared to the control group.
Conclusions The results point to the advantages of using an IBL approach for practicals, provided appropriate scaffolding is used in terms of equipment operation and inquiry process.

Keywords Inquiry-based learning · Self-determination theory · Intrinsic motivation · Science education · Secondary school practical

Introduction

In the humanistic tradition, as exemplified by the works of, e.g., Maslow and Rogers (Maslow & Rogers, 1979), all humans exhibit a natural tendency to explore and learn. The purely intrinsic drive to engage in these activities is often referred to as intrinsic motivation. The concept of intrinsic motivation was introduced about one century ago (e.g., Woodworth, 1918) as an explanation for people engaging in activities that are

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inherently fun, interesting, and generally their own reward, rather than a means to an end. This intrinsic drive is not clearly recognized within behaviourist or cognitivist view of human actions, which essentially assume that there is always some external driving force or ulterior motive behind human behaviour (Carton, 1996; Eccles & Wigfield, 2020; Skinner, 1965; Wigfield, 1994). Intrinsic motivation (referred to as IM from now on) has been the subject of considerable academic interest since the second half of the twentieth century and especially in the twenty-first century, since it is a central concept within self-determination theory (SDT), a leading theory on human motivation and well-being (e.g., Plant & Ryan, 1985; Ryan & Deci, 2000, 2008, 2017; Vallerand, 2000). In self-determination theory, IM has its place on one extreme end of an empirical motivational continuum, ranging from purely impersonal amotivation across several forms of extrinsic motivation to intrinsic motivation (e.g., Vansteenkiste et al., 2006).

Given the humanistic assumption that humans are intrinsically motivated to learn and explore, it is not surprising that IM has been regularly recognized as playing a central role in education (Grolnick & Ryan, 1987; Ryan & Deci, 2017; Taylor et al., 2014). IM has been shown to be a robust predictor of both student well-being and academic success in a range of fields, including Science, Technology, Engineering, and Mathematics (STEM) education (Cerasoli et al., 2014; Potvin & Hasni, 2014; Ryan & Deci, 2017; Taylor et al., 2014; Vansteenkiste et al., 2009). However, primary and secondary school students are showing a pronounced deterioration of their intrinsic drive for their school work (e,g, Gallup Student Poll, 2016), especially in STEM subjects (OECD, 2017, 2019). This deterioration has been linked to the use within education of extrinsic types of motivation, e.g., rewards and punishments mainly in the form of grades and rankings (Pulfrey et al., 2011; Ryan & Deci, 1999). Accepted practices, e.g., the use of grading and ranking, may thus eventually be detrimental to one of education's main aims, i.e., student learning (Vansteenkiste et al., 2009).

Self-determination Theory (SDT from now on), however, provides educators with tools to support IM in general and for school in particular in one of its sub-theories, Basic Psychological Need Theory (Ryan & Deci, 2017; Vansteenkiste et al., 2020). Basic Psychological Need Theory states that each human has basic psychological (as opposed to physiological) needs: the need for (1) autonomy, associated with volition and willingness, (2) competence, associated with mastery and effectiveness, and (3) relatedness, associated with connectedness to others. Following Basic Psychological Need Theory (BPNT from now on), support of these needs results in motivation becoming more internal (or: autonomous) and would consequently foster IM. Frustration of these needs leads to more controlled forms of motivation and has been shown to be largely detrimental to IM (Ryan, 1999; Vansteenkiste et al., 2004).

In the quest of educators to support more autonomous forms of motivation and, more explicitly, of IM, social constructivist ideas (e.g., Kuhn, 1979; Vygotsky, 1978) have been used to advocate interactive, student-initiated pedagogy. A well-known form is inquiry-based learning or IBL, in which students are actively engaging in a more or less authentic research cycle. IBL has therefore been advocated for STEM education by many scholars (Capps & Crawford, 2013; Edelson et al., 1999; Furtak et al., 2012; Lazonder & Harmsen, 2016; Pedaste et al., 2015; Schraw et al., 2006). IBL in STEM can take many forms, from open inquiry requiring full student autonomy to more teacher-directed forms as well as intermediate forms which can be referred to as guided IBL (Capps & Crawford, 2013; Lazonder & Harmsen, 2016). The fully student-directed, open inquiry variant of IBL has attracted some negative attention as well, mainly focussing on possible working memory overload for the students (Kirschner et al., 2006; Sweller et al., 2007). However, IBL has been shown to generally, although not universally, have a favourable effect on student learning (Furtak et al., 2012).

IBL appears to be an good candidate for the support of basic psychological needs (BPN): students are asking their own questions (autonomy), can address those at their level of experience (competence) and usually perform the activity in groups (relatedness). However, the open character of IBL pedagogy with its emphasis on student autonomy leaves open the possibility to frustrate the need for competence, since students may feel overwhelmed by the myriad options that are facing them during IBL assignments.

Contrary to a wealth of literature on IBL in general, there is a relative dearth in studies on the influence of IBL on IM (e.g., Espinoza, 2020). IBL has been reported to be beneficial for the experience of "flow" in students in Grade 5–9 (Borovay et al., 2019) and adding a touch of art to the IBL work in STEM-related subjects work demonstrated a stable rise in intrinsic motivation (Conradty & Bogner, 2019), but we have been unable to find a peer-reviewed comparative study on the effect of an IBL approach on IM. The present study aims to start filling that knowledge gap by investigating ways in which an IBL version of a physics practical influences the IM of secondary students compared to a more conventional, direct instruction variant of the same practical.

