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Exploring students' perception of and interaction with representations, feedback, and characters in virtual learning environments

Ternblad, Eva-Maria

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Abstract: This thesis is about learning. It is about how younger students (6–12 years old) use things on-screen (representations, feedback, or virtual characters) and how they handle digitalised learning environments. I have explored this subject using many perspectives and theories, not only focusing on handheld tools and physical or virtual materials, but also on the social interactions behind the screens, and how certain collaborative patterns may evolve when working alone or with a peer or tutor on a tablet. In some cases, comparisons between virtual and physical interaction have been made (Paper I and II); in others, specific features and behaviours in virtual learning environments (VLEs) have been investigated (Paper III-V).

The results from the 5 studies in this thesis are in line with present research in the field, which is heterogeneous and sometimes inconclusive. While mindless digitalisation of physical materials may deprive students from specific activities or input, and thereby diminish the learning experience, VLEs that are well-designed and equipped with specific features can contribute to increased learning. Rather than drawing general conclusions that one kind of interaction is better than another, I highlight the complexity of virtual learning environments and their possible effects on the students using them. In all studies, the ambition has also been to analyse student behaviour in depth, observing or logging their interactions, and scrutinising the fuzzy, complex interplay of materials, strategies, and learning outcomes.

The thesis contributes to the ongoing debate on the effectiveness of digital tools in education, providing insights into how virtual and physical contexts can shape learning outcomes in different ways.

Key words: Virtual interaction, physical interaction, VLE, representations, feedback engagement, collaboration, teachable agents, learning science

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To family and friends, past and present

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Populärvetenskaplig sammanfattning

Samhällets storskaliga digitalisering har inte bara påverkat människors vardag och yrkesliv, den har också påverkat undervisning och lärande på ett genomgripande plan – inte minst när det gäller det kunskapsbyggande som tar plats i skolor och klassrum, under ledning av lärare. Under de senaste decennierna har pappersbaserat material och laborationsutrustning ersatts av applikationer och digitala verktyg i allt från historia till algebra och fysik. Under dessa decennier har också en hel del forskning utförts där man försökt utreda hur lärandet skiljer sig åt mellan olika typer av inlärningsmiljöer och kontexter, och vad om händer när läromedel digitaliseras. Trots detta saknas fortfarande mycket kunskap kring vilka specifika egenskaper ett läromedel bör ha för att optimera elevers lärande och förståelse.

Den här avhandlingen ämnar bidra till det här forskningsområdet. I fem olika studier har jag undersökt hur yngre elever (6–12 år) utnyttjar och interagerar med representationer, feedback eller karaktärer i virtuella lärmiljöer, och utvärderat hur deras kunskapsinhämtning kan skilja sig åt beroende på läromedlets utformning. Jag har inte bara jämfört fysiskt och pappersbaserat material med skärmbaserade applikationer, utan även tittat på den mellanmänskliga interaktion som äger rum bakom/framför skärmarna om man arbetar tillsammans med en och samma applikation. I vissa fall har jämförelser gjorts mellan skärmbaserad och manuell/fysisk interaktion; i andra fall har specifika funktioner och beteenden i virtuella lärmiljöer undersökts. Jag har inte utgått från ett enskilt teoretiskt perspektiv, utan låtit en bred palett av tidigare beprövad empirisk forskning inom kognitionsvetenskap, utbildningspsykologi och det fält som på engelska kallas ’learning science’, ligga till grund för mina forskningsfrågor och mina analyser.

Resultaten från studierna i avhandlingen ligger i linje med aktuell forskning inom området, som är heterogen och mångtydig. Det finns, kort sagt, inga enkla svar. Medan en slentrianmässig digitalisering av fysiskt eller pappersbaserat material kan beröva eleverna värdefulla erfarenheter och aktiviteter, och därmed försämra lärandet, kan specifika funktioner i väldesignade virtuella lärmiljöer tvärtom ha stor potential. Vad som är viktigt i sammanhanget är insikten om att skärmbaserat lärande sällan eller aldrig är fullt *jämförbart* med att lära sig med fysiska hjälpmedel, såsom papper, penna, eller konkret material. Inte bara erbjuder olika typer av material olika interaktionsmöjligheter, utan vi som människor beter oss också olika beroende på vilken inlärningsmiljö vi befinner oss i. Man bör därmed vara medveten om det som går förlorat när värdefulla fysiska och konkreta handlingar ersätts av skärmbaserad interaktion – som inte bara är mer abstrakt och sensomotoriskt fattigare, utan i vissa fall också riskerar att distansera oss till varandra och de problem vi försöker lösa.

List of original papers

Paper I

Ternblad, E.-M. & Tärning, B. (submitted). Mediating an understanding of areas of parallelograms: Exploring middle-school students' learning from virtual or physical representations

Paper II

Ternblad, E.-M. & & Morell Ruiz, M. (submitted). Virtual versus physical number line training for 6-year-olds: Affordances matter!

Paper III

Ternblad, E.-M., Haake, M., & Tärning, B. (2022). I will help you, but will you help me? How the perception of a teachable agent may influence performance. In S. Iyer, J.-L. Shih, W. Chen, & M. N. MD Khambari (Eds.), *Proceedings of the 30th International Conference on Computers in Education: Vol. I* (pp. 63–72). APSCE. URL https://icce2022.apsce.net/proceedings/volume1/

Paper IV

Ternblad, E.-M., Haake, M., & Tärning, B. (2020). Far from success – Far from feedback acceptance? The influence of game performance on young students' willingness to accept critical constructive feedback during play. In *Artificial Intelligence in Education, Lecture Notes in Computer Science*, 12163, *Vol. 12163. Artificial Intelligence in Education* (pp. 537-548). Springer. DOI: 10.1007/978-3-030-52237-7_432020

Paper V

Ternblad, E.-M., Bagra, S., Gulz, A. & Haake, M. & Tärning, B. (2023). Are pairs more attentive towards feedback than individuals? A glance into feedback neglect for middle-school students using an educational game in history. In *Proceedings of the 16th International Conference on Computer-Supported Collaborative Learning-CSCL*, 2023, pp. 115–122. International Society of the Learning Sciences. DOI: 10.22318/cscl2023.184792

Other related work by the author

Alce, G., Ternblad, E.-M. & Wallergård, M. (2019). Design and Evaluation of Three Interaction Models for Manipulating Internet of Things (IoT) Devices in Virtual Reality. *Human-Computer Interaction – INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part IV* (pp. 267-286). Cham: Springer. DOI: 10.1007/978-3-030-29390-1_15.

Ternblad, E.-M. (2022). Understanding areas of parallelograms through virtual geometrical representations: A pilot study. In S. Iyer, J.-L. Shih, W. Chen, & M. N. MD Khambari (Eds.), *Proceedings of the 30th International Conference on Computers in Education: Vol. I* (pp. 206–209). APSCE. URL https://icce2022.apsce.net/proceedings/volume1/

Ternblad, E. M. (2023). What If Interaction Fails? A Comparison of a Virtual and a Physical Learning Environment for Learning About Areas of Parallelograms. In *Proceedings of the 17th International Conference of the Learning Sciences-ICLS 2023* (pp. 1062-1065). International Society of the Learning Sciences. DOI: 10.22318/icls2023.788401

Ternblad, E. M., & Gulz, A. (2018). Visualizing Knowledge in the Era of Instructional Software and Gamification. Challenges in Design, Method and Practical Use. In Kay, J. and Luckin, R. (Eds.) *Proceedings of the 13th International Conference of the Learning Sciences (ICLS) 2018, Volume 3* (pp. 1-2). London, UK. DOI: 10.22318/cscl2018.1463

Ternblad, E.-M., Gulz, A., & Tärning, B. (2022). ‘I know that I clicked but not if I read’: An exploratory study comparing data traces and self-reports on feedback engagement. In S. Iyer, J.-L. Shih, W. Chen, & M. N. MD Khambari (Eds.), *Proceedings of the 30th International Conference on Computers in Education: Vol. I* (pp. 73–82). APSCE. URL https://icce2022.apsce.net/proceedings/volume1/

Ternblad, E.-M., Haake, M., Anderberg, E., & Gulz, A. (2018). Do preschoolers 'game the system'? A case study of children's intelligent (mis)use of a teachable agent-based play-&-learn game in mathematics. In C. Penstein Rosé et al. (Eds.), *Lecture notes in computer science: Vol. 10947. Artificial Intelligence in Education* (pp. 557–569). Springer. DOI: 10.1007/978-3-319-93843-1_41

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Tärning, B., Ternblad, E. M., Haake, M., & Gulz, A. (2023). A Quest for Information – And Data Literacy: Can 6th Graders Make Informed Decisions? In *Proceedings of the 17th International Conference of the Learning Sciences-ICLS 2023,* (pp. 1969-1970). International Society of the Learning Sciences. DOI: 10.22318/icls2023.114494

Tärning, B., Ternblad, E.-M., Haake, M., Gulz, A., & Nirme, J. (2022). Lessons learned from a study on distractions in virtual learning environments: Reliability, ecological validity and an elusive social component. *PRESENCE: Virtual and Augmented Reality*, *28*, 65–85. DOI: 10.1162/pres_a_00342

1 Introduction

The digital transformation of modern society is nothing short of a revolution. The growth in digital information technologies over the last 40 years has transformed everything from consumption patterns and journalism to social bonding and dating. It has changed how we interact with information and one another. And it has changed teaching and learning. Today, interacting and learning with digital devices has become the new normal, while hands-on experiences and sensorimotor activities where we explore the world directly with all our senses are becoming less and less frequent.

