



# Investigating the process of learning with desktop virtual reality: A structural equation modeling approach

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## ABSTRACT

Virtual reality (VR) is gaining attention for having the potential to enrich students' educational experiences. However, few studies have investigated the process of learning with VR. With the use of structural equation modeling, this study investigated the affective and cognitive factors that play a role in learning with a desktop VR simulation when pre-to post-test changes in motivation, self-efficacy, and knowledge about genetics are used as outcomes. The sample consisted of 199 university students (120 females), who learned from a desktop VR genetics simulation as a mandatory part of an undergraduate medical genetics course. The results indicated that there were two general paths by which desktop VR led to increases in the amount of learning following a VR lesson: an affective path that went through VR features, presence, intrinsic motivation, and self-efficacy; and a cognitive path that went through VR features, usability, cognitive benefits, and self-efficacy. It is concluded that learners may benefit from desktop VR simulations in which efficacious VR features and a high level of usability are emphasized.

## 1. Background

The education sector is currently experiencing an upsurge in the use of technologies such as virtual reality (VR) and interactive simulations for teaching and enriching students' educational experiences. According to Burbules (2006, p. 37) VR can be defined as “a computer-mediated simulation that is three-dimensional, multisensory, and interactive, so that the user's experience is “as if” inhabiting and acting within an external environment”. Depending on the system used, VR simulations may vary in their level of immersion, which is defined as the objective level of sensory fidelity a VR system provides (Bowman & McMahan, 2007). Desktop VR (defined shortly) may be classified as being low-immersive, whereas head-mounted displays offer a high level of immersion (Cummings & Bailenson, 2016; Lee & Wong, 2008). The NMC/CoSN Horizon Report, which investigates emerging technologies for their potential influence on and use in teaching, learning, and creative inquiry in schools, anticipates that VR will be adopted by classrooms within two to three years, thereby testifying to the necessity of authentic and student-centered learning in schools (Freeman, Adams Becker, Cummins, Davis, & Hall Giesinger, 2017). This increased interest in VR for learning purposes is not unfounded, inasmuch as several meta-analyses thus far report positive educational outcomes when using VR and simulations, sometimes exceeding the outcomes associated with traditional classroom instruction (e.g., Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014; Smetana & Bell, 2012; Vogel et al., 2006).

Although many recent studies have investigated the educational value of VR and simulations (e.g., Chittaro & Buttussi, 2015; Gunn, Jones, Bridge, Rowntree, & Nissen, 2017; John, Pop, Day, Ritsos, & Headleand, 2018; Makransky, Terkildsen, & Mayer, 2017b;

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Makransky, Wismer, & Mayer, 2018; Yang et al., 2018), there is an increasing interest in studying learning as a process – that is, how and why learning takes place – rather than simply measuring the outcomes of learning (Gerjets & Kirschner, 2009; Makransky, Terkildsen, & Mayer, 2019). One way of investigating the process of learning is to develop and test a model that describes how important variables interact in the learning process. Using this approach, Lee, Wong, and Fung (2010) developed a model based on Salzman, Dede, Loftin, and Chen (1999) and technology-mediated learning models, and tested the process of learning with desktop VR by using structural equation modeling (SEM). They found that the relationship between VR features and learning outcomes was mediated by the interaction and learning experience. Makransky and Lilleholt (2018) built on Lee and colleagues' results by investigating the role of immersion in the process of learning with immersive VR. In their study, students were exposed to an immersive and a desktop VR simulation in a quasi-experimental design. Makransky and Lilleholt (2018) interpreted their results based on the Control Value Theory of Achievement Emotions (CVTAE; Pekrun, 2000), and concluded that there were two paths between the levels of immersion and perceived learning outcomes; an affective and a cognitive path.

The studies by Lee et al. (2010), and Makransky and Lilleholt (2018) provide a basis for understanding certain variables that are important, and how these variables interact when learning with VR, which can guide research and practice in this field. However, both studies investigated post-test outcomes rather than isolating the learning intervention and investigating it as a process. In this study, we isolate the learning process by using outcome variables that only take into account the change based on the learning intervention. That is, we investigate the difference between pre- and post-test results on the outcomes of knowledge, motivation, and self-efficacy, and investigate how important variables related to learning in VR influence these changes. This is different from previous work that investigated outcome variables, as these previous studies explored correlations rather than applying a more causal approach (which can be obtained by studying developments made when using a VR lesson, and measuring changes from prior to after the lesson). In addition to this, both studies included subjective evaluations of learning outcomes, including perceived learning, satisfaction, and behavioral intentions. There is evidence that subjective measures of learning outcomes are not highly correlated with actual learning outcomes. For instance, Sitzmann, Ely, Brown, and Bauer (2010) conducted a meta-analysis of 166 studies in the fields of education and workplace training in order to examine the validity of self-assessments of knowledge in relation to cognitive learning measures. Their results indicate that self-assessments of knowledge are only moderately related to learning outcomes; and the authors of this extensive meta-analysis advise researchers to be cautious in their use of self-assessments of knowledge as indicators of learning. Furthermore, the influence of common methods variance (CMV) has been persistently cited as a source of concern, particularly for research involving self-report measures (Spector, 2006). Therefore, it is important to investigate whether the results and conclusions obtained in previous literature on the process of learning in VR (e.g., Lee et al., 2010; Makransky & Lilleholt, 2018) remain with pre-to post-test changes in motivation, self-efficacy, and learning as dependent variables. That is, are the results of previous studies simply due to correlations that occur when measuring different variables that are relevant for learning in VR; or are these variables actual predictors of pre-to post-test changes in motivation, self-efficacy, and learning that result from exposure to a VR lesson?

In this study, we use SEM to test a model based on previous work in the field including Lee et al. (2010) and Makransky and Lilleholt (2018), but with pre-to post-test changes in intrinsic motivation, self-efficacy, and knowledge as dependent variables. The objective is to use SEM to investigate a model that describes the affective and cognitive factors that play a role in learning with a desktop VR simulation. In other words, we are interested in investigating the constructs that can influence changes in knowledge, motivation, and self-efficacy. That is, we do not focus on the level of knowledge, motivation, and self-efficacy per se, but rather on an understanding of the constructs that can lead to a positive change in these variables using VR. We therefore think of learning with VR as a process that is influenced by different variables, and we aim to isolate this process by looking at pre-to post-test changes in the learning outcomes. In agreement with Lee and Wong (2014), we define desktop VR as a 3-D virtual environment generated on a computer monitor, which can be explored interactively by using computer equipment such as keyboard, mouse, joystick or touch screen, and headphones. Including affective as well as cognitive factors in such a model is important because there is evidence that these factors play an important role in learning with VR (e.g., Makransky, Lilleholt, & Aaby, 2017a; Makransky & Lilleholt, 2018; Moreno & Mayer, 2002; Parong & Mayer, 2018). The following sections highlight some existing models that describe how affective and cognitive factors play a role in learning with VR, with the purpose of developing a framework that can be empirically tested in this study.

### 1.1. Theoretical and empirical framework

Unlike the cognitive domain, in which there are established theories that provide a unifying framework to describe the cognitive process that takes place in learning, there is still much to be understood about how affective factors interact with cognitive factors to produce learning. This field has been characterized by different definitions of affect, moods, and emotions; as well as the various theoretical and methodological lenses through which issues have been examined (Linnenbrink, 2006). Several models describing the link between cognitive and affective factors in learning have emerged during the last few years, including the Cognitive-Affective Theory of Learning with Media (CATLM; Moreno & Mayer, 2007), the Integrated Model of Multimedia Interactivity (INTERACT; Domagk, Schwartz, & Plass, 2010), and the CVTAE (Pekrun, 2000).

Previous research investigating the process of learning in VR has built on the CVTAE (Makransky & Lilleholt, 2018) and media technology models (Lee et al., 2010; Salzman et al., 1999). Fig. 1 illustrates the a priori research model investigated in the present study. This model builds on previous work including the CVTAE and the Lee et al. (2010) model, and is described in more detail below.