The research question is:

To what extent is secondary students' intrinsic motivation for a physics practical fostered by guided inquiry-based learning?

The question will be answered by a combination of a design study and a quasi-experimental comparative study.

Theoretical Background

The main concepts related to this study are briefly addressed in this section.

Direct Instruction (DI)

Since the early, seminal paper by Engelmann and Carnine (1982), which presents the first full theory of instruction per se -so without the prefix 'direct'- this cognitivist form of instruction has received much scholarly attention and has found its way to many teachers' manuals (e.g., Kinder & Carnine, 1991; Ziegler & Stern, 2016). Direct instruction relies on the concept of limiting the load on the students' working memory (e.g., Kirschner et al., 2006) and is strongly teacher-directed, with an emphasis on preconceptions, prior knowledge, face-to-face classroom instruction, practice, repetition, and reflection.

Practicals in secondary school science are usually performed in small groups and thus do not fit the general picture of a teacher-directed, direct instruction lesson. Therefore, in the present study, direct instruction (DI from now on) in the narrow case of a practical will be taken literally as a situation where students find themselves performing practical science work on the basis of direct, step-by-step worksheet instructions that lead them through the equipment operation and subsequent analysis from start to finish, leaving virtually no room for initiative. The teacher introduces the experiments and answers any questions that arise during the practical.

Inquiry-based Learning (IBL)

IBL is based in constructivist learning theories which assume that learning is a collaborative process that requires students to engage in constructing and co-constructing knowledge (L. Vygotsky, 1978; L. S. Vygotsky, 1987). Ideally, students experience a sense of authenticity while learning and they find themselves in the so-called zone of proximal development, defined as "the distance between what children can do by themselves and the next learning that they can be helped to achieve with competent assistance" (Raymond, 2014, p.176).

IBL in STEM classes aims to emulate the basic steps of an authentic scientific research cycle and make that experience available to students. During IBL science assignments, students are asked to wonder, predict or hypothesise, design an experiment, carry out the experiment, analyse the results, draw conclusions, and reflect on their work and on new questions (Harlen, 2013; Pedaste et al., 2015). A much-cited report by the National Research Council (Council, 2000) proposed eight essential elements of IBL in science classes. During IBL in science classes, 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, analyse, and interpret data;
(8) use mathematics in all aspects of inquiry.(Capps & Crawford, 2013, p. 500).

Capps and Crawford (2013) translated the National Research Council's eight characteristics into a framework in which each characteristic is placed in a four-level rubric, ranging from fully student-directed to fully teacher-directed. For example, regarding characteristic 3 above, "fully-student directed" (level 4) means that students determine what constitutes evidence and then proceed to collect it. On the other hand, "fully teacher-directed" (level 1) means that the teacher tells students what constitutes evidence and tells them how to collect it or provides it for them. The intermediate level 3 in the rubric includes substantial teacher guidance and is referred to as "guided IBL" or GIBL (Capps & Crawford, 2013; Council, 2000).

Guided IBL is not completely teacher-directed but does, obviously, still require some teacher assistance, or scaffolding, during the process. A well-known framework for IBL scaffolding, proposed by Quintana et al. (2004), focuses on seven main categories:

(1) Representations and language;
(2) Domain-specific semantics;
(3) Different ways of looking at data;
(4) Process management;
(5) Expert guidance on scientific practices;
(6) Handling of routine, non-salient tasks;
(7) Reflection (Quintana et al., 2004, p. 369).

This scaffolding framework is used in this study to design a support structure for secondary school students' practical work in physics education with IBL.

Basic Psychological Need Theory (BPNT)

The general motivational spectrum within SDT, ranging from amotivation through external regulation, introjected regulation, identified regulation, integrated regulation to intrinsic motivation, is well-documented (e.g., Ryan & Deci, 2017) and will not be repeated here, since this study exclusively deals with the most autonomous form of motivation, IM. The mechanism responsible for fostering or thwarting of IM is based on the support or frustration of basic psychological needs (BPN) in a process called internalization (Aelterman et al., 2019; Ryan & Deci, 2017; Vansteenkiste et al., 2020).

These needs are described below.

'Autonomy refers to the experience of volition and willingness. When satisfied, one experiences a sense of integrity as when one's actions, thoughts, and feelings are self-endorsed and authentic. When frustrated, one experiences a sense of pressure and often conflict, such as feeling pushed in an unwanted direction.' (Vansteenkiste et al., 2020, p.3).

Within IBL, students can easily be afforded autonomy (Lazonder & Harmsen, 2016). In all forms of IBL, students are confronted with open elements in the assignment, elements that they must themselves find solution directions for. Absence of any student autonomy precludes the label "inquiry-based". IBL can thus be expected to support the basic psychological need (BPN) of autonomy.