It is not surprising that digital interaction has become so popular. It is quick, effortless, and mobile. We can reach anything and anyone, anywhere, at any time, and all with a tiny piece of technology that fits in a pocket. The same is true when bringing digital devices to the classroom. No more heavy textbooks or outdated dictionaries. No more handling of costly, fragile, or dangerous laboratory equipment. No more lost handwritten notes or illegible essays. Repetitive and sometimes tedious tasks can be turned into motivating and engaging games. Students may engage with virtual characters or take on roles as avatars, exploring virtual worlds instead of reading or listening to instructions. By adding sound, interaction, or animations to an interface, static or unidirectional information becomes multimodal and immersive. Students seem happy and engaged. What more could we ask?

The long-term impact of digitalisation in schools is yet to be evaluated, even if we already today discern some of the negative effects of ‘digital cultures’ (Haidt, 2024; Penny, 2022). At the same time, research shows that educational technology cannot be ruled out as totally inefficient – quite the opposite (Bernard et al., 2023). In this discourse, it is important to remember that technologies tend to create modern myths, and thus sometimes portray digital tools as saviours that can transform hard work – such as learning – into an enjoyable, smooth, and swift enterprise (Suárez-Guerrero et al., 2023). Yet, as is frequently the case with myths, none of this is true. Neither does extensive digitalisation lead straight to improved digital skills (Eurostat, 2024).[1] Plainly, many questions remain unanswered.

1.1 Scope of the thesis

This thesis is about learning. It is about how younger students (6–12 years old) use things on-screen (representations, feedback, or virtual characters) and how they handle digitalised learning environments. I have explored this subject using many perspectives and theories, not only focusing on handheld tools and physical or virtual materials, but also on the social interactions behind the screens, and how certain collaborative patterns may evolve when working alone or with a peer or tutor on a tablet. In some cases, comparisons between virtual and physical interaction have been made; in others, specific features and behaviours in virtual learning environments (VLEs) have been investigated.

The results from the studies in this thesis are in line with present research in the field, which is heterogeneous and sometimes inconclusive. While mindless digitalisation of physical materials may deprive students from specific activities or input, and thereby diminish the learning experience, VLEs that are well-designed and equipped with specific features can contribute to increased learning. Rather than drawing general conclusions that one kind of interaction is better than another, I highlight the complexity of virtual learning environments and their possible effects on the students using them. In all studies, the ambition has also been to analyse student behaviour in depth, observing or logging their interactions, and scrutinising the fuzzy, complex interplay of materials, strategies, and learning outcomes.

The thesis consists of five papers, which are discussed in terms of the four central themes they raise: (i) differences between the interaction with physical representations and the interaction with virtual representations; (ii) how a social dimension can be added to a virtual interface by using virtual characters – such as teachable agents; (iii) how collaboration and tutoring may be affected when physical materials are digitalised; and (iv) aspects of self-regulation in virtual learning environments. Before going into these themes, I will give a

[1] The measurements from 2023 (Eurostat, 2024) show that digital skills, particularly among the younger population (16–24 years old), decreased significantly in Sweden in recent years.

brief overview of theoretical perspectives on learning and present some methodological considerations. The structure of the thesis is as follows:

In Chapter 2, I look at theoretical learning paradigms, from behaviourist perspectives to embedded and embodied learning. I also describe how these paradigms relate to teaching practices.

In Chapter 3, I discuss the methods used in my own research and in other studies.

In Chapter 4, I address how creating and manipulating representations by hand can differ from doing so on a screen, discussing aspects such as affordances, constraints, and tangibility (PAPERS I and II). I argue that such manipulations may scaffold or hinder different types of learning and discuss the difficulty of comparing materials.

In Chapter 5, I analyse how virtual characters – and especially teachable agents – may affect students' emotions, motivation, and engagement, as well as their resilience towards failure and criticism (PAPER IV). I argue that a student's perception of a teachable agent may have a significant impact on learning outcomes (PAPER III), and that the use of virtual characters to deliver feedback, whether positive or negative, carries certain risks (PAPER II).

In Chapter 6, I compare how collaborating with a physical material may differ from working together with a virtual material. I consider two aspects of how social interpersonal interaction may be affected when learning materials are digitalised: the interplay between instructors or teachers and students (PAPER II), and the communication between collaborating students (PAPER I). I also present how sharing tablets may affect students' inclination to engage in feedback (PAPER V).

In Chapter 7, I look at how VLEs may affect students' self-regulation and feedback acceptance, both in a broad sense and in specific learning situations. I also discuss the role of feedback according to different theoretical perspectives and how it may influence learning. The difference between delivering and receiving feedback in virtual or physical learning environments is analysed (PAPER II), and how students might be strengthened to accept negative feedback in VLEs (PAPERS IV and V).

Finally, Chapter 8 presents concluding remarks.

1.2 What do I mean by a virtual learning environment?

Before introducing my research questions, I will explain what I mean by a virtual learning environment. According to Dillenbourg et al. (2002), a virtual learning environment (VLE) is:

- A designed information space.
- A social space. Educational interactions occur in the environment, turning spaces into places.
- Explicitly represented. The representation of this information or social space can vary from text to 3D immersive worlds.
- A place where students are not only active, but also actors.
- Not restricted to distance education. VLEs also enrich classroom activities.
- A place that integrates heterogeneous technologies and multiple pedagogical approaches.
- A place that often overlaps with physical environments.

The virtual learning environments discussed in this thesis are slightly more constrained, however. A VLE can be a simpler educational game or an app targeting a specific academic subject or concept. As the title of the thesis implies, the VLEs in the thesis are also primarily screen-based, and the notion ‘virtual’ is used to contrast with ‘physical’, ‘real’, or ‘concrete’ learning environments. Thus, 3D virtual immersive worlds are not included either.

The reason for using the term VLE rather than ‘educational software’, ‘digital apps’ or the like is my focus on *interaction*. In a VLE, the student interacts with representations, characters, or information. The interface not only presents or visualises something, but also reacts to the student’s actions. VLE is also the standard term when discussing the digitalisation of laboratories in STEM subjects.

2 A brief history of theoretical perspectives on teaching and learning

I will begin with a brief history of theoretical perspectives on learning. First, I show that the meaning of 'learning' may differ depending on the view of the cognitive processes involved and the students who use them. Second, I show that the lens used to study learning not only can affect what is studied and how but can also be used to shape teaching practices.

2.1 Behaviouristic, constructivist, and socio-cultural views

Historically, and especially in experimental psychology, learning has primarily been seen as the strengthening of associative neural patterns by the impact of external stimuli. In other words, a learner memorises a certain behaviour as positive and rewarding or negative and uncomfortable due to reinforcements (Greeno et al., 1996; Hall, 2002; Shettleworth, 2013). The key to successful learning, according to this behaviourist approach, lies primarily in instruction, repetition, and delivering appropriate feedback about trials and errors.

At first glance, such a mechanistic perspective on learning may seem outdated and irrelevant – especially when it comes to classroom practices and knowledge-building. The days seem long gone when students were 'fed' facts, memorised them by endless repetition, and then recalled them by heart when asked about them. However, this does not mean it is not important to automatise certain skills, such as reading or basic arithmetic. Similarly, memorizing facts in subjects like history or social science is a prerequisite for later being able to analyse and reflect on historical events or complex social phenomena (Willingham, 2021). Thus, optimising learning by well-designed instruction with learning goals in mind is still a potent way of teaching, especially if it is accompanied with appropriate scaffolding and immediate, constructive feedback (Hattie & Timperley, 2007; Mory, 2013; Ohlsson, 2008; Shute, 2007). The body of research on how to design and deliver feedback is also comprehensive and instructive (ibid.).

Still, not even ‘perfect’ feedback is of any use if the students do not actually engage in it. Hence, one of the major critiques of this theoretical view is not taking the student’s emotional and cognitive states into account. This brings us to the cognitivist view of learning – also called constructivist learning theory – dating from the 1980s (Bada & Olusegun, 2015). It holds that learning does not primarily consist of memorising and feedback loops, but instead is a constructive process taking place in the in the learner’s mind. Learning is assumed to go from practical problem-solving to the mentalisation of concepts and transfer and has a strong metacognitive component. Hence, constructivists often advocate interactive settings where students can construct new knowledge and pay attention to the principles of generality (as opposed to repeating and memorising specific facts) (Greeno et al., 1996; Gärdenfors, 2010).

Constructivist approaches to teaching and learning are today common in all types of educational settings all over the world. The framework has also led to new scientific findings and domains, such as the importance of self-regulation in learning, how to motivate students to explore and investigate, and the benefits of interactive, manipulable learning materials. However, the focus on teaching more general learning strategies – at the expense of memorising factual knowledge – has also been debated and criticised (Barton, 2018; Gärdenfors, 2010; Linderoth, 2017). Furthermore, the automaticity of constructing mental models from perceptual input and exploration should not be overestimated, especially not for less capable students. It also important to bear in mind that the human brain relies on an efficient but parsimonious cognitive economy, where deduction and logic take time and effort while the motor tasks, the use of tools, and the search for visual cues are often less demanding (Kirsh, 2010; Linderoth, 2012).

A third way of studying teaching and learning processes is by applying a more socio-cultural and situated perspective. This widens the unit of analysis from a single learner to the social and cultural aspects of learning, including peers, tutors, tools, and learning materials (Greeno et al., 1996; Sawyer & Greeno, 2009). Knowledge and learning are then treated as distributed processes in a larger system, where some facts exist in the heads of individuals while others reside in the properties of artefacts or group activities. The perspective also implies that it is impossible to separate declarative knowledge ('knowing what') from procedural skills ('knowing how'), making it difficult to transfer knowledge from one situation or domain to another (ibid.).