The CVTAE is a framework describing the antecedents and effects of emotions experienced in achievement and academic contexts;

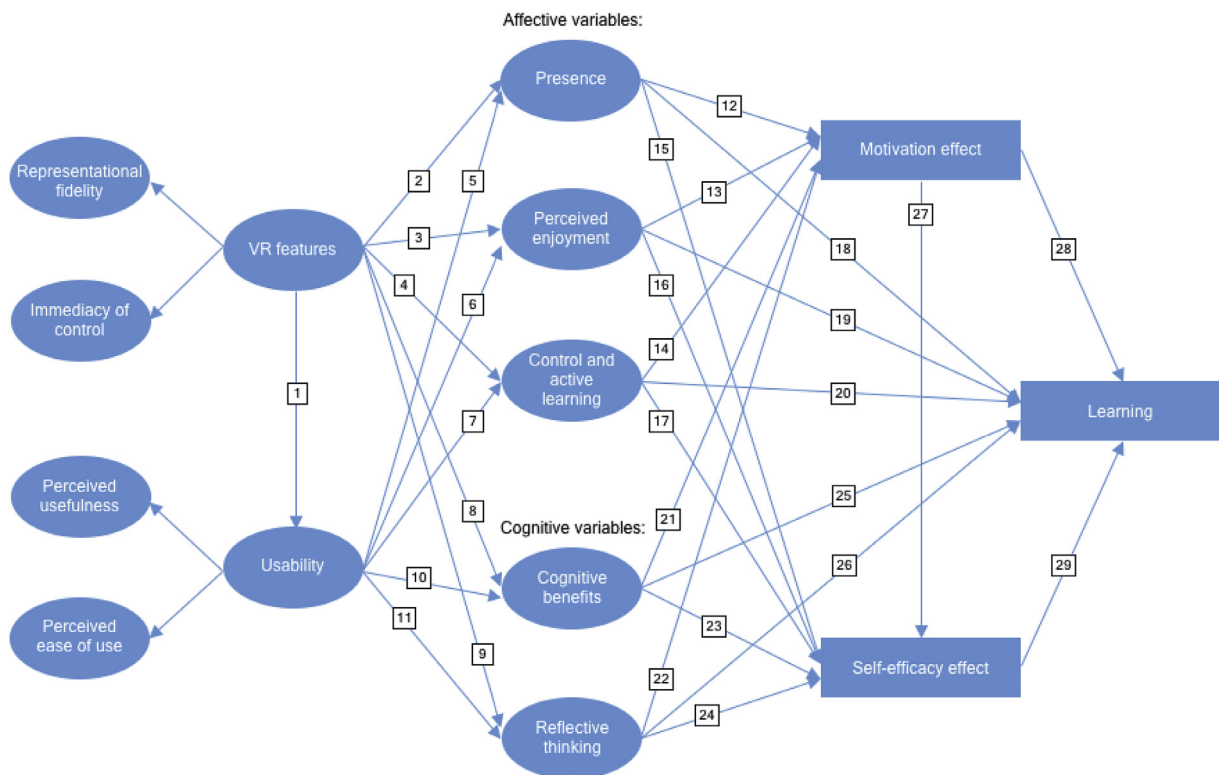


Fig. 1. The hypothesized model.

and it considers these emotions important for academic learning and achievement. The theory distinguishes between two types of achievement emotions, namely activity emotions pertaining to ongoing achievement-related activities; and outcome emotions pertaining to the outcomes of said activities (Pekrun, 2006).

One such important activity emotion is enjoyment, which is assumed to be triggered when the achievement activity and its corresponding material is positively valued by the learner, and is perceived to be sufficiently controllable. Enjoyment of the learning activity benefits performance by focusing attention on the task itself, and is presumed to lead to higher intrinsic and extrinsic student motivation (Pekrun, 2006). Similarly, enjoyment may facilitate learning by stimulating self-regulation of learning and the use of flexible cognitive strategies, as well as interest and motivation to learn (Pekrun, 2006; Pekrun & Stephens, 2010; Plass & Kaplan, 2016). Another assumption made by the theory concerns the influence which factors such as quality of tasks might have on achievement emotions. For instance, the cognitive quality of tasks as defined by their structure, clarity, and potential for cognitive stimulation most likely affects achievement emotions positively, which in turn influences learning and motivation (Pekrun & Stephens, 2010). It is worth noting that cognitive quality of tasks resembles the factor called “cognitive benefits” in the model by Lee et al. (2010), which will be addressed later. In sum, the CVTAE incorporates affective factors such as enjoyment and appraisals of control together with cognitive factors such as cognitive quality of tasks, and it considers these important with regard to the process of learning in academic contexts.

While the CVTAE framework is intended for general academic learning, other models that specifically emphasize learning within VR environments also exist. Lee et al. (2010) developed and tested a theoretical framework that specifies the causal relationships between factors that play a role in enhancing learning in desktop VR-based learning environments. Their framework is based on an initial model of learning with immersive VR by Salzman et al. (1999) and technology-mediated learning models, but it adds to these by examining the individual effect of psychological factors on learning, instead of merely conceptualizing these under the general construct of learning experience (Lee et al., 2010).

Using SEM, Lee et al. (2010) proposed a framework wherein learning experience (measured by individual psychological factors) play a vital role in affecting the learning outcomes of a VR-based learning environment. More specifically, VR features (made up of representational fidelity and immediacy of control) and usability (made up of quality and accessibility) predict mediating factors consisting of presence, motivation, cognitive benefits, control and active learning, and reflective thinking, which in turn predict perceived learning, satisfaction, and performance achievement (Lee et al., 2010). Furthermore, the framework holds that VR features also predict the mediating factors indirectly by influencing usability. The mediating factors include affective and cognitive factors implicated in other more established affective frameworks such as CATLM, INTERACT, and CVTAE. Key differences between these and the framework by Lee et al. (2010), however, are that Lee's model includes a number of important factors from the media literature (e.g. VR features and presence) critical for learning in VR environments, as well as the fact that their model provides a more

detailed description of the causal relationships between important variables.

## 1.2. Variables used in the study

In the following section, we provide a quick introduction to the variables that are used in present model and their relevance. This is followed by a description of the hypothesized relationships between the variables in section 1.3 which is also shown graphically in Fig. 1. We refer readers to Lee et al. (2010) and Pekrun (2006) for a more detailed overview. These variables were chosen among other variables for inclusion in the model due to previous research identifying them as especially relevant for describing the process of learning in VR.

### 1.2.1. VR features

VR features is a construct that pertains to the qualities of the virtual reality technology, which is measured by representational fidelity and immediacy of control. Representational fidelity refers to the resemblance between the virtual environment and the real world – the degree of realism provided by the environment (Lee et al., 2010); while immediacy of control refers to the control factors in the environment, such as the ability to change the point of view or to interact with or manipulate objects in the virtual environment (Lee et al., 2010). These features were coined in Whitelock, Brna, and Holland (1996), as part of a theoretical framework for exploring the relationship between virtual environments and conceptual learning. Later, Dalgarno and Lee (2010) reasoned that representational fidelity and learner interaction (which includes aspects of immediacy of control) of 3-D virtual environments lead to various learning benefits by affecting aspects of the learner's experience (e.g. presence). This connection was empirically validated in Lee et al. (2010) and Makransky and Lilleholt (2018). More specifically, VR features were found to be significant antecedents to interaction experience (i.e. usability) and affective (i.e. presence, perceived enjoyment, control and active learning) and cognitive (i.e. cognitive benefits, reflective thinking) variables, ultimately enhancing learning outcomes (Lee et al., 2010). Consequently, we chose representational fidelity and immediacy of control as the VR features to be used in present study, as these features constitute unique characteristics of 3-D virtual learning environments, explaining the educational value of virtual simulations.