'Competence concerns the experience of effectiveness and mastery. It becomes satisfied as one capably engages in activities and experiences opportunities for using and extending skills and expertise. When frustrated, one experiences a sense of ineffectiveness or even failure and helplessness. (Vansteenkiste et al., 2020, p.3). In education in general, the support of competence is crucial (Ryan & Deci, 2017), since the understanding, digestion, and application of content is central to the educational process. Especially in situations where the teacher is not in complete control, such as in IBL, capably engaging in educational activities requires scaffolding by the teacher (Quintana et al., 2004) and, often, working together with peer students who may or may not be more knowledgeable in the specific field. Supporting the BPN of competence is not self-evident within IBL and guidance is essential (Lazonder & Harmsen, 2016). This guidance needs to be properly designed to not to be too rigid and thus detrimental to the BPN of autonomy. The above-mentioned scaffolding framework for IBL can be used to design support that is adequate without being too restrictive.

'Relatedness denotes the experience of warmth, bonding, and care, and is satisfied by connecting to and feeling significant to others. Relatedness frustration can come with a sense of social alienation, exclusion, and loneliness.' (Vansteenkiste et al., 2020, p3). IBL in science classes is usually performed by groups of students (Pedaste et al., 2015), thus fostering interrelatedness, accountability, and interdependence. Since the IBL process is open and multi-faceted, students can adopt different roles, based on their preference or experience, thus fostering this interdependence.

On the basis of BPNT we can formulate a hypothesis for the case of a physics practical:

An IBL physics practical that is designed to support the students in an adequate, but not restrictive, way, will support the basic psychological needs of students and, consequently, foster their IM.

Methods

The main research question is quantitative and will be answered by a quasi-experimental comparative design. However, the design of the actual intervention needs to be addressed first and this requires a brief description of pilot experiments that have been carried out. Figure 1 gives an overview of the general design of the study.

Context: the Ionizing Radiation Practical

Ionizing radiation, or radioactivity in its more familiar connotation, is a subject that is part of the upper secondary school physics curricula in many countries, mainly because of its relevance to such important societal issues as nuclear energy and the medical applications of ionizing radiation (e.g., Eijkelhof, 1986; Lijnse et al., 1990; Linet et al., 2021; Rego & Peralta, 2006). The so-called Ionizing Radiation Practical (IRP) provides a set of 21 experiments ranging from half-life measurement and Bragg reflection to radiation penetration of materials and X-ray applications (*Ioniserende Stralen Practicum | English information*, (n.d.) for upper secondary school students (Grades 10–12) in the Netherlands. Schools can either choose to have their students perform the experiments on the campus of a large, urban university in the centre of the Netherlands or at their school (using a dedicated mobile set up). In both cases, the experiments are supervised by specially trained university staff. The project has about 20,000 secondary school students participating each year.

Since working with radioactive materials requires safety precautions, the experiments were originally set up in a highly directive, step-by-step fashion, with each stage of the experiment, data analysis, and the use of the equipment spelled out in a detailed worksheet with virtually no room for student initiative. As discussed above, this version will be referred to as the DI variant in this study. However, in the past decade, more open variants of several of the same experiments have been designed and implemented, leaving more room for students to engage in what has been referred to as IBL. In the IBL version, the use of the equipment is explained in a separate booklet (*Ioniserende Stralen Practicum | English information*, n.d.). The original version (i.e., before the addition of video and redesigned worksheets) of the IBL practicals was studied by four independent researchers (Nooijen et al., 2017; Verburg, 2018), rated according to the NRC-rubric and labelled as "guided IBL" (level 3) or GIBL by all four researchers.

Pilot Experiments

In a first, modest, quasi-experimental pilot on the influence of the original variant of the IBL practical on the IM of the students (Nooijen, 2017; Nooijen et al., 2017), one upper secondary school class of students (aged 16–19) was offered the DI variant ($N = 17$), while

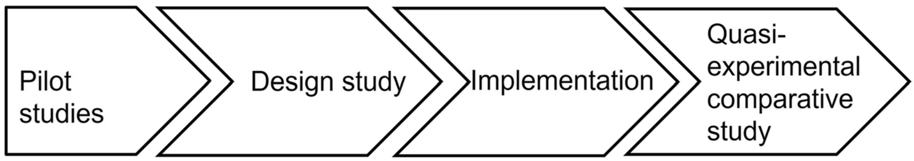

Fig. 1 The design of the present study

two other classes of the same level performed the IBL variant ($N = 38$). Using subscales of the Intrinsic Motivation Inventory or IMI (McAuley et al., 1989; Ryan, 1982), a significant difference was shown for the constructs "interest/enjoyment" (the self-reported measure of IM) and "perceived competence", favouring the IBL version of the experiment.

An effort was made to replicate these promising pilot results on a larger scale. However, larger follow-up studies ($N = 376$) failed to replicate the results, reaching no or very marginal significance (Nikandros, 2020; Van Asseldonk, 2018). This situation warranted the inclusion of a qualitative approach, resulting in the design study.

Design Study

In two separate studies, Grade 11 and Grade 12 students ($N = 38$) of four urban secondary schools in the centre of the Netherlands were asked to take part in a total of seven semi-structured focus group interviews after they had finished both an IBL and a DI variant of the IRP practicals (Blekman, 2020; Nikandros, 2020). Focus groups were chosen, since interaction between the students was valued and an open discussion was encouraged (McLafferty, 2004; Morgan, 2012). The interview protocols for the two studies are very similar and can be found in the appendix. After transcription, axial coding on the total of 156 quotes was performed along the axes autonomy support/frustration and competence support/frustration (e.g., Meulenbroeks, 2022). Since both DI and IBL experiments were performed in groups, the BPN of relatedness was not considered. Interrater reliability was satisfactory. All quotes were subsequently axially recoded along the IBL support guidelines as discussed in the theoretical section (Quintana et al., 2004). Each of the 156 quotes was thus assigned two categories: one in terms of scaffolding and one in terms of BPN being frustrated or fostered. This approach of coding along different axes (e.g., Meulenbroeks, 2020) was expected to lead to an especially rich set of information. Interrater reliability was studied, Cohen's kappa reaching a very satisfactory 0,88.