The idea of treating learning processes as heavily influenced by activities 'outside' the learner's own mind has its roots in ethnography and anthropology (for example, Hutchins, 1995; Lave, 1988). It is also influenced by activity theory (Nardi, 1995) and the sociocultural school of thought founded by Vygotsky (1962; 1978). Important pedagogical ingredients advocated in this paradigm are meaningful, goal-oriented activities where actions can be gradually internalised, often by verbalisation and visualisation. Other important elements are the sharing of information, discussions, and collaboration. The sociocultural approach to teaching and learning is, together with the constructivist view, popular in many Western countries. The research community has contributed important findings about students' reasoning, cooperation, and interaction (for example, Mercer & Howe, 2012). It is an appealing theoretical framework, which transforms learning from a rather esoteric and solitary activity to an engaging social practice.

However, the socio-cultural perspective has also been criticised for underestimating students' needs for teacher-led instruction. In a recent publication, Gulz and Haake (2024) discuss how this paradigm has permeated the curricula in Sweden in the last decades, stating this perspective as 'very powerful in identifying and describing how learning can take place […] without formal instruction when humans participate in various activities in social contexts, utilizing different resources. The problem arises when all kinds of learning is described in the same way: humans participating in knowledge-building through social interaction and with the help of cultural resources. Even if not intended, the role of a teacher here risks being reduced to organizing social interaction between students and appropriate cultural resources for students' learning to emerge. As such this may work, but only if there are no requirements or expectations regarding *what* students should learn and *what experiences* they should take part of.' (my italics, pp. 30-31).

Thus, the authors argue, if we want all young people to acquire certain skills and certain knowledge the socio-cultural perspective needs to be complemented with other perspectives. They also point out how the perspective does not allow a differentiation between biologically primary and biologically secondary learning (Geary, 1995, 2005, 2008), thereby downplaying the importance (and existence) of adequate instruction, and trivialising the drawbacks of a very strong focus on the system level. 'If learning consistently is described as participating in a social practice with other people and different kinds of resources, the focus is heavily on the group or system level, with the learning individual more or less invisible. This can obscure discussions of individuals' opportunities – and rights – to learn'. (p. 35).

2.2 Embodied and embedded paradigms

A more novel paradigm is 'embodied learning' – an educational approach that emphasises the role of the body in the learning process. Invoking theories such as 'grounded cognition' (Barsalou, 2020) and 'embedded cognition' (Clark, 2008), this perspective expands the learning process from being purely a mental activity to also involving physical experiences, sensory input, and motor action. At the time of writing, the research on embodied learning is very heterogeneous. For example, while some researchers point out the significance of gestures or action schemas as a way of grounding mental concepts (Nathan & Walkington, 2017; Nathan et al., 2021), others emphasise the importance of touch, advocating that haptic cues carry important information and may scaffold learning in everything from chemistry to algebra (Dörr et al., 2022). The concept of an action being 'embodied' can also comprise everything from moving objects on a screen (Dubé & McEwen, 2015) to walking along a number line (Link et al., 2013).

Today it is a well-established fact that the body plays an important role in human cognition. Still, there is a difference between making this statement and implying that various movements will infallibly lead to a better understanding of abstract concepts. Recent research also reveals that advanced movements may impair working memory, hindering memorisation and learning (Montero-Melis, 2022).

2.3 To choose a theory, or not

What theoretical framework have I chosen in this thesis? The answer is none. Or, more accurately, all. On inspection, none of the theories (or learning traditions, as they also may be called) seem mutually exclusive. Rather, they can be regarded as separate ways of studying different cognitive aspects of learning at different levels. A synthesis of the paradigms would then be to acknowledge that the learning context, the used materials, the sensorimotor activities, the emotional state of the agent, and the social interaction between peers not only may affect learning but are all significant parts of the learning process. It is also easy to admit that procedural knowledge (for example, using a ruler) sometimes can be hard to distinguish from declarative knowledge (knowing what a centimetre is).

But just because one never learns something completely 'on their own' or 'in their mind alone' does not necessarily rule out the individual is mentalising facts and concepts and constructing new knowledge in their head. Equally, ‘practice makes perfect’ is not only applicable to motor skills or craftsmanship. Practising maths, by repetition and feedback, has an impact on your ability to do maths. And the more you write, the better you write. So, instead of contrasting these paradigms with each other, they should be seen as complementary, describing different aspects of learning. In the thesis, I have tried to illuminate how these paradigms relate to the research questions posed and the phenomena studied.

3 Methodological considerations

When trying to compare different types of learning materials it is easy to end up evaluating the pedagogical activities and instructions used with them instead of the materials themselves. This is a point made by both Sarama and Clements (2009) and Clark (1994) when discussing studies investigating the possible benefits of concrete manipulatives. Still, it may be the case that changing a material also transforms the learning situation. A specific material may be strongly associated with a certain pedagogy, learning tradition, or teaching practice, which makes it hard to change the one without changing the other.

How students learn can be investigated in many ways, with varying degrees of generalisability to other domains or situations. Thus, before moving on to the core of this thesis, it is worth considering the challenges involved in any study of learning, especially if conducting studies in real-world naturalistic contexts. Not only can it be hard to balance ecological validity with experimental rigour when comparing different materials but studying younger students in ordinary classrooms can also be demanding. Such methodological considerations are presented here, with an overview of different methods for collecting data and their limitations.

3.1 Comparing different learning environments and the problem with apples and pears

When trying to make a fair and accurate comparison between virtual and physical learning contexts, you immediately run into several problems. First, converting conventional materials (for example, textbooks, pen and paper, ruler, compass, laboratory materials, etc.) into a digital app inevitably alters the learning situation in several ways. It is not just the interactions that change, but also the access to different types of information (visual, auditory, tangible, and so on), the timing and nature of feedback and scaffolding (delivered by a system or by a teacher), and the degree of freedom in the learning situation. Even the tasks themselves may change, making some exercises redundant and others more prevalent. Second, the whole point of digitalising learning materials is to somehow either augment the learning experience (by, for example, adding specific features, impossible to perceive in reality) or to facilitate it (for the student, teacher, or both). To compare a static or inanimate virtual interface (for example, printed text on a screen) or a completely unconstrained interface (sketching apps, etc.) with, for example, pen and paper, is rather pointless – at least if studying teaching and learning. Such an evaluation may tell us something about specific interactions and how we might perceive information differently when it is screen-based rather than, say, in print. However, this is a small aspect of what learning – and especially school learning – truly encompasses.

Two studies in this thesis concern comparisons between virtual and physical learning environments. In both, we have focused on maintaining a high ecological validity, designing the virtual and physical stimuli in ways that correspond to what such materials 'normally look like'. That means, for example, restricting the virtual interaction to on-screen activities – not adding any extra material or exercises outside the interface. It also means adding automatic feedback, sometimes displayed for a fixed amount of time.

In PAPER I, students worked with one of two versions of a learning material in geometry, designed to mediate an understanding of the areas of parallelograms. The students in the physical condition interacted with a deck of cards and a plastic frame, shaping different parallel figures, and solving tasks on paper. The students in the virtual condition, on the other hand, interacted with virtual representations of the cards and the frame and solved tasks on-screen. The screen-based tasks had to be completed one after the other – a constraint that was impossible to implement in the physical condition. To 'save' the created shapes, the students in the physical condition drew them by hand. In the virtual condition, the students saved them on-screen. The students in the physical condition also marked out specific properties of the figures (base and height) by hand, while these concepts were shown on-screen in the virtual interface.

In PAPER II, the students estimated target numbers on a number line, either playing a game on a tablet (virtual condition) or on paper with instructions and feedback from a researcher (physical condition). In the virtual interface, the students could drag their fingers back and forth along the number line, but as soon as they lifted their finger, their estimation was logged and followed by automatic feedback (showing the correct response together with their own estimation). This automatic feedback was displayed for a fixed amount of time (but could be clicked away), after which it was followed by a new target number. In the physical condition, however, the students could change their response before the researcher provided feedback. This feedback had no time restrictions, allowing the researcher to be certain the students paid attention to what was said. Even though the students in the virtual condition were also scaffolded by a researcher, who followed their play and occasionally gave hints or guidance, the interactive environment they worked in was more constrained than the corresponding physical environment.

It is of course possible to design experiments where two learning environments are more alike, and where the internal validity is higher. Still, one of the central issues when converting traditional materials into VLEs is that apples are often – quite literally – turned into pears, making it hard to avoid confounds when comparing their effects. Hence, the comparative studies in this thesis are partly explorative, aiming not only to highlight learning outcomes, but also to show how constraints and affordances can shape the learning process and affect what is learnt and how.

3.2 The messy business of classroom studies

All the studies in this thesis were conducted in real learning situations in schools, and the experiments were set up as a part of the students' ordinary classroom activities. This sometimes entailed a quasi-experimental setup, where a total randomisation of participants between conditions was hard to accomplish. Students may, for example, be pre-assigned to different groups for instruction in half-sized classes – a format that can be suitable when conducting experiments. If the experimental conditions in a study differ significantly – such as in the studies in PAPER I and PAPER II – it is not suitable to let students in different conditions work side by side simultaneously, since they may glance at one another's work or start to swap materials between them.