### 1.2.2. Usability

Usability is assumed to be impacted by VR features, and is also expected to be an antecedent to the affective (i.e. presence, perceived enjoyment, control and active learning) and cognitive (i.e. cognitive benefits, reflective thinking) variables in the model. Usability refers to the quality and accessibility of the technology in use, and it is measured by perceived usefulness and perceived ease of use. Perceived usefulness is the degree to which the learners believe that using the platform in question will enhance their performance. Perceived ease of use is the extent to which the learners experience the platform as being easy or difficult to use (Davis, 1989; Lee et al., 2010).

### 1.2.3. Affective factors

The affective factors used in present study include presence, perceived enjoyment, and control and active learning. Presence has been described as “the psychological sense of ‘being there’ in the environment generated by the system” (Lee et al., 2010, p. 7), meaning that users tend to overlook the virtuality of the experience when interacting with virtual environments (Lee, 2004). Along these lines, Witmer and Singer (1998, p. 225), define presence as “the subjective experience of being in one place or environment, even when one is physically situated in another”. In a ten-year review of empirical research conducted on the use of VR for educational purposes, Mikropoulos and Natsis (2011) report that presence can contribute positively to learning outcomes, which is consistent with Lee et al. (2010). Perceived enjoyment is defined as “the extent to which the learning activity is perceived to be enjoyable in its own right, apart from any performance consequences that may be anticipated” (Davis, Bagozzi, & Warshaw, 1992, p. 1113). According to the CVTAE, positive activity emotions like enjoyment can facilitate learning (Plass & Kaplan, 2016). Control and active learning refer to the degree of autonomy afforded by the virtual environment in question. Through this autonomy, the learners are actively taking control of their pace and their own learning (Lee et al., 2010).

### 1.2.4. Cognitive factors

The cognitive factors used in present study are cognitive benefits and reflective thinking. Cognitive benefits pertains to the improved understanding, application, and positive perception of learning material that the virtual environment affords (Lee et al., 2010). According to the CVTAE, the related term of cognitive quality of tasks, which is related to the structure, clarity, and potential for cognitive stimulation embedded in the lesson, is expected to affect achievement emotions positively (Pekrun & Stephens, 2010). Reflective thinking is defined by Dewey (1933) as a state of mental difficulty and perplexity which incites an act of inquiring to resolve this state of doubt. By reflecting on the perplexity that a learning experience may instigate, learners integrate the new experience with earlier acquired knowledge to create meaning (Lee et al., 2010).

### 1.2.5. Outcome variables

The learning outcome variables used in this study include the pre-to post-test changes in intrinsic motivation, self-efficacy, and knowledge (learning). That is, the change from pre-to post-test on these variables, which are each measured with a carefully constructed psychometric scale (presented in Appendix A). Pre-to post-test changes were used because the goal was to measure the effects of a desktop VR learning intervention and to investigate whether variables that have been previously identified as influencing learning in VR could predict these effects. We prioritized the use of change scores to avoid artificially high relations among variables

due to CMV (Spector, 2006).

Intrinsic motivation is defined as the performance of an activity for the inherent satisfaction associated with the activity itself, rather than for some separable consequence (Ryan & Deci, 2000). In this study we measured intrinsic motivation for medical genetics because this was the topic of the lesson in the study. Self-efficacy is defined as one's perceived capabilities for learning or performing actions (Schunk & DiBenedetto, 2016). In this study, we specifically measured self-efficacy in medical genetics. Learning is defined as the change in the student's knowledge about the material presented in the VR simulation, which in this study specifically refers to knowledge of medical genetics. Three types of knowledge based on Mayer's (2008) five kinds of knowledge taxonomy were the focus of the VR lesson including: facts, concepts, and procedures.

### 1.3. Hypotheses

The predicted relationships in the a priori model are presented in Fig. 1 and described in more detail below. Based on the CVTAE and the Lee et al. (2010) framework, we predict that VR features can be measured by representational fidelity and immediacy of control; that usability can be measured by perceived usefulness and perceived ease of use; and that VR features will predict usability in this study.

**Hypothesis 1.** VR features, which is comprised of representational fidelity and immediacy of control, will be a significant antecedent of usability, which is made up of perceived usefulness and perceived ease of use (path 1 in Fig. 1).

Furthermore, we expect that VR features and usability will predict the affective variables of presence, perceived enjoyment, and control and active learning.

**Hypothesis 2.** VR features will be a significant antecedent of presence (path 2 in Fig. 1), perceived enjoyment (path 3), and control and active learning (path 4).

**Hypothesis 3.** Usability will be a significant antecedent of presence (path 5), perceived enjoyment (path 6), and control and active learning (path 7).

We also expect that VR features and usability will predict the cognitive variables of cognitive benefits and reflective thinking.

**Hypothesis 4.** VR features will be a significant antecedent of cognitive benefits (path 8) and reflective thinking (path 9).

**Hypothesis 5.** Usability will be a significant antecedent of cognitive benefits (path 10) and reflective thinking (path 11).

Furthermore, we expect that each of the affective and cognitive variables will predict the three outcome variables; that is pre-to post-test change in intrinsic motivation, self-efficacy, and knowledge (learning).

**Hypothesis 6.** Presence, perceived enjoyment, and control and active learning will each act as significant antecedents to change in motivation (paths 12–14), change in self-efficacy (paths 15–17), and learning (paths 18–20).

**Hypothesis 7.** Cognitive benefits, and reflective thinking will each act as significant antecedents to change in motivation (paths 21–22), change in self-efficacy (paths 23–24), and learning (paths 25–26).

#### 1.3.1. Link between motivation and self-efficacy

Self-efficacy is defined as one's perceived capabilities for learning or performing actions (Schunk & DiBenedetto, 2016), and thus plays an important role in educational contexts. Importantly, self-efficacy influences a range of educational variables, including motivation (Schunk & DiBenedetto, 2016). According to Schunk (2012), self-efficacy can influence motivational outcomes such as the amount of effort people will expend on an activity, how long they persevere when confronting obstacles, and how resilient they are in the face of difficulties. One useful framework for considering the link between motivation and self-efficacy is based on self-determination theory (Deci & Ryan, 2012). This theory is based on the notion that learners have a need for autonomy, competence, and relatedness, and are more motivated to learn when they are in a learning situation in which they believe that these needs are being met. The competence component is consistent with self-efficacy theory, which suggests that learners are more motivated to try harder when they believe they are able to succeed on a task (Schunk & DiBenedetto, 2016; Schunk & Usher, 2012). Research has found positive correlations between self-efficacy and achievement motivation (Pouratashi, Zhub, Mohammadi, Rezvanfara, & Hosseinia, 2013), and has established the utility of self-efficacy for predicting motivational outcomes (Schunk, 1991). In agreement with described theory and research, and as shown in the a priori model (Fig. 1), we predict that pre-to post-test changes in intrinsic motivation will be positively related to pre-to post-test changes in self-efficacy.

**Hypothesis 8.** There will be a significant path from intrinsic motivation effect to self-efficacy effect in the SEM model (path 27).

#### 1.3.2. Link between motivation and learning

In addition to the CVTAE, established motivational theories including interest theory (Dewey, 1913; Renninger & Hidi, 2016), and CATLM (Moreno & Mayer, 2007) describe the link between motivation and learning which can be applied to the context of learning in VR. Interest theory (Renninger & Hidi, 2016; Renninger & Su, 2012) suggests that an understanding of the motivational appeal of e-learning tools is essential for learning, since situational interest can be a first step in stimulating learning (Renninger & Hidi, 2016).



VR applications can spark situational interest (Makransky & Lilleholt, 2018; Makransky Lilleholt et al., 2017a; Makransky Terkildsen et al., 2017b), and are able to effectively develop self-efficacy by providing guided discovery learning opportunities with appropriate feedback (Bonde et al., 2014; Makransky et al., 2016a; Makransky, Thisgaard, & Gadegaard, 2016b).