Redesign of the IBL Experiments

Interventions were designed on the basis of the two main scaffolding issues mentioned by students during the interviews: process knowledge and non-salient tasks.

Process knowledge refers to the different aspects of the inquiry cycle which need to be adhered to in some way to make the process effective in education (Harlen, 2013). In the scaffolding framework adopted here, process knowledge corresponds to the combination of Category 4 (Process management) and Category 5 (Expert guidance on scientific practices). Student utterances frequently refer to the need to "know where they stand" at a certain moment during the practical. In order to provide enough guidance, i.e., supporting the BPN of competence, without frustrating the BPN of autonomy, worksheets had much open space, but with specific guiding remarks (e.g., "Make sure you have arrived at a research question after about 15 min.") and student hints (e.g., "Use this diagram to sketch your hypothesis.", with the principal axes drawn already). Templates for tables and figures are also given in the worksheet, but without labelling the axes or table columns. Figure 2 gives an example of the worksheet lay out.

Non-salient tasks refers to tasks that are essential to perform an experiment, but which are not salient to the inquiry process at hand. In the case of the Ionizing Radiation Practical (IRP), these tasks include the operation of the measuring equipment, e.g., Geiger-Müller counters, the associated high-voltage power supplies, as well as safety precautions. In

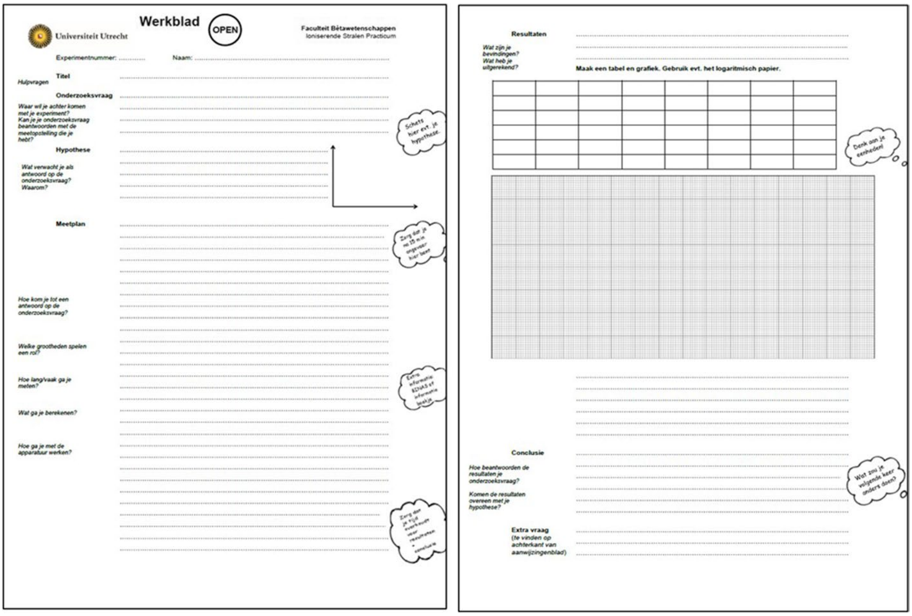

Fig. 2 The general lay out of an IBL worksheet with guiding questions and student tips. Note that the example is in Dutch. Examples of the types of questions and hints in the worksheets are given in the main text

redesigning the original IBL practicals, these non-salient tasks were supported either by instructional videos or by written instructions. Note that the DI experiments do not require such scaffolding, since they rely on a step-by-step process guiding the students through each step of the experiment, including the detailed operation of all equipment involved.

Based on theory on educational videos (e.g., Wijnker et al., 2018, 2021), a tailored video clip of 3–5 min, explaining the way the equipment for that specific experiment was to be handled was made for each IBL experiment. Figure 3 shows a still from one of these educational videos.

Quasi-experimental Comparative Study and Participants

Having arrived at redesigned Guided IBL (GIBL) practicals with scaffolding on process knowledge by worksheets and non-salient tasks by either video or written instructions, a quasi-experimental comparative study was performed, as outlined in Fig. 4.

Seven schools of varying sizes throughout the Netherlands took part in the comparative study. All 242 students who fully completed a questionnaire were from pre-exam classes, i.e., Grades 11 and 12 (5 havo and 6 vwo In Dutch terminology). The two experimental groups received GIBL practicals with the aforementioned worksheets and either videos or written instructions. The students with a DI approach to the practical received the step-by-step worksheets and were used as a control group. It was not determined beforehand which experiment would be given to which students.