Moreover, to randomly assign students from a class to a control group is a delicate matter, especially in lower grades where students expect to be treated equally, and often participate collectively in similar activities. For that reason, control groups often consist of whole classes, sometimes with a different teacher than for the experimental ones. One experimental condition can also be more time-consuming and demanding than the other, which may result in differences in group sizes. In the study in PAPER I, we used a stratified randomisation of the participants in the two experimental conditions. After having performed the pre-test, we ranked the students in each experimental class. We then assigned the most high-achieving students to the virtual condition. We also assigned a handful of students with special needs, who risked not taking part in the study, to the virtual condition, The others – approximately two thirds of the students – were then randomised to either the virtual or the physical condition. The reasons for our strategy were the following: First, the physical condition was slower and quite resource intensive. Thus, to ensure that the students in the physical condition received enough practice time during the intervention, this group had to be smaller than the group in the virtual condition. Second, higher-achieving students are often less affected by different materials and teaching practices. By not assigning possible outliers to the physical condition, we hoped to compensate for that group's lower statistical power.

Classroom studies also mean recruiting engaged teachers who are prepared to hand some of their precious instructional time to us researchers and let students use our materials or VLEs instead of other materials. This means finding appropriate classes and fitting the study to their schedules and prerequisites. You must plan long in advance and ensure teachers and other pedagogical staff are aware of how the study will affect their regular work. When you start, you cross your fingers for fear half the class will be off sick for the lessons you have 'booked' for the study, leaving you with an experiment with low power and less significance. To enrol new classes would take too much time, and to try to reach the absent students by rearranging the schedule is rarely an option. In the study in PAPER II, I made an optimistic beginner's mistake of not recruiting two more classes (or more) from the outset.

In all the studies but one (PAPER V), we researchers were the ones giving the instructions, helping the students, and guiding them through the tasks we have designed for them. The teachers were there as support and had the overall responsibility for the lessons and students, but they were not the ones providing instructions during the actual interventions. In our experience, this is a beneficial way to conduct explorative classroom studies – not least with respect to intervention fidelity. The study in PAPER V, however, took place during the Covid-19 pandemic, making it impossible for us to visit schools. Thus, we had to do the study remotely, joining in via a link, and leaving the teachers to help students log into the VLE. This was not only slow, but it was also very frustrating to 'observe' the students at one remove, with no real sense of what was going on.

Finally, studying children is not the same thing as studying adults, of course. Children are unpredictable: wonderful to study and fun to meet, but also full of surprises, approaching tasks in unexpected ways. However enthusiastic and curious they may be, they can be hard to keep on track, occasionally wanting to do other things than the ones you have prepared. In the studies presented here, we insisted on welcoming *all* students, without excluding those with specific challenges or special needs. Incomplete or inaccurate data from such students has sometimes been excluded, but inclusion has been a top priority. It also means that classes participating as control groups have been offered the opportunity to use the materials (games, etc.) after the study.

3.3 Measuring and evaluating learning

Cognitive science is an empirical research field, which involves gathering, analysing, and evaluating quantitative and qualitative data. When studying learning, the goal is not only to statistically evaluate an effect of an intervention, but also to disentangle the reasons for such effects and their possible implications. For this purpose, you can use a variety of methods and data gathering techniques. Performance, for example, can be measured with separate pre- and post-tests (such as in PAPER I and II), but also with data logs in an app (such as in PAPERS IV and V). These two types of measurements can also be combined (PAPER III).

Data logs can also be used to evaluate behavioural patterns (PAPERS II, IV and V) and even to infer inner cognitive states or strategies. In PAPERS II and V, for example, the time for displaying feedback on-screen was used as a behavioural indicator for students' attention to and processing of feedback. To use data traces and timestamps for modelling students' learning, however, is a difficult enterprise (Torrington, 2024; Wilson et al., 2017). Longer response times may indicate confusion but can just as well signal effort and thoroughness. Shorter response times, on the other hand, may suggest that a student finds a task easy but may just as well be due to wild guesses and low engagement. Moreover, we cannot be sure that a student is attending to screen-based information just because it is in front of them. Even though we can assume that a very short display of a feedback message may imply that a student could not possibly have read it (as in PAPER V), a longer display of the same message is no guarantee it has been read by the student in question.

Of course, not all behaviours can be reduced to clicks, and especially not if the study concerns physical materials. Consequently, we have also observed students and taken notes of their conversations (PAPER I) or observed their strategies and categorised them (PAPER II). In the study in PAPER II, we complemented the observation protocols with audio recordings. Transcriptions of these recordings were later used to classify different actions, such as estimating target numbers, presenting feedback, and off-task behaviour. This made it possible to some extent to compare qualitative differences between playing the digital game and doing it on paper.

Finally, it can also be relevant to ask students about their attitudes and feelings, using surveys or similar. We did this in one of the studies where we were curious about the relationship between students' attitudes towards a teachable agent and their performance in an educational game (PAPER III). However, it is important to point out that children's metacognitive capacities are limited, so to ask them about their preferences or emotional states is less straightforward than with adults. It is even harder to ask them about their actions and why they do things the way they do. For the study in PAPER II, we tried to make the students talk about their strategies when estimating target numbers on the number line, asking 'How did you know the number was there?' or 'Why do you think this number is over here?' Often, they were unable to explain, and said things like 'I don't know, I just guessed.' However, when we quietly observed them, they were often thinking aloud and gesturing: counting, pointing at different positions on the number line, and reasoning with themselves.

4 Working with physical or virtual representations

4.1 Creating representations by hand or selecting, moving, and changing representations on-screen

One of the most important differences between screen-based interactions and the use of pen and paper is the way we handle representations. While traditional handwriting and drawing is based on creating representations by recalling and executing visual-motor patterns, interactions in VLEs are most often based on *choosing* representations – or parts of representations – and arranging or changing them. When working with pen and paper, motor actions are widely varied and complex. In VLEs, however, a handful of motor patterns are used to create or manipulate a large variety of representations. The neural basis of such interactions and how different areas of the brain are used in different settings are beyond the scope of this thesis, but I will give some examples of how the creation of virtual and physical representations can differ, and how it may affect learning.

Let’s assume you are about to solve a geometry problem and want to draw a circle inside a square. This is hard, if not impossible, to do without specific tools and aids. Without the help of technology, you would probably use a ruler to draw the square and then a compass to shape the circle. You would have to pay close attention to scales and measurements and be careful about where you place things. Even after some time and effort, the drawing would not be perfect. Now let's examine a widely used VLE: GeoGebra. In this software, it is easy to create, change, and move geometric representations. You simply choose a function to create a specific shape (polygon, circle, etc.), click on the screen to start drawing, insert the measurements (radius, length, number of sides, etc.), and finish. The shape is created, but also defined numerically in the interface. If you want to change the figure’s properties, you merely change the measurements or drag it on-screen.

In GeoGebra, it is also possible to construct graphs, which is a very useful method when solving algebra problems. You just enter a function, and the corresponding graph is plotted immediately in an x- and y-coordinate system. This is a huge improvement compared to the slow, traditional way of drawing graphs manually. It is plain why GeoGebra has done so much to revolutionise maths education: students using the software are less anxious, engage better in problem-solving activities, and reach a deeper understanding (see, for example, Yohannes & Chen, 2023; Zhang et al., 2023). Does this mean that drawing imperfect figures or plotting graphs manually is unnecessary? Why not spare students from the difficult art of writing or drawing by hand when solving advanced abstract problems?

Answering this is not entirely straightforward. First, a large body of research shows a strong correlation between young students' visual-spatial skills (such as drawing a human body) and later mathematical achievement (Sinclair et al., 2018). Second, visualising abstract problems by sketching and diagramming is not only a powerful tool, but it is also essential when studying or practising higher level mathematics. Students who graph formulas by hand also often outperform students that do not (for example, Kop et al., 2020). And third, visual-spatial abilities can be trained. For example, when students draw and copy geometric figures, they not only improve their ability to draw but they also enhance their spatial understanding, discovering similarity, symmetry, congruency, and the like. By discussing what they are drawing, they learn essential spatial concepts (middle, above, below, side, etc.), and the spatial relationships become clearer. Sinclair et al. (2018), building on Duval (1998), made a study on the topic and found an intriguing, dynamic interplay between 6-year-olds' drawing and their visual perception, gestures, and language development. Evidently, drawing by hand can be a tool *for* learning, not only an artefact showing what has already been learnt.

When it comes to my own research, I found that students who used specific geometry materials (a deck of cards and a tiltable frame) sometimes found it difficult to depict parallel shapes by hand (PAPER I). However, when comparing students in different conditions (those using physical materials and creating representations on paper versus those manipulating and working with 'perfect' representations in a virtual interface), the activity of drawing figures and marking specific properties in these figures by hand turned out to be a fruitful exercise. Even if both student groups reached a similar level of understanding of how to calculate the areas of parallelograms, the students in the physical condition had a significantly better understanding of the concepts of base and height. As Duval (1998) and Sinclair et al. (2018) also point out, making students create, compose, and deconstruct geometric representations forces them not only to think more about them, but also to define them verbally and reason more about them. This, in turn, ought to increase their spatial understanding.

4.2 The benefits of interaction and manipulation

It is easy to think of representations as semi-abstract figures or models, representing real-world objects or events. Yet, they can equally well include physical or virtual objects, designed to concretise or visualise more abstract concepts. In educational settings, such materials are often used to represent elements or processes that can be hard for students to grasp, such as chemical or biological models, physical laws (magnetism, resistance, electricity), or numbers.

One specific type of concrete representations are physical manipulatives, i.e. malleable physical objects that can be built, grouped, or reshaped. A well-known example of a physical manipulative in early mathematics is base ten blocks (Figure 1, left), which students use to compare cubes (representing ones) with rods (representing tens) and flats (representing hundreds). Other examples are tangram puzzles (Figure 1, right) and geoboards (Figure 1, middle), which can be useful for making young learners aware of geometric shapes and relations.

Figure 1 Examples of physical manipulatives: base ten blocks (left), a geoboard (middle), and a tangram puzzle (right).