The CATLM is a framework that describes the link between cognitive, metacognitive, and motivational factors in technology-enhanced learning interventions (Moreno & Mayer, 2007). The model is based on several main assumptions, including: 1) Humans have separate channels for processing different information modalities, 2) Only a few pieces of information can be actively processed at any time in working memory within each channel, 3) Meaningful learning occurs when the learner expends conscious effort in cognitive processes, 4) Motivational factors mediate learning by increasing or decreasing cognitive engagement, and 5) Metacognitive factors mediate learning by regulating cognitive processing and affect (Moreno & Mayer, 2007). The model predicts that higher motivation will lead to more learning because learners who lack motivation will fail to engage in generative processing even when the cognitive capacity is available (Pintrich, 2003); and metacognitive factors regulate cognitive processing and affect (Bruning, Schraw, & Ronning, 1999). Empirical findings support these assumptions. For example, Richardson, Abraham, and Bond (2012) conducted a systematic review and meta-analysis of the psychological correlates of university students' academic performance. They found a correlation of 0.17 between GPA (grade point average; Groth-Marnat, 2003) and academic intrinsic motivation (i.e. self-motivation for and enjoyment of academic learning and tasks). Consistent with above-mentioned theory and research, and as shown in the a priori model (Fig. 1), we predict that a pre- to post-test change in intrinsic motivation will significantly predict learning in present study.

**Hypothesis 9.** Change in intrinsic motivation will act as a significant predictor of learning (path 28).

### 1.3.3. Link between self-efficacy and learning

In his self-efficacy theory, which focuses on expectancies for success, Bandura (1997) proposed that individuals' efficacy expectations (i.e. beliefs about whether one can effectively perform the behaviors necessary to produce an outcome) are the major determinant of goal setting, activity choice, willingness to expend effort, and persistence (Eccles & Wigfield, 2002), all of which may have a positive effect on academic performance and learning (Pajares, 1996). This is consistent with empirical literature, wherein high personal academic expectations have been found to predict subsequent performance (Eccles & Wigfield, 2002). A similar notion about the relationship between self-efficacy and academic performance and learning appears in the Handbook of Motivation at School (Schunk & DiBenedetto, 2016). Here it is suggested that students who feel more efficacious about learning should be more inclined to engage in self-regulated learning and create effective learning environments for themselves.

In their systematic review and meta-analysis of the psychological correlates of university students' academic performance, Richardson et al. (2012) found a medium correlation of 0.31 between GPA and academic self-efficacy (i.e. general perceptions of academic capability), and a correlation of 0.59 between GPA and performance self-efficacy (i.e. perceptions of academic performance capability). In sum, there is an important association between students' self-efficacy levels and academic attainments. Consistent with above-mentioned theory and research, and as shown in the a priori model (Fig. 1), we predict that a change in self-efficacy will predict learning in the present study.

**Hypothesis 10.** Change in self-efficacy will act as a significant predictor of learning (path 29).

## 2. Materials and methods

### 2.1. Sample

The sample consisted of 199 (120 females and 79 males) first-year undergraduate students with a major in medicine from a large European University. The entire first year class of 300 students were contacted to participate in the study; however only those who gave permission to use the responses for research purposes were included in this study.

### 2.2. Procedures

The simulation session was a part of a mandatory medical genetics course that the students attended. The session lasted for three hours and was conducted in a computer laboratory with approximately 25 students per session. The session consisted of a pre-test (approximately 30 min), the VR simulation lesson about medical genetics (approximately 2 h), and a post-test (approximately 30 min). The pre-test consisted of demographic questions including age and gender, in addition to the three outcome variables: a measure of intrinsic motivation related to medical genetics, self-efficacy for medical genetics, and a knowledge of medical genetics test. These questions were used to determine the individual students' baseline level on the three constructs. Immediately following the pre-test, students used the VR simulation for a 2 h session. Three teachers were available to assist the students during this session. Students typically worked independently and only asked for help from teachers and other students when they encountered obstacles. The post-test consisted of the same three outcome variables: intrinsic motivation, self-efficacy, and the knowledge test as in the pre-test. Furthermore, the post-test consisted of self-report measures of representational fidelity and immediacy of control (VR features), perceived ease of use and usefulness (usability), presence, perceived enjoyment, control and active learning, cognitive benefits, and reflective thinking. The students were instructed to work alone and were not allowed to talk during the pre- and post-tests.

## 2.3. Materials

### 2.3.1. Pre-test

The pre-test included demographic questions including age and gender. Intrinsic motivation was assessed with five questions adapted from the Interest/Enjoyment Scale from the Intrinsic Motivation Inventory (Deci, Eghrari, Patrick, & Leone, 1994; e.g., I enjoy working with medical genetics) and had a Cronbach's alpha of 0.88. Self-efficacy for learning medical genetics was assessed using five questions adapted from the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich, Smith, Garcia, & McKeachie, 1991; e.g., I am confident and can understand the basic concepts of medical genetics) and had a Cronbach's alpha of 0.82. The items in the intrinsic motivation and self-efficacy scales used a five-point Likert scale ranging from (1) strongly disagree to (5) strongly agree. The knowledge test was based on 20 multiple choice questions (e.g., Which of the following syndromes is not a trisomy? A) Edwards syndrome, B) Klinefelter syndrome, C) Down syndrome, D) Turner syndrome) and had a Cronbach's alpha reliability of 0.68. A full list of items and the source of the scale is included in Appendix A.

### 2.3.2. Post-test

The post-test included the same intrinsic motivation, self-efficacy, and knowledge tests as the pre-test. These measures had Cronbach's alpha reliabilities of 0.90, 0.88, and 0.68 for the intrinsic motivation, self-efficacy, and knowledge measures respectively in the post-test. Representational fidelity was measured with three items from Lee et al. (2010; e.g., The realism of the 3-D helps enhance my understanding) and had a Cronbach's alpha of 0.86. Immediacy of control was measured with three items from Lee et al. (2010; e.g., The ability to change the view position of the 3-D objects allows me to learn better) and had a Cronbach's alpha of 0.76. Perceived usefulness was measured with four items adapted from Davis (1989; e.g., This type of virtual reality simulation will allow me to progress at my own pace) and had a Cronbach's alpha of 0.84. Perceived ease of use was measured with four items adapted from Davis (1989; e.g., Learning to operate this type of virtual reality program is easy for me) and had a Cronbach's alpha of 0.82. Presence was measured using four items adapted from Sutcliffe, Gault, and Shin (2005; e.g., My interaction with the simulation environment seemed natural) and had a Cronbach's alpha of 0.78. Perceived enjoyment was measured with three items adapted from Tokel and Isler (2015; e.g., I find using computer simulations enjoyable) and had a Cronbach's alpha of 0.93. Control and active learning was measured with five items adapted from Lee et al. (2010; e.g., This type of virtual reality program allows me to have more control over my own learning) and had a Cronbach's alpha of 0.88. Cognitive benefits was measured with four items adapted from Lee et al. (2010; e.g., This type of virtual reality program makes the comprehension easier) and had a Cronbach's alpha of 0.88. Reflective thinking was measured with four items adapted from Lee et al. (2010; e.g., Virtual reality simulations enable me to reflect on how I learn) and had a Cronbach's alpha of 0.81. All items with the exception of the knowledge test used a five-point Likert scale ranging from (1) strongly disagree to (5) strongly agree. A full list of items and the source of the scale is included in Appendix A.