After obtaining informed consent, all students taking part in the experiment completed a questionnaire based on the IMI (Ryan, 1982) with a five-point Likert scale. Due

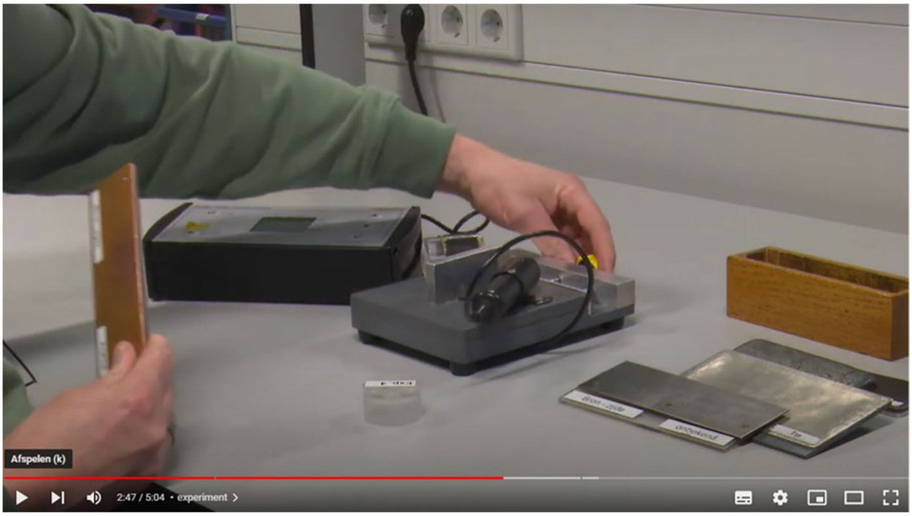

Fig. 3 A still from the educational video on the handling of a Geiger-Müller counter

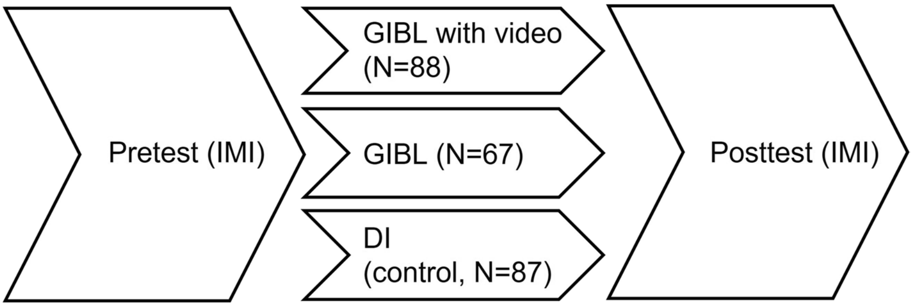

Fig. 4 Outline of the quasi-experimental comparative study design. “GIBL with video”: Guided IBL with instructional videos for the use of the equipment. “GIBL”: Guided IBL with written instructions for the use of the equipment. “IMI”: Intrinsic Motivation Inventory. “DI”: Direct Instruction (step-by-step practical instructions)

to time constraints while working at a school, the full IMI was not used, but rather a subset of five constructs:

1. Pleasure/enjoyment (self-reported measure of IM)
2. Perceived competence
3. Effort/importance
4. Perceived choice
5. Value/usefulness

The questions were slightly adapted to refer to the situation of a physics practical.

Several measures were taken to avoid bias. Since grading of work is known to lead to more controlled forms of motivation and thus to a decrease in IM, (Pulfrey et al., 2011), only schools that did not grade the experimental work carried out during the experiment were included in the study. At each school, students were free to choose an experiment before finding out whether their experiment was going to be an IBL or DI version, i.e., before the worksheets were handed out. Both the distribution over the different experiments and the distribution over the variants are therefore considered to be random. This, however, implies that differences may arise in the numbers of students within each group. As students often perform multiple practicals within one IRP session, the experiment was carried out only on the first practical they performed. The post-test (with the same questions) was thus administered directly after the first practical and before any other practicals were embarked upon.

Some confounding factors have to be mentioned at this point. The time duration of each practical was not determined beforehand: usually a DI practical took less time (about 30 min) than an IBL version of the same practical, which could take up to one hour. Moreover, due to covid regulations at the time, not all students were allowed to work in groups. Out of the seven schools, four (110 students) did not allow working in groups, whereas the other three (132 students) did. Since all schools had students in the experimental and control groups, though, it is assumed that this (working alone or in groups) was again randomly divided over the three research groups.

Data Collection and Analysis

All questionnaires were completed on paper and entered into a spreadsheet to be analysed within the Statistical Package for Social Sciences (SPSS). By conducting a MANOVA, potential differences between the three categorical groups of the independent variable (DI, GIBL and GIBL-with-video) on the five dependent variables (Interest/Enjoyment, Perceived Competence, Effort/Importance, Perceived Choice and Value/Usefulness) were analysed. Several operations were then performed:

1. Results from students with multiple missing values were removed. The data were hand-searched for students missing more than one value per IMI construct. This led to the removal of eight students.
2. Construct averages were calculated by averaging the scores of all items for each construct (Wu & Leung, 2017).
3. Cronbach's alphas were calculated for each construct in all tests and found to be > 0,75 for all constructs in all tests, indicating satisfactory internal validity.
4. For each student, the gain (post minus pre) was calculated for each construct.
5. The conditions for performing MANOVA analyses were checked. No outliers were found. Shapiro–Wilk tests demonstrated that nine out of 18 gains were not normally distributed. However, MANOVA being robust for violations of normality and the corresponding Q-Q plots showing relatively minor deviations, it was decided that this was not an objection. Homogeneity and multicollinearity were satisfactory.
6. A one-way MANOVA was performed, as was a post-hoc Tukey's Honest Significance Difference (HSD) test.