The pedagogical principles of physical manipulatives rely mainly on a constructivist theoretical framework (Chapter 1), as the students are actively engaged in discovery during the learning process (for example, Glasersfeld, 1997; Goldin, 1990). Likewise, theorists such as Piaget (2003) advocate the use of this kind of materials, stating that children learn to master concepts by progressing through three levels of knowledge: concrete, pictorial and/or representative, and abstract. Many researchers in cognitive science also argue it is essential to ground abstract concepts and causal relations in concrete, real-world experiences, not at least in STEM subjects (Duijzer, 2019; Hayes & Kraemer, 2017).

The actual benefit of using manipulatives in schools has been a matter of debate for decades, however. Ever since Ball stated that 'Understanding does not travel through the fingertips and up the arm' (1992, p. 3), some researchers have said mere manipulation is not sufficient for learning, and that it may hinder knowledge acquisition and impair transfer (Carbonneau et al, 2013; Kaminski et al., 2006). Several also argue that even if interactions with manipulatives may be beneficial, it is probably not the environment's actual *physicality* that is important, but the opportunity to meaningfully interact with artefacts and representations (concrete or virtual) and to receive proper instruction how to do so (Sarama & Clements, 2009; Clark, 1994).

It has also been shown that the specific design of a manipulative is important, not least for transferring knowledge from one situation to another. This has been highlighted by Schwartz and Martin (2006), who applied a distributed theoretical framework to how Year 5 students use tiles to learn about fractions. In a series of studies, they investigated how both the format of the representations (squares or pie wedges) and the presentation of them (with the tiles pr wedges grouped differently) influenced learning outcomes. The authors discovered that working with a more unstructured material (squares) lead to slightly less efficient *immediate* learning than working with more structured material (pie wedges). However, the opposite was true when measuring transfer, since the squares resulted in a significantly deeper understanding. Schwartz and Martin also found that if the tiles were prepositioned in such a way that the students did not need to rearrange them to solve the task, the students learnt less.

From this the researchers draw two main conclusions: First, that if a manipulative material is too well-structured to fit a set of problems, transfer might not take place. Instead, the learner probes the environment to infer its structure, without necessarily learning the underlying general rules that the material is supposed to mediate. Schwartz and Martin (2006) call this 'induction' and compare it to using an abacus or learning to read. A more flexible and adaptive material, on the other hand, may help the learner to reinterpret the meaning of the material, leading to deeper learning and transfer ('multiple adaptation'). The authors also conclude that, if using this type of material, the restructuring of the environment itself is essential for learning.

These findings are in line with theories of distributed cognition (for example, Hutchins, 1995) and the hypothesis on epistemic actions proposed by Kirsh and Maglio (1994). Apparently, we may propose that manipulating or rearranging objects per se may change our cognitive state, making us see things differently, helping us learn. However, there is an important difference between offloading cognition by pragmatic or epistemic actions and acquiring generalisable knowledge. The former can be explained as using a 'cognitive economy', trying to solve problems 'without thinking', while the latter is a slower process, hard to achieve without cognitive effort.

The problem with simply using 'doing' as a short-cut to formal learning and knowledge-building is that learners do not necessarily interpret their own actions in the way intended. When using the virtual or physical manipulatives presented in PAPER I, for example, it was evident that this type of environment may place great demands on students. Even though the manipulative and explorative material (a deck of cards and a tiltable frame) were complemented with structured exercises, precise written instructions, and feedback, many students struggled. They not only found it hard to interpret the effects of their own interactions, but they were also sometimes confused about what they were supposed to learn (in this case calculating the areas of parallelograms).

One of the challenges of physical manipulatives is that students risk using the material incorrectly. Tiles, cards, rods, or paper-based materials can easily be handled in other ways than originally intended (PAPERS I and II). The degrees of freedom offered by the physical space can be beneficial, but manipulatives can also be a distraction and create mess. Thus, one advantage of digitalising manipulative material is that interactive constraints can be implemented in the interface. However, the lack of 3D tangibility in such interfaces can sometimes complicate interactions. Minimal sensorimotor input may also impair learning, especially if such input is an important property of the elements being studied (such as friction, softness, force, etc.). In a VLE, though, visual, verbal, or even auditive information can be added, making specific properties of the material more salient.

4.3 Virtual versus physical manipulation

Virtual or physical manipulatives can be compared in many ways, with respect to a variety of aspects of the materials' properties or functionality.[2] Typical research questions might be: Is tangibility or haptic perceptual input that affects learning or memorisation? Or is it the difference in interactive patterns and what the learner can do with the material that matters? Without claiming that one is more important than the other, it would be fair to say that many things can impact the learner's use and understanding. I concentrate here on describing two main aspects: how differences in constraints and affordances can affect learning; and if and how a material's concreteness and tangibility may be important for perception, memorisation, and knowledge building.

4.3.1 Constraints and affordances in different learning contexts

While it is possible to add affordances using digitalisation, interactive possibilities can also be removed. Still, both transformations may be beneficial for learning. For example, multiple studies have shown that virtual base ten blocks can be just as (or even more) effective for learning than manipulating physical cubes and rods (Litster et al., 2019). Similarly, interaction with virtual chemical models may be more beneficial than manipulating physical ones (Stull et al., 2013; Stull & Hegarty, 2016). However, while Litster et al. (2019) conclude that the main advantage of virtual base ten blocks is that the VLE provides more features and affordances, Stull et al. (2013) point out that interaction with virtual chemical models can be favourable because of the spatial constraints in the virtual interface. This may seem contradictory – but let me explain.

In the widely used maths app Montessori Numbers (Abel, 2018), new base ten blocks appear on the screen as the existing ones as used (Figure 2). The app also counts and presents both the number of cubes and the number of cubes represented by the rods and flats. The app also allows 'gluing' cubes and rods together to make larger entities, and dividing rods and flats into smaller ones. That is impossible with physical base ten blocks, where the various representations are fixed and can only be placed together. Several researchers

[2] For an excellent review of theoretical perspectives to use in such studies, see Rau 2020.

point out how these *affordances* support mathematical understanding and improve learning (Litster et al., 2019).

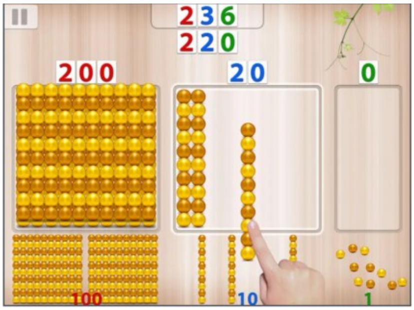

Figure 2 Examples of virtual versions of manipulatives: Montessori numbers (left), and a tangram puzzle (right).

In another study by Stull et al. (2013), a handheld virtual interface was specifically designed for teaching molecule structures. The interface allowed students to rotate virtual 3D chemical models, providing many of the perceptual cues present when handling physical models (such as stereo depth). However, the model could only be rotated around its centre, and the VLE did not include any additional features or functions compared to a physical concrete material. The researchers asked students to match the virtual or physical models with 2D diagrams and found that both types of models were equally useful and led to the same number of correct matches. However, the virtual models were slightly more efficient, possibly due to the *constraints* in the VLE that stopped the students from rotating them unproductively (Stull et al., 2013).

Even though this example shows that lesser degrees of freedom may be valuable when using manipulatives, constraining interaction can also be detrimental, not least for younger students. In a study on numerical partitioning strategies, Manches et al. (2010) compared how children 4–8 years old moved manipulatives with or without restrictions (i.e., whether they were allowed to use both hands and move several items at once, or if they could only move one item at a time). The children were introduced to a character (Mary) with two shopping bags. They were then shown a number of items (say three bananas), and given tasks such as ‘Show all the ways Mary could put the bananas in the bags.’ It was shown that when restricting interaction (independently if this was done in a physical condition or in a virtual one), the children had a harder time solving the tasks. Evidently, it can be crucial to enable this type of interaction when designing VLEs for younger students.

That also older students and adults can benefit from physical interaction has been shown by Goodman et al. (2016), who have studied university students solving a tangram task with a physical material or on a digital tablet. The students using the physical puzzle not only outperformed the ones using the tablet, but also did better on a subsequent maths test. The authors maintain this was not due to limitations in the virtual interface, but to that the virtual environment lacked *cues* on how to physically manipulate the tangram pieces. When introducing an instruction video on how to interpret the properties of the virtual tangram pieces, the difference between the physical and virtual condition disappeared. The authors conclude that altering a material's representational format may not only affect the learners' strategies when using it to solve a task, but also influence their understanding of the task, their awareness of the options available for solving it, and what they can or cannot do.

When it comes to the research presented in this thesis, the physical or virtual interactive qualities in PAPER I and II differ. In PAPER I, the students learnt about the areas of parallelograms and worked either with a physical deck of cards and a physical frame or with virtual representations of the same objects. The 3D cards were clumsy and hard to handle, slowing the students down. Since the material was intended to mediate the properties of parallelograms and only needed to be seen from the front, the third dimension was unnecessary. Still, these flaws did not impair learning compared to using the 2D VLE (which was designed specifically for this study).

In PAPER II, we compared a physical number line game on paper with a virtual game on a tablet. The physical condition was slower, with significantly fewer tasks solved. However, when marking the number line with a pen, the students had the opportunity to rethink their answers and revise them before being corrected (by the researcher). This was not possible in the virtual game, where a click on the number line was immediately followed by automatised feedback. This automaticity – which is common in many educational games – gave rise to occasional slips, which frustrated some students. Since the virtual feedback was only displayed for a limited time – unlike the feedback in the physical condition (delivered by a researcher), which had no restrictions – the pedagogical quality for a single trial differed between conditions. We argue this was one of the reasons the students performed better when playing with the physical material, even though they practised far less, compared to the students playing the virtual game.