### 2.3.3. Desktop VR medical genetics simulation

The desktop VR medical genetics simulation was developed in cooperation between the department of Cellular and Molecular

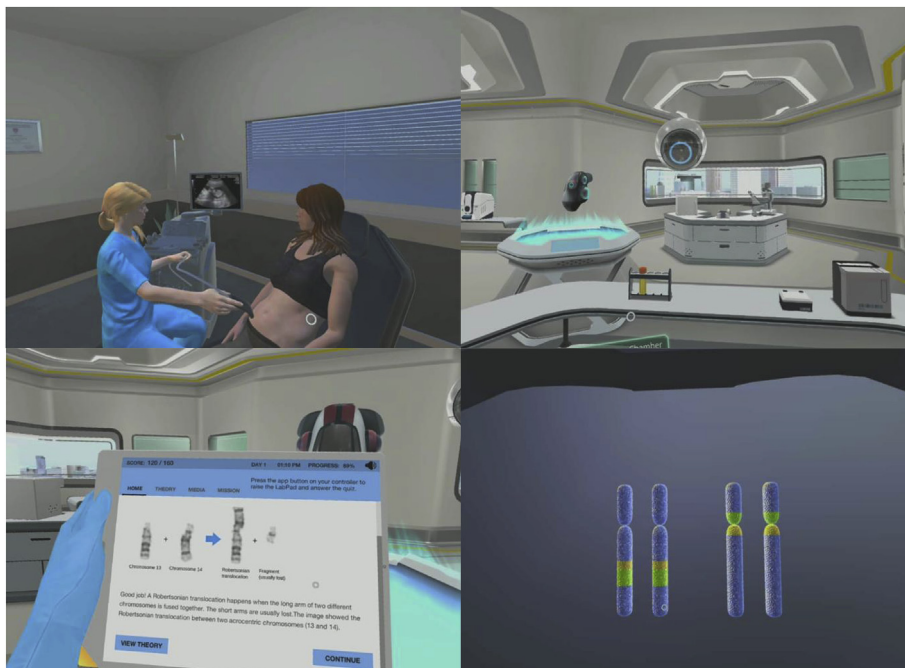


Fig. 2. Screenshots of the cytogenetics virtual lab simulation (Labster, 2019).

Medicine at the University of Copenhagen and the simulation development company Labster (see Fig. 2 for screenshots of the simulation). The simulation was designed to be a part of the core curriculum within the field of genetics at a university level. The simulation allows students to virtually work through relevant genetic procedures in a lab by using and interacting with state-of-the-art lab equipment, thereby learning essential content through an inquiry-based learning approach. The simulation starts by introducing the students to the virtual laboratory environment. Then students are introduced to a young pregnant couple, where the fetus may suffer from a syndrome caused by a chromosomal abnormality. The students are able to make a genome-wide molecular cytogenetics analysis of the fetal and parental DNA and karyotypes in the virtual laboratory, and practice communicating their conclusions to the couple using a simulated genetic counseling approach. The simulation contained three main parts: 1) An introduction of the case story (the fetus that may suffer from a syndrome caused by a chromosomal abnormality), where students are presented with a case-based challenge aimed at engaging the students emotionally and providing them with essential basic knowledge of the material, 2) A series of laboratory experiments that the students have to carry out in order to answer the research question associated with key learning goals, and 3) A final part where the students have to interpret their results and give genetic counseling, designed to stimulate reflective thinking and deep learning (for a short video that gives an overview of the simulation, see Labster, 2019).

The genetics VR simulation was developed according to the following general goals in line with guidelines from the National Research Council (2011): 1) To increase motivation by having students experience the excitement and interest of learning about genetics phenomena with a realistic case. 2) To increase conceptual understanding by providing students with retrieval practice of key terms through quiz questions which are presented throughout the simulation. 3) To increase science-processing skills by having students manipulate, test, explore, predict, observe, and make sense of relevant material in a virtual environment that simulated real lab equipment. 4) To understand the nature of science by having students play the role of a doctor who has to diagnose and communicate the lab results to a patient and their family. 5) To have students participate in scientific activities and learning practices using scientific language and tools. 6) To give students the opportunity to experience what it is like to use genetics in a realistic setting to solve a realistic problem. The VR simulation includes progressively challenging material that builds on the knowledge that is gained throughout. Reflective thinking is prompted through students' interaction with the laboratory environment, and by obtaining explanatory feedback to multiple choice questions wherein the accuracy of their results provides a running score. Self-paced and guided learning principles are used throughout the simulation to enhance learning.

#### 2.4. Statistical analyses

The SEM analysis were performed in Mplus version 7.4 (Muthén & Muthén, 2015). The items were treated as ordinal variables and are reported using the following goodness-of-fit indices according to Hu and Bentler (1999): the Comparative Fit Index (CFI), the Tucker-Lewis Index (TLI), and the Root Mean Square of Approximation (RMSEA). Acceptable fits were indicated by CFI and TLI scores  $\geq 0.90$  and an RMSEA score  $\leq 0.06$ . Data was collected with SurveyMonkey software.

### 3. Results

A confirmatory factor analysis was conducted to test the fit of the hypothesized relationship between the constructs in the a priori model shown in Fig. 1. This hypothesized model nearly reached an acceptable fit (RMSEA = 0.063, CFI = 0.957, TLI = 0.952), but contained several non-significant paths which were deleted by an iterative procedure. Each of these paths were evaluated and removed one at a time based on the greatest misfit until all of the remaining paths were significant. This resulted in a simplified model containing only significant loadings (see Fig. 3). The final simplified model in Fig. 3 obtained an acceptable fit (RMSEA = 0.057, CFI = 0.964, TLI = 0.960). Furthermore, all the standardized path coefficients shown in Fig. 3 are significant at the alpha level of 0.01. Below we present the results related to each of the 10 hypotheses proposed in this study.

#### 3.1. Hypothesis 1: VR features will predict usability

Hypothesis 1 was supported. VR features was a significant antecedent to usability as predicted in the a priori model (beta = 0.894,  $p < 0.001$ ). Furthermore, representational fidelity (beta = 0.874,  $p < 0.001$ ), and immediacy of control (beta = 0.823,  $p < 0.001$ ) had significant paths to VR features, indicating that the construct could be measured with these two variables. Finally, perceived usefulness (beta = 0.924,  $p < 0.001$ ), and perceived ease of use (beta = 0.732,  $p < 0.001$ ) had significant paths to usability.

#### 3.2. Hypothesis 2: VR features will predict the affective variables of presence, perceived enjoyment, and control and active learning

Hypothesis 2 was partially supported. VR features was only a significant antecedent to presence (beta = 0.871,  $p < 0.001$ ) and perceived enjoyment (beta = 0.835,  $p < 0.001$ ), but was not significantly related to control and active learning in the final model.

#### 3.3. Hypothesis 3: usability will predict the affective variables of presence, perceived enjoyment, and control and active learning

Hypothesis 3 was partially supported. Usability was a significant antecedent to control and active learning (beta = 0.985,  $p < 0.001$ ), but was not significantly related to presence or perceived enjoyment.



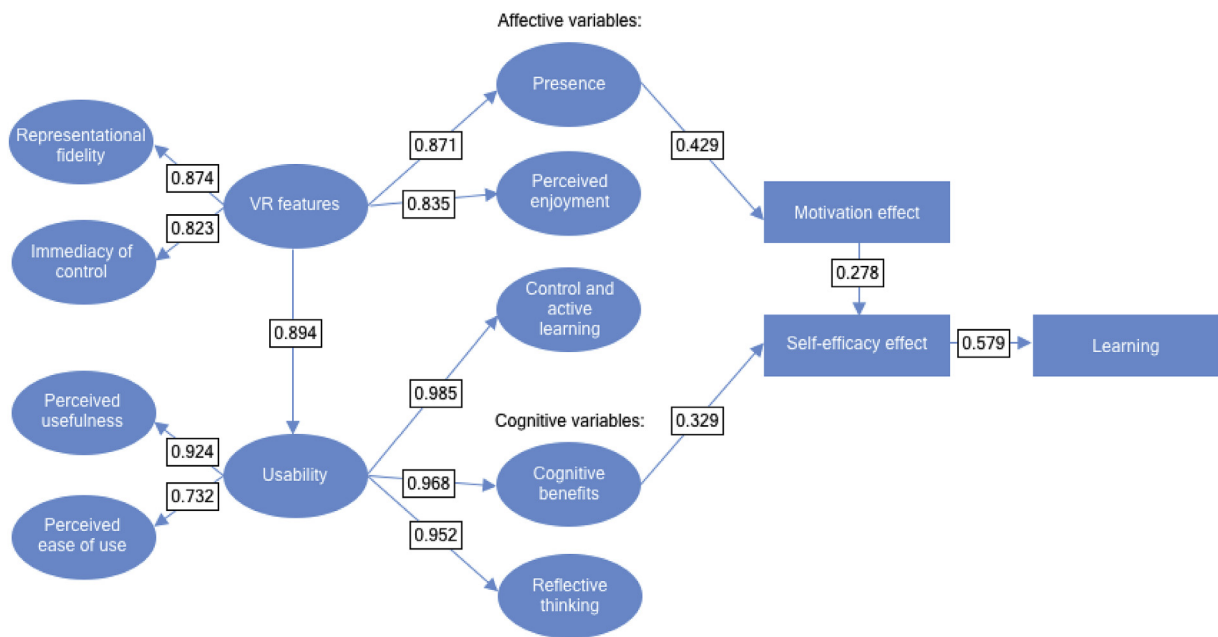


Fig. 3. The final model.