Ethical Statement

All work within this study was performed following the guidelines of the Science-Geo Ethics Review Board. The quasi-experimental comparative design of this study was explicitly approved by the Science-Geo Ethics Review Board under number ERB Review Bèta S-21537.

Results

This section discusses in more detail the results of the recoding of the student quotes on the IBL version of the practicals and the results of the quasi-experiment.

Student Quotes

The 156 student utterances (Design Study, $N = 38$) referring to BPN satisfaction or frustration related to IBL were distributed very unevenly over the scaffolding categories, with 147 of the 156 quotes falling into only two categories: "process knowledge" which combines process management (scaffolding Category 4) and expert guidance on scientific practices (scaffolding Category 5), with 126 quotes and, "non-salient tasks" (scaffolding Category 6) with 21 quotes. Other categories were rarely mentioned. As elaborated in the methods section (Design Study), all these utterances refer to the original version of the IBL practical without the worksheets or videos. Figure 5 gives the results.

The quotes on process knowledge paint a clear picture of the students' experiences with the IBL version of the practical before the introduction of the videos and the adapted worksheets. Autonomy support is mentioned in 40 quotes, for example:

> [In] an [IBL] experiment, you can also put your own ideas into an experiment and come up with your own experiment so it's more creative, so I'd prefer that.
> I liked the fact that there were little guidelines so you really had to do it yourself, and it felt like it was your own research, so I liked that.

Some frustration of the BPN of autonomy was also mentioned (15 quotes):

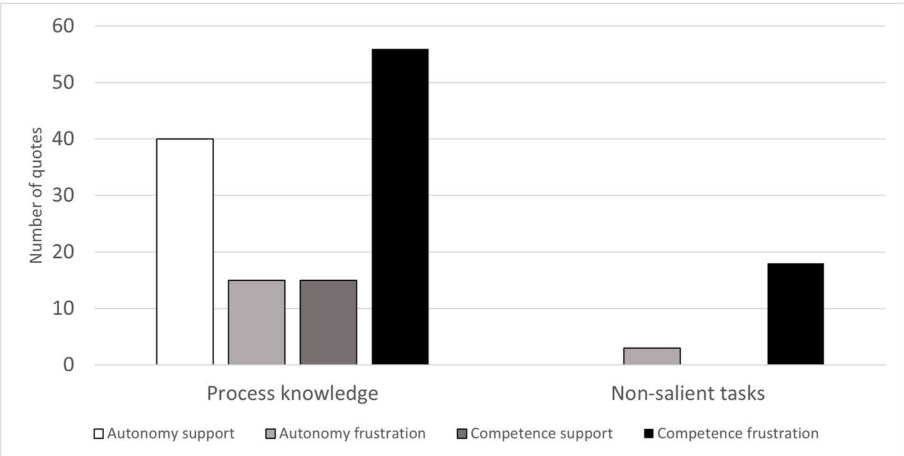

Fig. 5 Distribution of quotes over the main categories of scaffolding (Quintana et al., 2004) and their relation to BPN support or frustration after performing a GIBL practical experiment ($N = 38$)

> Well, I think, you know, every step was on the paper, so you didn't really have to think for yourself what to do.

Interestingly, this student apparently interpreted the open-formulated steps on the worksheet as instructions, much like the steps in the DI variant. The BPN of competence appears to be mainly frustrated, as indicated in 56 quotes, such as:

> I just kind of thought, well maybe this is correct but maybe not. And then, yeah, I just didn't know if it was the right thing I was doing.
> I found it very confusing and difficult, and also annoying that I didn't know if I was doing it correctly.
> Am I doing everything I should do? Because we didn't receive a sheet with 'you should do this'.

As for non-salient tasks, most quotes (18) are about competence frustration:

> Because I think that was our biggest struggle, to actually find out what the, what the devices actually measure, when we were doing the experiment.
> I found it difficult… Also, there was no explanation how you could use the device.

A few quotes pointed to ease of use of the equipment (competence support):

> It wasn't very hard [to] measure accurately.

As mentioned in the methods section, these qualitative results were used as input for the design of the worksheets and the instruction videos on the experimental equipment.

Comparative Study Results

The design of supportive materials based on the scaffolding categories afforded the quantitative comparison of Guided IBL practicals (with or without videos) as the intervention groups while the DI versions of the practicals serve as the control group. The one-way MANOVA demonstrated a statistically significant difference in the a linear combination on the three variants, F (12, 496) = 3.92, $p < 0.0005$; Pillai's trace V = 0.17, partial $\eta 2 = 0.09$ (Finch, 2005). A Multi Comparisons test (Tukey's Honest Significance Difference test) was performed on the gains in the different constructs of the IMI. The results are given in Table 1 and Fig. 6.

The difference in gains in all constructs of the IMI used here are positive when compared to the gain in the control group. Furthermore, when scaffolding on non-salient tasks is provided by a video, all differences are significant, favouring the GIBL version. Most importantly for our research question, the interest/enjoyment construct demonstrates a significant difference in gain post–pre between both GIBL variants and the control group (DI), favouring the GIBL variants. When scaffolding in terms of non-salient tasks is provided by videos, the level of significance is higher. Significance is only reached for two of the five constructs (interest/enjoyment and effort/importance) if the support for non-salient tasks is provided in the form of written instructions.