4.3.2 Sensory input, tangibility, and haptics

But what of the sensorimotor aspect of physical versus virtual interaction? What if Ball (1992) is wrong, and our fingertips do convey important information? Taking an embodied perspective on cognition and learning (Clark, 2008; Hayes & Kramer, 2017; Pouw et al., 2014), we may argue that physical interaction affords rich multimodal sensory input, which may offload working memory resources, strengthen and widen memory traces, and support mental visualisations of performed actions (ibid.).

We can also think of our hands as indispensable tools for thinking. Not only does the human hand have an exceptionally wide range of motion (Santello et al., 2013), it can also decode a wide range of tactile stimuli. This helps us recognise and discriminate between objects, but it also has somatosensory effects, linking touch to various introspective states and emotions (Abraira & Ginty, 2013). The importance of touch for cognition has been debated for centuries, dating back to the days of Aristotle (for example, Brandt et al., 2024), but whether and how haptic sense can enhance learning and understanding has not been thoroughly investigated, whether in multimedia learning or in embodied learning paradigms.

To redress this, Novak and Schwan (2021) investigated whether touching real objects would affect learning by setting up four showrooms: one containing no physical objects, one with physical objects that the participants could touch, one with physical objects that the participants could not touch, and one where the objects were hidden inside boxes (but could be touched and manipulated). Each participant visited two showrooms. In the first they listened to an audiotape with descriptions of the objects, in the second there was written information about the objects. Three weeks later, the participants took a test. The researchers found that the haptic experience had a significant effect on participants' ability to recall objects – but not on their general knowledge about them.

Even if sensorimotor experiences may affect memory, and memory is important for learning, recall is not the same as comprehension. But what about touch as a mediator for understanding specific properties or relations, such as in STEM subjects? Does tangibility help students learn? Judging by the literature, the answer is not straightforward (for example, Zacharia, 2015). It is not surprising, however, that students seem to benefit from haptic exploration when studying properties that are impossible to perceive visually, such as force, mass, friction, and magnetism – especially if they have limited experiences of contemplating these concepts (ibid.).

Hands-on manipulation has also been shown to be beneficial for understanding and interpreting shapes and spatial relations. For example, Gori et al. (2024) explored how 5–10–year olds' abilities to understand cross-sections of 3D shapes were affected by multisensory visual–haptic experiences. Touching the 3D objects plainly helped the children learn compared to only studying them visually. That 4–5-year-old children find virtual representations of space difficult to interpret is shown in a study by Schenke et al. (2020), who gauged their understanding of basic concepts of measurement by letting them play a digital educational game about 'length', 'weight', and 'height'. Interestingly, while the game significantly affected the children's understanding of weight, it had only a modest effect on their understanding of length, and almost no effect on their understanding of height.

In PAPER I, we conclude that the students who used a physical deck of cards and a plastic frame had a better understanding of the concept of height than those who manipulated virtual representations of the objects. However, whether this knowledge was facilitated by the material's tangibility is impossible to know, since the two experimental conditions differed in more than one way. Students in the virtual condition did not draw representations by hand, for example. Nonetheless, the potential of physical tools and materials (cardboard, string, paper, etc.) should not be underestimated when introducing new spatial concepts that may be difficult for students to understand (see Leung, 2010)

When discussing VLEs and their possible shortcomings or benefits, being 'touched' can mean more than merely sensing something through your skin. Since digital tools also enable the creation of virtual worlds, narratives, and virtual characters, you may be moved or otherwise emotionally engaged in a different sense. This is one of the strengths of VLEs, which is discussed in the following section, where I discuss how virtual characters – and especially teachable agents – can support learning and increase performance.

5 Virtual characters: A social dimension to individual work

A different type of interaction enabled by the digitalisation of learning materials is with virtual characters of various kinds. Virtual characters occurring in VLEs can be anything from advanced chatbots to cartoon characters jumping along a course, trying to hit prime numbers. In open-ended learning platforms or intelligent tutoring systems, virtual characters can serve as adaptive instructors, doing some of the teaching or guiding students through the curriculum (for example, Lippert et al., 2020; Sikström et al., 2022). In simpler educational games or in drill- and practice software, where the students solve well-defined tasks, virtual characters are often more one-dimensional and have only two functions: to present information (instructions, tasks, or feedback) and to add a social or emotional component to the learning experience.

These simpler, non-adaptive virtual characters are the ones discussed in this thesis. They function mainly as part of the narrative, asking the students for help, asking or responding to questions, or presenting facts. Interaction with them is often limited, and either unidirectional (PAPER II) or restricted to pre-structured text-based dialogues (PAPERS III, IV, and V). In PAPERS III and IV, however, one of the characters in the game is designed as a 'teachable agent', transforming the role of the student from learner to tutor. I will return to the potential of such characters, but first the question of whether adding virtual characters to a learning material can affect students' emotions, and so influence learning.

5.1 The emotional impact of virtual characters and its relation to learning

As stated above, virtual characters are interactive to varying degrees. Yet they evoke emotions by simple means. For example, having a virtual (and sometimes emotional) character delivering feedback can reinforce its impact. This is applicable in all teaching and learning paradigms – also from a behaviourist perspective, where emotions are rarely considered the driving force in learning. By allowing an appealing character to respond to a student's actions and evoke positive emotions when the student performs well (and less positive emotions after mistakes and errors), it is assumed that the student will try to maximize their efforts and perform better. This is a well-proven technique, even if it does not always work as intended (for example, Wang et al., 2020).

From a more constructivist perspective, however, emotions play large role in the learning process. Not only are they important for accepting and engaging in feedback, but they also affect cognitive functions and serve as internal motivators. Consequently, virtual characters can be used for enhancing the learning experience, making it more positive, meaningful, and engaging. This can be done by, for example, constructing a narrative where the tasks and characters are carefully integrated, or by introducing empathetic learning companions (Arroyo et al., 2014). Making the student care about their characters and wanting to help them also adds a social and empathetic component in the learning situation (Chen, 2012). And if looking at learning as a social process mediated by language and interpersonal relationships, virtual characters can be used for facilitating collaboration (Njenga et al., 2017), but also for affecting students' values, attitudes, and understanding for others – through role play, perspective-taking, and dialogue (see for example Lindgren, 2012).

Even though virtual characters have been shown to positively affect students in several ways, it is not easy to design them to improve students' actual learning (Sikström et al., 2022). In the number line game in PAPER II, we chose to frame the tasks narratively and use the characters to give instructions and feedback. The figures – a frog, a kangaroo, and a rabbit – were searching for food, and students were told to help them by estimating target numbers on a number line. After each answer, the animals delivered positive feedback if the estimation was sufficiently accurate (+/- 1 unit), and negative feedback if the error was larger. The positive feedback consisted of items of food, displayed on-screen, accompanied by a positive verbal statement (‘Yippee! Pancakes, that’s nice!’ or similar). The negative feedback also had items of food, but then the character sounded disappointed (‘Oh, the food was over there’). Although we varied the design of the feedback and many students liked the animals and thought the game was engaging, several found the utterances repetitive and annoying. Evidently, the risk of causing frustration or boredom when letting a virtual character react to a student’s actions or mistakes should not be underestimated.

5.2 Teachable agents: protégées, scapegoats, or proxies

A different type of virtual figure is the ‘teachable agent’, operating at the boundary between individual and collaborative learning. Being partly social and partly individual, partly a proxy for learning and partly a friend needing help, it affects students’ ideas and behaviours in a multitude of ways, and so has a strong potential for encouraging students to learn.

Teachable agents (TAs) build on the well-known pedagogical approach of learning by teaching (LBT) (for example, Annis, 1983) and are virtual characters that the student is supposed to teach. The student takes the role as a tutor, and after having instructed the TA, it is the TA that takes a test, or presents a solution, which is later assessed and (if necessary) corrected. Thus, the TA’s actions will reflect on the student’s teaching. TAs have repeatedly proven beneficial for learning in terms of motivation, metacognitive scaffolding, and learning outcomes (Biswas et al., 2005; Blair et al., 2007; Chase et al., 2009; Tärning et al., 2019).

By monitoring the performance of their digital tutee, the student goes from the challenging task of monitoring their own behaviour (which requires self-regulation and self-reflection) to the more manageable task of monitoring someone else. Thus, the TA functions as a ‘proxy’ for learning, offloading working memory resources and regulatory processes. Further, despite their inherent digital nature, TAs also support social behaviours, as students care for their TA and take responsibility for their teaching – the so called ‘protégé effect’ (Chase et al., 2009; Sjödén et al., 2011). Reflecting on the actions of their TA also means reflecting on their own teaching and their own underlying understanding of the tasks, and ultimately the entire domain at hand. In this, the student can take advantage of the TA's social role as a scapegoat: the TA can function as an 'ego-protective buffer' (Chase et al., 2009), diverting responsibility for failure from the student to the virtual agent. TAs thus seem to improve students' inclination to accept criticism and to self-reflect and act on their errors, helping them to evaluate their own knowledge and to apply adequate learning strategies to reach preset goals, such as accepting or acting on feedback (Silvervarg et al., 2020; Tärning et al., 2020). TAs have primarily been shown to improve learning for less capable or less confident students, closing the gap between higher and lower achievement levels (Chase et al, 2009; Tärning et al., 2017).