#### 3.4. Hypothesis 4: VR features will predict the cognitive variables of cognitive benefits and reflective thinking

Hypothesis 4 was not supported. VR features did not significantly predict cognitive benefits or reflective thinking, indicating that the representational fidelity and immediacy of control experienced in the VR genetics simulation were not related to student's perceptions of the cognitive benefits or their reflective thinking when using the simulation.

#### 3.5. Hypothesis 5: usability will predict the cognitive variables of cognitive benefits and reflective thinking

Hypothesis 5 was supported. As expected, usability was a significant antecedent to cognitive benefits ( $\beta = 0.968$ ,  $p < 0.001$ ), and reflective thinking ( $\beta = 0.952$ ,  $p < 0.001$ ) in this study.

#### 3.6. Hypothesis 6: the affective variables will predict the outcome variables in this study

Hypothesis 6, that the affective variables of presence, perceived enjoyment, and control and active learning would predict the outcomes of change in motivation, change in self-efficacy, and learning, was partially supported. In general the affective variables turned out to be less strong predictors for the measured effect variables than the a priori model projected. Perceived enjoyment and control and active learning were not significant antecedents to any of the measured outcome variables. Presence was the only psychological variable that was a significant antecedent to change in motivation ( $\beta = 0.429$ ,  $p < 0.001$ ), but it did not directly predict change in self-efficacy or learning.

#### 3.7. Hypothesis 7: the cognitive variables will predict the outcome variables in this study

Hypothesis 7, that the cognitive variables of cognitive benefits and reflective thinking would predict the outcomes of change in motivation, self-efficacy, and learning, was partially supported. Reflective thinking was not a significant antecedent to any of the measured outcome variables. Cognitive benefits was a significant antecedent to change in self-efficacy ( $\beta = 0.329$ ,  $p < 0.001$ ), but it did not directly predict change in intrinsic motivation or learning.

#### 3.8. Hypothesis 8: a change in intrinsic motivation will be related to a change in self-efficacy

Hypothesis 8 was supported. As expected, in this study the change in intrinsic motivation was significantly related to the change in self-efficacy from prior to after the learning intervention ( $\beta = 0.278$ ,  $p < 0.001$ ).

#### 3.9. Hypothesis 9: an increase in intrinsic motivation will predict learning

Hypothesis 9 was not supported. That is, there was not a significant direct relationship between the change in intrinsic motivation

and students' learning. However, as can be seen in Fig. 3, the relationship between motivation and learning goes through self-efficacy.

### 3.10. Hypothesis 10: an increase in self-efficacy will predict learning

Hypothesis 10 was supported. In this study an increase in self-efficacy was significantly related to learning ( $\beta = 0.579$ ,  $p < 0.001$ ).

## 4. Discussion

### 4.1. Empirical contributions

The major empirical contribution of this paper is the finding that there are two paths that lead to learning with desktop VR when measures of pre-to post-test change are used as dependent variables. These are labeled the affective and the cognitive paths, and provide a framework by which learning in VR can be investigated.

#### 4.1.1. Path 1: the affective path

The results support the hypothesis that the features of the VR technology, i.e. the degree of realism provided by the environment and the control factors in the environment, are related to a greater sense of presence or “being there” in the VR environment. This heightened sense of presence is furthermore related to an increase in intrinsic motivation, which in turn relates to changes in self-efficacy for the learning material. Finally, positive changes in self-efficacy are related to more learning.

Although the affective path in the a priori model is proposed as directional starting with VR features and ending with learning, the causal relationship between these variables is likely more complex. According to Witmer and Singer (1998), the experience of presence arises from an interplay of both technological (VR features) and psychological contributing factors, such as willing suspension of disbelief and involvement, which is a form of mental vigilance facilitated by being fully focused and cognitively engrossed. Based on this, it is possible that the interpersonal variance in changes in intrinsic motivation could relate to the learners' differences in involvement, which might in turn have impacted the degree of presence they experienced from the VR simulation. On the other hand, it is also plausible that the learners who are willing to suspend disbelief report more presence, which leads to positive changes in intrinsic motivation, self-efficacy and ultimately learning. Several recent articles have found an increase in presence when comparing higher fidelity VR simulations to low fidelity versions of the same simulation (e.g., Buttussi & Chittaro, 2018; Makransky Lilleholt et al., 2017a; Parong & Mayer, 2018). However, the increase in presence in these studies did not result in more learning. This has led researchers to conclude that higher fidelity can cause higher presence; but this can often result in lower learning because irrelevant sensory information in high fidelity VR environments leads to extraneous processing which is not necessary for learning (e.g., Makransky Terkildsen et al., 2017b). The results of this study suggest that the role of presence in developing learning is not simple, but rather depends upon a number of other important variables (such as intrinsic motivation and self-efficacy).

The finding of an affective path where presence plays a key role in predicting learning outcomes is consistent with the findings in Makransky and Lilleholt (2018), in which they investigated the process of learning with immersive VR. This research found that VR features was a significant antecedent of presence, and that presence in turn was a significant antecedent of intrinsic motivation and enjoyment, both of which led to greater perceived learning outcomes. Similarly, presence played a mediating role leading to learning in the present study. While also being affected by VR features and predicting intrinsic motivation, however, the path that was uncovered in the present model went through the additional variable of self-efficacy to increase learning. These results are also similar to the findings in Lee et al. (2010); however they found that presence directly predicted the learning outcomes with desktop VR. Furthermore, their finding that VR features and not usability was an antecedent of presence was reproduced in this study, and seems to confirm that presence is induced by the fidelity of the representation and the degree of user control. Therefore, a major empirical contribution of this study is the finding that an affective path also leads to learning when the learning outcomes are measured as changes from pre-to post-test scores.

Another interesting finding, or lack of finding, in the present study is that of a missing association between usability and presence. One way of conceptualizing presence is with respect to its associated “forgetting” of the display medium itself, meaning that the learner experiences a sense of being there in the virtual environment, and hence forgets the virtuality of the experience (Lombard & Ditton, 1997; Makransky Lilleholt et al., 2017a). This conceptualization of presence bears a resemblance to the purpose of developing usable user-interfaces, in the sense that highly usable interfaces are so intuitive and transparent that the user forgets the medium and technology itself, and instead focuses on engaging with the content. Consequently, so-called usability breakdowns may be described as a failure of an interface to be usable, which directs attention to the interface itself as opposed to the content (Hartson & Pyla, 2012). The finding that usability was not significantly related to presence in this study may have occurred because there were few usability breakdowns (such as technical problems). This may have caused lower variability across users on this variable, which would lead to a weaker relationship with presence, as compared to a setting wherein some students have usability breakdowns and others do not. Another explanation of the missing link between usability and presence could be that we measure perceived usability, e.g. perceived ease of use; and that subjective usability measures in previous literature has been shown to be affected by factors such as the aesthetics of the interface (Tractinsky, Katz, & Ikar, 2000). Consequently, actual measures of usability such as usability “breakdowns” (i.e. when learners got stuck in the simulation), or efficiency and effectiveness measures (i.e. time taken to perform tasks, or accuracy and completeness of achieved goals; Bevan, Carter, & Harker, 2015), might have shown a relationship between usability and presence.