Note that both GIBL versions employ identical scaffolding in terms of process knowledge, which incorporates scaffolding Categories 4 and 5 in the scaffolding framework adopted here (Quintana et al., 2004). The only difference between the two GIBL groups lies in the scaffolding for non-salient tasks (video versus written instructions).

Table 1 Results of the Multi Comparisons Test performed on gains in five subscales of the Intrinsic Motivation Inventory

Dependent Variable	Control group	Variant	Mean Gain	Std. Error	Sig
Gain interest/enjoyment	DI	GIBL	0.2898	0.10217	0.014
		GIBL-with-video	0.4602	0.09741	0.000
Gain Perceived competence	DI	GIBL	0.1089	0.12491	0.659
		GIBL-with-video	0.4556	0.11910	0.000
Gain Effort/Importance	Di	GIBL	0.2477	0.09452	0.025
		GIBL-with-video	0.2544	0.09012	0.014
Gain Perceived choice	DI	GIBL	0.0906	0.09093	0.580
		GIBL-with-video	0.2653	0.08669	0.007
Gain Value/Usefulness	DI	GIBL	0.0270	0.09928	0.960
		GIBL-with-video	0.2976	0.09466	0.005

DI: $N=87$, GIBL: $N=67$, GIBL-with-video: $N=88$

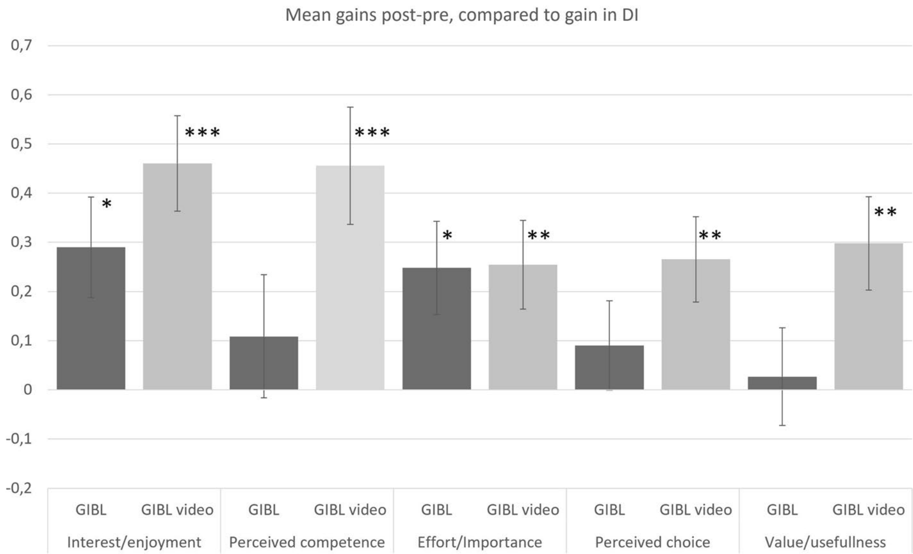

Fig. 6 The descriptive statistics (average gains post–pre and standard deviations) in the form of a bar graph. Asterisks denote the level of significance. If a p-value is less than 0.05, it is flagged with *; less than 0.01, flagged with **; less than 0.001, flagged ***

Discussion

Research Question

We now revisit our research question: *To what extent is secondary students' intrinsic motivation for a physics practical fostered by guided inquiry-based learning?*

As Fig. 6 shows, students' intrinsic motivation (interest/enjoyment) is fostered significantly more by either GIBL variant, as compared to the DI variant. As the construct "effort/importance" is also supported significantly more in both GIBL variants, students apparently put more effort into the practical as compared to the students in the control group. When the videos were used as scaffolding on non-salient tasks, all constructs showed a significantly higher gain, indicating that students felt more competent or effective (perceived competence), perceived more choice (autonomy), and perceived the practical as more useful or valuable for themselves.

The results demonstrate that one can indeed foster intrinsic motivation by offering secondary school students a carefully scaffolded GIBL practical, as it offers students support in their need of competence and autonomy. They also see the practical as more valuable to them and put more effort into it.

The accompanying hypothesis was: *An IBL physics practical that is designed to support the students in an adequate, but not restrictive, way will support the basic psychological needs of students and, consequently, foster their IM.*

This hypothesis is confirmed by this study. It is especially noteworthy what is meant by "adequate, but not restrictive" support. Student quotes indicate that mainly the scaffolding categories "process knowledge" (a combination of "process management" and "expert guidance on scientific practices") and "non-salient tasks" are in need of support in this particular situation (Quintana et al., 2004). These scaffolds have been implemented in the form of dedicated worksheets (Fig. 2) and instructional videos (Fig. 3). The worksheets deserve considerable attention, since it is here that the instructions could well turn out to be "restrictive". For example, it was only indicated that after about 15 min, the students are supposed to have arrived at some sort of research question. Furthermore, templates for tables and graphs were given without column and axis labels.

Limitations

The quasi-experiment precluded full randomization of students and variants. However, at all the schools in this study, students were asked to first pick a practical without knowing which variant they would be performing. The same holds for the actual practical performed by the students: the students themselves chose the practical from a list. It is assumed that the distribution over the practicals can be considered random.