Evidently, a TA may act at different levels and moments in the learning process, affecting both explicit behaviours (for example, asking for feedback) and less observable inner cognitive processes (for example, memorising information and so performing better). However, a TA's effectiveness derives not only from how well its performance reflects the student's knowledge, but also from whether the student likes the TA and can relate to it. A TA's personality can be of great significance (Tärning et al., 2019), but also how it is introduced and framed. The latter has been explored in a study by Silvervarg and Månsson (2018), who evaluate different ways of introducing a TA for middle-school students playing an educational history game. Before starting, students either had only the game's built-in introduction to the TA or they were also given a verbal introduction to the TA in the classroom. Based on the students' self-reporting, the researchers conclude the additional introduction significantly impacted the students' perception of the TA as someone wanting to learn. These students also reported making more effort and not wanting to give up, compared to the students who only had the system-based introduction.

In the study in PAPER III, we pursued this line of inquiry by questioning whether a student's attitude towards a TA would influence their performance. Playing a game where a specific character acted either as a TA or solely presented the narrative, students rated the character's need for help on a Likert scale. As hypothesised, the students playing with a 'true' TA rated the agent's need for help significantly higher. Surprisingly, though, these ratings turned out to be the *sole predictor* for the students' learning outcomes. Since in most studies about learning, results differ between performance levels, this was an interesting finding.

Figure 3 The virtual character Timy from the history game used in PAPER III, PAPER IV, and PAPER V.

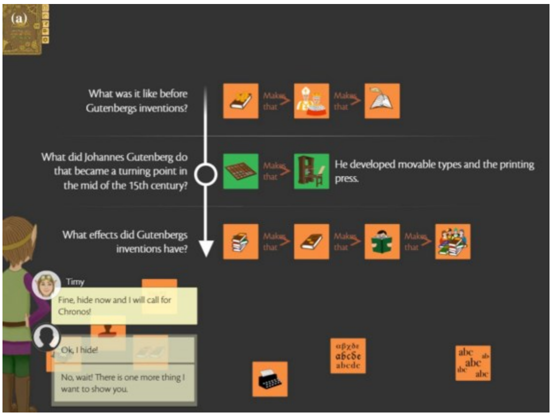

Figure 3 Timy as a teachable agent (PAPER III and PAPER IV).

6 Collaboration and tutoring in different learning contexts

The social dimension of being engaged in a virtual narrative, helping virtual characters to solve puzzles, or teaching them facts, is remarkable. It turns individual work into a cooperative activity, increases motivation and engagement, and helps students learn. A different social aspect of virtual interaction, however, is its impact *outside* the virtual context, e. g. how we, as humans, can share a screen-based material and use it together. In what follows I discuss three different aspects of cooperation relating to screens. The first covers the difference between teaching with and without the help of VLEs and how teacher–student dialogue and interaction may differ depending on the material used. The second concerns how peers collaborate in different learning contexts (virtual or physical) and how this can affect learning. Finally, I discuss the difference between working individually and working in pairs with an educational game on a tablet.

6.1 Sharing the art of teaching with intelligent software

Before the advent of tablets and laptops in the classroom, the teacher – along with textbooks or other printed material – was the main source of information. The teacher was also the one giving instructions, presenting examples, delivering feedback, and asking questions. Yet, doing this in front of a whole class is not the same as giving individualised instructions or tailoring feedback for one student on the spot. Surely this is possible with the help of technology? To a certain degree, yes, but not totally. In the aftermath of the Covid-19 pandemic, we can all agree that IRL face-to-face instruction cannot totally be replaced by online tutoring or the individual use of intelligent software – at least not without significant drawbacks for many students (for example, Erlangga, 2022).

That said, there is a substantial body of research that confirms that technology can enhance classroom practices in more general terms. A common conclusion in this line of inquiry is that digital technologies, if used appropriately, can have a significant positive impact on teacher–student relations and the quality of teaching (Haleem et al., 2022; Harper, 2018; Major, 2020). Another finding is that the teacher's role often changes, from an instructor who presents specific content and carefully monitors the students' activities to a facilitator who oversees the students' own knowledge-building and exploration (ibid.). This is in line with the constructivist paradigms of teaching and learning, which often go hand in hand with the use of digital tools.

The design of advanced educational systems for specific purposes, adding educational value to traditional instructions and textbooks, is outside the scope of this thesis. Instead, I would like to take a more sociocultural standpoint on cognition and learning and discuss how interpersonal behaviours may change when physical learning materials are digitalised. According to the theories of Lev Vygotsky (1962; 1972), human learning is first and foremost a social activity, evolving in the discourse between a novice and more competent person. Sociocultural theories thus emphasise the importance of tailored instructions and reciprocal feedback, where the tutor and tutee can reach a mutual understanding (Vygotsky, 1972).

To meet such requirements, a VLE may be designed to individualise instructions and deliver adapted feedback, but it can never totally replace human relations and interpersonal talk. It can never be as flexible, adaptive, and engaging as a human, and it can hardly support students with embodied cues (pointing, looking, gesturing) or place a hand on their shoulder when they are struggling. But what if a tutor and system could complement each other? What if the tutor were in close contact with the tutee using a VLE, affording support and additional feedback, and humanising the learning situation? Surely that would be similar to the teacher giving the tasks to the student directly, if not better? It seems there is little research about such effects, at least regarding quantitative experimental studies. Instead, research targeting these questions is often qualitative. It is also common to treat traditional teaching and instruction as asocial, passive, one-way activities, with no dynamic when compared to a more informal, explorative digital context (for example, Lantolf & Xi, 2023).

Beyond VLE use, however, there are studies of adult–child interactions that pose these types of research questions, although in more informal settings. For example, Strouse and Ganea (2017) looked at verbal and non-verbal behaviour when caregivers read printed books or e-books for their toddlers (17–26 months old), concluding that even if the parents pointed less and read less of the actual e-book, there was no significant effect on their content-related utterances compared to reading printed books. In fact, the children were more active with the e-books (pointing and talking more, turning pages, etc.), leading to better memorisation of specific elements in the text. Nonetheless, De Vries et al. (2021) came to a different conclusion in a study of parent–child interactions during digital play, when slightly older children (3–5 years old) played a physical or a digital version of a maths board game with their caregivers. The results reveal that both caregivers and children engaged in significantly more maths talk (such as counting or identifying numerals) in the physical condition than in the digital one. De Vries et al. (2021) suggest this may be due to the parents being distracted by the features of the game and allowing the digital device to lead the interaction.[3]

De Vries et al. (2021) are echoed by findings in the study in PAPER II, which explored how playing a physical number line game differed from playing a virtual one. Preschool children (6 years old) either played the game on paper, with tailored instructions and feedback from a researcher (me), or they played a digital version of the game on a tablet, still with individual support and scaffolding from a researcher (one of my colleagues). When analysing the tutors' verbal utterances, they were not only more frequent in the physical condition, but they were also more elaborate. This was true both for feedback and for introducing tasks and giving hints, etc. And even if some of the talk was off topic (in both conditions), the reasoning process seems to have positively influenced the children's learning.

[3] This is in line with a series of other studies, showing that digital media may create a digital bubble and hinder children's spontaneous talk (Bochiocchio et al., 2022; Munzer et al., 2019).

6.2 Collaborative learning with virtual screen-based materials

Evidently, handing over some of the tutoring to a system not only places immense demands on the system, but the human tutor also risks ending up in the back seat, only commenting on the tutee's learning instead of leading and guiding it (see Selwyn, 2017). But what about the student's own interactions when collaborating in different contexts, sharing virtual or physical tools? Do they differ too? I will return to this question, but first an explanation of collaborative learning.

6.2.1 The theory of productive agency

The concept of collaborative learning is tricky. Ever since Dillenbourg (1999) raised concerns about how to define the concept, the amount of research on the topic has grown exponentially. Collaborative learning is a very appealing way of engaging students in different domains, and, if done correctly, a potent one. To let students work together and construct knowledge by social interaction is also in line with popular contemporary constructivist and sociocultural learning theories. Still, if studying collaborative learning and trying to measure its possible outcomes and effects, it is also necessary to specify the possible mechanisms that underlie it. And, perhaps more importantly, to do this transparently when experimenting and observing. A researcher's view of why and how collaborative learning may be beneficial for learning will not only affect what is studied, but also the conclusions. For those reasons, I prefer to see collaborative learning through the lens of Schwartz and Lin's (2000) theory of 'productive agency'.

The theory of productive agency holds that collaborative learning is not a smooth process where students simply help one another to achieve a goal, by, for instance, dividing the work. Instead, true collaboration consists of sharing ideas, compromising goals, and putting equal effort into a task. It can be time-consuming, messy, and sometimes inefficient. For collaborative learning to be beneficial for learning – at least if we acknowledge some knowledge to be situated internally, in an individual's own mind – all individuals in a group need to both deliver and interpret content. Consequently, the measurable value of collaborative learning lies primarily in the group members' rich, productive interactions, both with one another and with the material used. It is not enough for a collaborative task to result in a better solution or 'product' than an individual task to say that the students have learnt more – that is only a matter of efficiency.

6.2.2 Collaborating with a physical or virtual material

But what occurs when materials intended for collaboration are digitalised? What happens to students' interactions if we put them on-screen? Naturally, the specific design of the material may affect students' ability to share it and cooperate. Thus, working together in a VLE that is explicitly designed for collaboration, and where, for example, students can work on separate devices and still share the same view, may support cooperation and collaborative learning (Falloon, 2015; Sachisthal et al., 2024). However, some activities are more suitable for group work than others, which also places high demands on not only the app, but also on the design of the tasks as such (Sachisthal et al., 2024).