#### 4.1.2. Path 2: the cognitive path

The features of the VR technology also played a role in the cognitive path by increasing students' beliefs about the usefulness of the simulation and its ease of use. This increases students' ratings of the virtual environment as leading to improved understanding, application, and positive perceptions of the learning material (cognitive benefits), which in turn leads to higher self-efficacy and more learning.

The finding of a cognitive path wherein cognitive benefits plays a key role in affecting the learning outcomes is consistent with the study by Makransky and Lilleholt (2018). They found that VR features both directly and indirectly (through usability) predicted cognitive benefits, and that cognitive benefits in turn was a significant antecedent of the perceived learning outcomes. However, while cognitive benefits directly affected the learning outcomes in their study, it played a mediating role in present study by first predicting higher self-efficacy for the learning material, which then led to more learning. Another key difference between the Makransky and Lilleholt study and the present study is the fact that VR features in their study was an antecedent of cognitive benefits, whereas this relationship only exists indirectly through usability in present study. These results are also similar to the ones presented in Lee et al. (2010); however they found that cognitive benefits directly predicted the learning outcomes with desktop VR. Nevertheless, their finding that VR features did not directly relate to cognitive benefits, and that the effect was mediated by usability, was reproduced in this study. A major empirical contribution of this study is the finding that a cognitive path comprising cognitive benefits also leads to learning when the learning outcomes are measured as changes from pre-to post-test scores.

Although the results in this study partially support the previous research that has used SEM to investigate the process of learning in VR, there were also a substantial number of hypothesized relationships that were not found in this study. This could be the consequence of using measures of change as the outcome variables in this study, rather than self-report measures (as has been used previously).

#### 4.2. Practical implications

This study provides a model for understanding the factors that play a role in learning with desktop VR simulations, as well as their mutual relationships. We highlight how features of the VR technology and the interaction experience may impact central affective and cognitive factors, and in turn how these may affect objectively measured learning outcomes.

The findings of this study can be used to inform practitioners and educators who wish to use desktop VR for educational purposes. First, the results suggest that VR features is an important variable to emphasize when designing virtual environments. Specifically, the degree of realism provided by the environment and the ability to control factors in the environment is related to learners' sense of presence. Learners who have a high level of presence have greater increases in intrinsic motivation and self-efficacy for learning, which ultimately influences how much they learn. Ensuring high quality VR features could, for instance, be achieved in the design process by allowing for a realistic display of the environment, smooth display of view changes and object motions, 3-D audio technology as well as a high degree of view control, navigation, and object manipulation (Dalgarno & Lee, 2010). Secondly, the results suggest that usability is an important variable to take into account when designing virtual environments. Making sure that the simulation is perceived as useful and easy to use is important for increasing learners' ratings of the cognitive benefits associated with the VR lesson. This is related to their self-efficacy for learning, which finally leads to more learning. A high level of usability in VR simulations may be achieved by designing virtual environments that provide navigation and orientation support, clear entry and exit points, cues and explanations for active objects etc. (see Sutcliffe & Gault, 2004).

An important point to consider is how teachers should incorporate VR simulations in their teaching. One way of accomplishing this is through the use of blended learning systems, which combine face-to-face instruction with computer-mediated instruction (Graham, 2006). Twigg (2003) identified different blended learning models that are used in higher education. One of them, the replacement model, suggests that teachers replace some class meetings with online, interactive learning activities for students, under the assumption that certain activities are better approached online. High-fidelity laboratory VR simulations, such as the one used in present study, could fit well with such a blended learning model, as some laboratory activities are difficult and expensive to carry out in class and therefore may be better accomplished through VR (Jones, 2018). Educators could benefit from incorporating simulations in the shape of digital learning objects in their teaching (Turel & Gürol, 2011). Learning objects can be described as small, reusable units of learning, and the term can be used to describe some virtual learning simulations (Frantiska, 2016). In general, learning objects are self-contained (each learning object can be used independently), reusable (a single learning object may be used in multiple contexts for multiple purposes), and versatile (they can be grouped into larger collections of content, including traditional course structures; Frantiska, 2016). Most VR simulations for learning are versatile, as they are often intended to be used as part of a conventional course. However, it could be beneficial from an economical and practical point of view to invest in simulations that, in addition to their versatility, are self-contained and reusable. An example could be a VR science simulation on general laboratory safety behavior, which could stand alone, be used in several STEM disciplines, and be used as part of an introductory chemistry course.

#### 4.3. Limitations and future directions

This study tested a framework for learning in VR based on previous research that has identified the most relevant variables for describing the process of learning in VR. Since there are many variables that could play a role in this process, future research should investigate additional variables that were not included in the a priori model investigated in this study. For instance, variables such as identity construction, co-presence, and flow (Dalgarno & Lee, 2010) or simulator sickness and field-of-view (Lin, Duh, Parker, Abi-

Rached, & Furness, 2002) could all potentially play a role in the process of learning in VR. Furthermore, SEM is based on the relationship between variables. However, some of the investigated relationships are likely complex, and may only be understood by developing carefully constructed experiments that provide a detailed understanding of the relationship. An example from this study is the fact that presence played a role in learning because higher presence was related to a positive increase in intrinsic motivation, which led to a change in self-efficacy and learning. However, recent research investigating the effect of immersive VR in learning has found that immersive VR leads to more presence but less learning (e.g., Makransky Lilleholt et al., 2017a; Makransky Terkildsen et al., 2017b; Parong & Mayer, 2018), suggesting a complicated relationship between these variables. Future research should further investigate the relationships found in this study by developing experiments that provide a deeper understanding of how the variables are related when learning in VR. This could be done by comparing different versions of VR simulations, or through comparisons with other teaching materials that vary the relevant constructs systematically. Future research should also investigate if the model used in this study generalizes to other samples of students and for different subject matter. As students were allowed to interact during the learning session, it is a limitation that we did not measure collaborative construction of knowledge as this potentially could have affected the learning outcomes. However, in general the students worked independently, and asked for help from teachers, other students, and researchers only when they were stuck in different parts of the simulation. Furthermore, the students used the VR simulation for two hours, which could have impacted the results. Future research should investigate the effect of time spent in VR simulations on learning outcomes and affective and cognitive variables.

Another limitation in this study is the fact that we exclusively focus on the learning model and not on learner effects. Since the SEM model used in this study is based on individual variability, there are inevitably some students who did not experience as much presence or see the cognitive benefits of the simulation and hence did not benefit as much from it. Future research should investigate variables related to individual differences to obtain a better understanding of the learner characteristics that influence learning in VR. One variable that could be investigated is prior knowledge, as variations in prior knowledge has been highlighted as an individual difference that can play an important role in multimedia learning (e.g., Kalyuga, Ayres, Chandler, & Sweller, 2003).

The learning effect was assessed immediately following only one VR simulation session in this study. Most of the studies on learning in VR have investigated single VR interventions, which means that little is known about the long term implications of repeatedly using VR for learning. Future research should therefore investigate the learning implications of repeated sessions as well as mid-to long-term knowledge acquisition and transfer. Future research should also seek to combine objective and subjective process measures of learning to gain a deeper understanding of the process of learning in VR. This could include the use of log files to measure factors such as control and usability. Psychophysiological measures such as electroencephalography (EEG), galvanic skin response, tracking of facial expressions, and eye tracking are other examples of objective process measures that could be investigated in future research.

5. Conclusions

Through the use of SEM, the present study tested a model based on previous work in the field of learning with VR. This resulted in a simplified model with two general paths by which the desktop VR simulation led to increased learning; an affective path in which presence was the key psychological variable; and a cognitive path with cognitive benefits as the key psychological variable. Furthermore, the influence of presence and cognitive benefits on the process of learning in VR was underscored by the use of objectively measured learning outcomes. Practitioners and educators may benefit from the findings of this study, as the results may be used to inform the design process of virtual environments for educational purposes. That is, VR features was found to contribute significantly to the affective path by increasing learners' sense of presence, which led to higher intrinsic motivation, self-efficacy and learning. Furthermore, VR features was found to contribute significantly to the cognitive path by increasing usability and learners' ratings of the cognitive benefits associated with the VR simulation, which influenced self-efficacy and learning. Consequently, emphasizing efficacious VR features and a high level of usability when designing virtual environments may benefit learners partaking in VR lessons.