An important factor limiting generalizability is the nature of the COVID-19 measures in place at the time. Four out of seven schools therefore did not allow students to work in groups. IBL usually involves students working in groups (Harlen, 2013). The students in the control and experimental groups were distributed over the schools in the sample, so we may expect this factor to be randomly distributed. In other words: both the experimental groups and the control groups contained students from all seven schools, working either alone or in dyads.

The Ionizing Radiation Practical involves the use of radioactive materials, sophisticated equipment, and strict safety measures. This makes it a very a-typical secondary school physics practical. It is not clear to what extent this specific character might influence the results, but the character and context of the practicals in both in the experimental and control groups were identical.

Lastly, we did not study gender effects in this study.

Implications

The results of this study suggests several implications in relation to students' intrinsic motivation. First, the use of inquiry-based approaches in itself does not guarantee the support for BPN's and thus, intrinsic motivation. Although autonomy is readily supported by the inherently open and student-directed approach, IBL practicals can be perceived by the students as being too open and therefore thwarting their BPN of competence. Second, IBL scaffolding guidelines (Quintana et al., 2004) do offer a range of support mechanisms that can be tapped into by teachers aspiring to implement IBL in their practice. However, in the specific case of physics practicals only three of the seven support categories were mentioned by students during the focus groups. Students indicated that they required support in process knowledge (Categories 4 and 5) and non-salient tasks. Thirdly, with proper scaffolding, GIBL can be employed to foster students' intrinsic motivation for these kinds of practicals.

For STEM teachers in secondary education aspiring to use IBL approaches in practicals, it would be advisable to look into the structure of the worksheets they are offering their students. Guiding questions and hints can support students' BPN of competence without resulting in restrictive rules and recipes that can frustrate their BPN of autonomy. Furthermore, as any practical necessarily requires some equipment of varying sophistication, offering the students support on the non-salient task of using this equipment in the form of short instructional videos has been shown to be a very effective way to support them in carrying out these non-salient tasks.

Future Research

It would be good to attempt to reproduce these semi-experimental results by creating a truly randomized control trial experiment. This is not an self-evident endeavour given the nature of the experiments and the time restraints that are prevalent in schools.

Furthermore, the present study uses a specific and possibly "exciting" practical involving such exotic equipment as Geiger Müller counters, high voltage power supplies, and actual radioactive sources. Future research could be focused on supporting IBL versions of more mundane and common physics (or chemistry or biology) practicals such as classroom experiments on classical mechanics or electricity, involving more everyday equipment such as springs, weights, voltage and current meters, low voltage power supplies, and simple coils or transformers. Support on non-salient tasks could be less important in these situations, even though the correct use of, e.g., voltage or current meters might still warrant support. Support on the actual process of IBL, however, may be equally required in other practicals. Therefore, extending this study to practicals in the fields of chemistry and biology seems a promising route.

Conclusion

The results of the present study demonstrate the effectiveness of a mixed-methods approach including student focus groups to elucidate mechanisms that were not evident from purely quantitative research on the influence of IBL physics practicals on students' intrinsic motivation towards practicals. Students were eloquent and outspoken about their need for specific types of support, support that could be linked to known theoretical frameworks on scaffolding. The implementation of scaffolding in terms of process guidance and non-salient tasks, by dedicated worksheets and instructional videos, resulted in a significant increase of students' intrinsic motivation towards science practicals. Actually listening to students' needs proved to be the key to supporting their BPN's and thus foster their intrinsic motivation.

Appendix

Interview Protocol Pilot Study 1

1. What did you think of the ionizing radiation practical?
2. You did two variants of the practical: open [IBL] and closed [DI].

Could you tell something about how it went?

3. How did the preparation, the actual experiment and working out of the practical go?

Did you have enough freedom with conducting the experiments, could you investigate what you wanted to investigate?

4. Was there enough freedom with both, or only open [IBL] or closed [DI]?
5. Did you find it difficult?

Were the experiments equally difficult? Wat was difficult?
Do you have the feeling that you understood everything during the experiment?
Did the worksheets help you?
How was it to do the experiments in a group?

6. Did the cooperation go smoothly during this practical?
7. How was the teacher support during the practical?

How was the support of the teacher from your school?
How was the support of the teacher from the university?

8. Which of the experiments was most interesting to conduct?

Why?

Interview Protocol Pilot Study 2

1. What did you like the most about the experiments you performed?
2. During the session you performed experiments in two different approaches (or ways). What do you remember about the two approaches?
3. Which one did you enjoy more and why?
4. How would you describe the level of difficulty of the experiment(s) you performed?

5. Did you feel supported by the worksheets/ How much did the worksheets help you during the experiments?
6. Imagine you had to do another experiment in one hour, not necessarily a physics experiments, it could be chemistry or biology for example, that would last one hour, and you would not be graded for your effort. Would you choose to do another closed – open (depending on the group) experiment or would you try the other "kind" of experiment? Why is that?
7. What would you improve about the experiments? Specifically, about the organization, worksheets, planning, equipment grading, etc.

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Authors' Contributions Ralph Meulenbroeks: co-designed and supervised all experiments in this study, performed the literature study, analysed the data, wrote the paper.

Rob van Rijn: carried out the quasi-experimental comparative study, analysed the data.

Martijn Reijerkerk: carried out the design study.

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Declarations

Competing Interests The authors declare that they have no competing interests.

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