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Appendix A

Survey items and sources.

Construct	Items	Source
Representational fidelity	1. The realism of the 3-D images motivates me to learn. 2. The 3-D images make learning more interesting. 3. The realism of the 3-D helps enhance my understanding.	Lee et al. (2010)

Immediacy of control	<ol style="list-style-type: none"> <li>1. The ability to change the view position of the 3-D objects allows me to learn better.</li> <li>2. The ability to change the view position of the 3-D objects makes learning more motivating and interesting.</li> <li>3. The ability to manipulate the objects (e.g.: pick up, cut, change the size) within the virtual environment makes learning more motivating and interesting.</li> <li>4. The ability to manipulate the objects in real time helps to enhance my understanding.</li> </ol>	Lee et al. (2010)
Perceived usefulness	<ol style="list-style-type: none"> <li>1. Using this type of virtual reality/computer simulation as a tool for learning will increase my learning and academic performance.</li> <li>2. Using this type of virtual reality simulation will enhance the effectiveness of my learning.</li> <li>3. This type of virtual reality simulation will allow me to progress at my own pace.</li> <li>4. This type of virtual reality simulation is useful in supporting my learning.</li> </ol>	Davis (1989)
Perceived ease of use	<ol style="list-style-type: none"> <li>1. Learning to operate this type of virtual reality program is easy for me.</li> <li>2. Learning how to use this type of virtual reality program is too complicated and difficult for me. (R)</li> <li>3. It is easy for me to find information with the virtual reality program.</li> <li>4. Overall, I think this type of virtual reality program is easy to use.</li> </ol>	Davis (1989)
Presence	<ol style="list-style-type: none"> <li>1. My interaction with the simulation environment seemed natural.</li> <li>2. My experiences in the virtual environment seemed consistent with real world experiences.</li> <li>3. I was engaged in the virtual environment experience.</li> <li>4. I was involved in the experimental task to the extent that I lost track of time.</li> </ol>	Sutcliffe et al. (2005)
Perceived enjoyment	<ol style="list-style-type: none"> <li>1. I find using computer simulations enjoyable.</li> <li>2. Using computer simulations is pleasant.</li> <li>3. I have fun using computer simulations.</li> </ol>	Tokel and Isler (2015)
Control and active learning	<ol style="list-style-type: none"> <li>1. This type of virtual reality program helps me to have a better overview of the content learned.</li> <li>2. This type of virtual reality program allows me to be more responsive and active in the learning process.</li> <li>3. This type of virtual reality program allows me to have more control over my own learning.</li> <li>4. This type of virtual reality program promotes self-paced learning.</li> <li>5. This type of virtual reality program helps to get me engaged in the learning activity.</li> </ol>	Lee et al. (2010)
Cognitive benefits	<ol style="list-style-type: none"> <li>1. This type of virtual reality program makes the comprehension easier.</li> <li>2. This type of virtual reality program makes the memorization easier.</li> <li>3. This type of virtual reality program helps me to better apply what was learned.</li> <li>4. This type of virtual reality program helps me to better analyze the problems.</li> </ol>	Lee et al. (2010)
Reflective thinking	<ol style="list-style-type: none"> <li>1. Virtual reality simulations enable me to reflect on how I learn.</li> <li>2. Virtual reality simulations enable me to link new knowledge with previous knowledge and experiences.</li> <li>3. Virtual reality simulations enable me to become a better learner.</li> <li>4. Virtual reality simulations enable me to reflect on my own understanding.</li> </ol>	Lee et al. (2010)

#### Outcome variables measured in pre- and post-test.

Constructs	Items	Source
Intrinsic motivation	<ol style="list-style-type: none"> <li>1. I enjoy working with Medical Genetics.</li> <li>2. Medical Genetics activities are fun to perform.</li> <li>3. Medical Genetics is boring.</li> <li>4. Medical Genetics does not hold my attention at all.</li> <li>5. I would describe Medical Genetics as very interesting.</li> </ol>	Makransky et al. (2016a)
Self-efficacy	<ol style="list-style-type: none"> <li>1. I am confident and can understand the basic concepts of Medical Genetics.</li> <li>2. I am confident that I understand the most complex concepts related to Medical Genetics.</li> <li>3. I am confident that I can do an excellent job on the assignments and tests in the Medical Genetics exercises.</li> <li>4. I expect to do well in Medical Genetics.</li> <li>5. I am certain that I can master the skills being taught in Medical Genetics.</li> </ol>	Makransky et al. (2016a)
Learning	<ol style="list-style-type: none"> <li>1. If a girl with Turners syndrome has X-linked recessive red-green color blindness, and the girl's father has red-green color blindness, then her chromosome disorder has originated through non-disjunction, but when and in whom?</li> <li>2. A pair of siblings both suffer from dyslexia, and so do their mother and her father (the maternal grandfather). A chromosome analysis revealed that ...</li> <li>3. A baby boy with malformations and signs of developmental delay is diagnosed with Wolf-Hirschhorn syndrome. He has the karyotype 46,XY,del(4)(p16; pter). Which of the following most accurately describes his condition and the mechanisms behind it?</li> <li>4. A young couple is expecting a child, but the routine ultrasound examination reveals an abnormality which could be a sign of Down's syndrome in the fetus. The father's father has a cousin with Down's syndrome. Which of the following karyotypes ...</li> <li>5. A woman experienced seven spontaneous miscarriages and had no offspring while married to her first husband; whereas she gave birth to healthy twins two years after marrying her second husband. Which of the following combinations of karyotypes could ...</li> <li>6. A newborn girl with multiple malformations had what seemed to be normal chromosomes after chromosomal banding and karyotyping, but array-CGH revealed a duplication of a small part of chromosome 11q22. Why did her karyogram look normal?</li> <li>7. Which of the following syndromes is not a trisomy?</li> <li>8. If a child with Down's syndrome has the karyotype 47,XX,+21, which of the following karyotypes do you expect to find in one of the parents?</li> <li>9. A young man is diagnosed with Klinefelter syndrome. What are his chances for having healthy children without medical assistance?</li> <li>10. What chromosomal rearrangement must have taken place in order to change the chromosome on the left into the derivative chromosome on the right?</li> </ol>	



11. A child is born with the karyotype 47,XXX. This can be caused by non-disjunction, but what can we determine about in whom and at which meiotic division?
12. A young couple has for two years tried to have children without success. The wife has experienced several miscarriages. Their karyotypes are 46, XX and 45,XY,der(22; 22)(q10; q10). What different phenotypes can we expect in their future children?
13. A person with the karyotype 46,XX,der(18)t(12; 18)(p13; q12) carries 46 chromosomes ...
14. This karyotype derives from a child with a chromosomal abnormality which leads to a very severe phenotype. What is the risk that the biological parents of this child in the future will have another child with the same abnormality?
15. An analysis of the chromosomes from a young girl with Down's syndrome showed that she carries a Robertsonian translocation between the two chromosome 21. How do you write her karyotype?
16. The karyotype originates from a phenotypically normal woman who had three spontaneous miscarriages. Which of the descriptions best fits her?
17. Which one of the following statements is most correct?
18. A healthy man carries a balanced reciprocal translocation which can be described by: 46,XY,t(1; 18)(p22; q23). What does this karyotype mean for his chances of getting normal and healthy children?
19. Individuals with three copies of autosomal chromosomes normally do not survive (except trisomies of e.g. 13, 18 and 21); whereas individuals with an extra X chromosome have relatively mild phenotypes. Why?
20. A 15 year old boy has mental retardation and malformations of the testes. Karyotype analysis showed 46 chromosomes with a duplication on chromosome 5q22-31. How does his karyotype explain his phenotype?

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