From an embedded and embodied perspective on cognition and learning, the practicalities of different learning contexts may also impact students' interpersonal interactions, affecting turn-taking, gaze behaviour, distribution of work, and so on. For example, students using physical material may be sitting opposite one another, while sharing a VLE on a screen may force them to be seated in a row. Some materials (physical and virtual) may be possible for several students to manipulate simultaneously, while others must be handled by one individual at a time. Further, the complete digitalisation of the learning environment – encompassing everything from manipulatives to instructions, tasks, and feedback – means the material cannot be shared among group members. Instead, it must be used and interpreted simultaneously through the screen(s) that mediate(s) it.

To highlight the importance of simultaneous interaction in collaborative settings, Harris et al. (2009) studied how shareable interfaces may affect collaboration. Looking at 7–10-year-old children collaborating around single-touch or multitouch tabletops for a design task, they showed that even if the condition did not affect the actual physical interactions, it influenced the children's discussions. While the children in the multiple-touch condition talked more about the task at hand, the children in the single-touch condition instead discussed turn-taking and the distribution of work.

Evidently, additional features in a VLE compared to more traditional materials may support collaboration and result in satisfying outcomes. However, this is not always the case. An illustrative example of how the physical limitations of a VLE may be detrimental to collaboration is a study of music production by Huovinen and Rautanen (2020). Students, 10–12 years old, worked together in groups of four to create sound landscapes for a film in one of two ways: either using a set of traditional instruments or using the app GarageBand on individual tablets. The difference between the two groups was obvious. While the students using traditional instruments engaged in fruitful peer teaching, improvisation, and rapid negotiations, the students using GarageBand relied on solitary and parallel work with much less productive interaction and group flow. The authors conclude this was due to the app's lack of physical and spatial affordances and its reliance on abstract conceptual labels. This left the GarageBand students administrating their work instead of hands-on musical play.

However, children's collaboration may not always deteriorate due to the use of digital technology. For example, in a study by Mercier et al. (2017), 10–11-year-old students collaborated to solve maths problems, either by using a large screen-based multitouch interface or using paper notes. The students were given separate clues (written on virtual or physical pieces of paper) and were supposed to put them together to solve the problems. The results indicate that even if the students came up a similar number of ideas, independently of condition, the discussions were more detailed when students collaborated around the digital interface. Mercier et al. (2017) claim that one of the main advantages with the large multitouch screen was that students used it from the same direction, helping with joint reading. The students working on paper were instead seated around a table and divided the clues amongst them and just read them aloud for one another.

To my mind, all these studies speak to the situated and embodied nature of collaboration. It apparently seems that smooth, seamless interaction, simultaneous contributions, and direct access to all information for all participants is important – also for interpersonal communication and sharing ideas.

In PAPER I, students collaborating with a VLE were compared with students collaborating with physical material to learn about areas of parallelograms. The software was not specifically designed for collaboration, and the reason for letting students work in pairs was mainly to listen to their conversations and observe their behaviour. The students using the physical material not only discussed more during the lessons, they also more frequently mentioned the key concepts important for learning (such as base, height, and area). It was also noted that students using the physical material often shared it: while one student read a question the other handled the cards, or while one student created card shapes the other one drew the 2D representations. The students using the virtual interface, on the other hand, often took turns working on the tablet, and were much more passive when not interacting with the screen. Once a full analysis of the observation notes is complete, it will be interesting to see if it too shows there were differences in turn-taking and negotiations in the two settings.

6.2.3 Sharing tablets or working alone?

Finally, some remarks on the difference between sharing a VLE on a digital device (such as a tablet) and working with it alone. The issue is relevant for several reasons, not least since mobile devices often are now used for unstructured group activities both in and outside the classroom. It is common, for example, to let students collaborate informally on mobile phones or tablets during school excursions or for creative and artistic work, even if the software is not always designed for collaboration. Students sometimes also share devices because of lack of equipment, and some teachers prefer students to use technology together (for example, Fleck et al., 2021; Haßler et al., 2015).

However, even if it is common to share screens, measuring and comparing differences between students working alone or in pairs and/or groups with a single unit is rare, not to say non-existent. Even when studies look at the possible benefits of abandoning the one-to-one use of mobile devices in schools, they often focus on the students' social interactions (Fleck et al., 2021). Another line of inquiry is to see how well student groups progress – compared to single users – when using a specific app (for example, Azhar et al., 2020). Yet, progression and success are not enough to evaluate collaborative learning (Section 4.2.1). This research gap is thus addressed in the study in PAPER V, where students were set to playing an educational game in history, alone and in pairs, to evaluate aspects of self-regulation – or more specifically, their feedback engagement. By tracing the students' digital behaviours, it was evident that collaborative game-playing affected lower- and higher-achieving students differently, and that the benefits of collaboration were heavily dependent on task difficulty. Plainly, VLEs may both evoke and reduce unproductive, less regulated learning behaviours (this is discussed in more detail in Chapter 7).

7 Self-regulation and feedback engagement in VLEs

For effective learning, a student should apply metacognitive and regulatory strategies, for example to reflect on what and how to learn, to keep up trying even though they are failing, and to use their learning environment productively. This is often called self-regulated learning, a set of strategies and processes that refers to 'self-generated thoughts, feelings, and actions for attaining one's learning goals' (Zimmerman & Moylan, 2009, p. 299). Examples of such strategies are reflecting before answering questions or solving tasks, evaluating and comparing existing and missing knowledge, and making use of feedback. Other productive learning strategies related to self-regulated learning are seeking for relevant information, picking out and memorising important facts, and taking in instructions (Zimmerman & Moylan, 2009).

The question is whether students' ability to self-regulate is affected when more conventional learning materials are transformed into VLEs. And often the answer is – it depends. The literature points to the difficulties of regulating students' digital behaviour. Even if students who use educational software may seem motivated and engaged (Brinson, 2015; Wang et al., 2022), there are certain drawbacks to using screen-based technology in schools.

7.1 Monitoring digital behaviour

A challenge for teachers in the situation when students are working on-screen is to know what the students actually are doing. Not only may they, with unlimited access to non-educational content, be doing things not related to the class work (so called 'off-task' activities) or be doing things 'simultaneously' (so called 'multitasking') and therefore learning much less (May & Elder, 2018; Ravizza et al. 2017; Zhang, 2015). They may also be skimming or occupied in fruitless trial-and-error behaviour (Beck & Gong, 2013; Falloon, 2014). In a study on 5-year-olds' tablet use in school, Fallon (2014) found that teachers had problems monitoring and assessing the children's progress and achievements. The author concludes, amongst other things, that: 'At a glance from a distance (the usual scenario in a busy junior classroom), it *appeared* as if students were thoughtfully engaged in learning with the app. However, it was not until display recordings were reviewed that the nature of the *actual* activity was revealed' (p. 332). A similar concern is raised in by Nilsen (2018), who in her thesis on the use of digital devices in pre-school found that teachers and children often have different perspectives on how and why technology is used, which also makes it difficult to establish intersubjectivity.

Just as teachers may have difficulties monitoring students' on-screen activities, the students themselves often struggle to self-regulate. This is known both in more open-ended learning environments (Torrington et al., 2024) and when students use intelligent tutoring systems in subjects such as maths or physics (Baker, 2016). Of course, also in a conventional learning environment, where students use textbooks or work with physical materials, it is possible to go off-task, doodling instead of solving problems or disturbing classmates instead of attending to what the teacher is saying. When students receive feedback from a teacher, they may ignore it, just as they may ignore automatic feedback in an educational game or an intelligent tutoring system. Still, such behaviours differ between contexts, and they tend to be less visible and possible to influence in VLEs.

Even though it is popular to conduct studies about self-regulated learning – not least to evaluate whether specific software helps support and scaffold students to self-regulate, and how (Taub et al., 2020) – it is not very common to compare self-regulated learning behaviours in different learning contexts. And many of the studies that do so address the problems of learning online (for example, Torrington et al., 2023). Much research on self-regulated learning also focuses on older students, often at the university level, using more sophisticated software. Thus, comparisons of how younger students regulate their learning in simpler learning environments (when, for example, textbooks are transformed into more engaging software) are less common.

None of the studies in this thesis set out to evaluate children's self-regulation in a broader sense. Still, there are some interesting observations. In the study in PAPER II, for example, inhibition immediately comes to mind. Not only did the students playing the game on paper have longer response times than the students playing the game on the tablet, but they also wanted to change or correct their answers more often. The students in the virtual condition, on the other hand, more often guessed, eager to interact with the screen. The students in the physical condition also often went off-task, asked for help (wanting the researcher to respond on their behalf), or tried to cheat by looking at the feedback before responding. Thus, while the researcher in the physical condition sometimes had to encourage the students to focus and give a proper answer, the researchers in the virtual condition more often commented on the students' hastiness, telling them they did not need to rush. It was also easier for the students playing the virtual game to ignore feedback – a problem discussed below.

7.2 The power of feedback and students' inclination to neglect it

An important piece of the puzzle when it comes to self-regulated learning is to pay attention to and engage in feedback (Butler & Winne, 1995; Zimmerman & Cleary, 2009). Feedback can be both a source of guidance for set goals and a motivator, pushing students to use self-regulating activities to improve. In an ideal situation, the feedback gives the learner valuable information about the knowledge they lack, and how their performance should change to reach a desired state (Hattie & Timperley, 2007; Shute, 2008). It is especially true for critical constructive feedback, which is designed not only to tell the student whether they are right or wrong, but also points them in the right direction (Shute, 2008). However, negative feedback can also be perceived as a punishment, affecting students' self-belief and self-confidence (Tärning et al., 2020). This can make students neglect feedback altogether, ignoring comments on their work and protecting themselves from discomfort and shame.

All the different learning theories (Chapter 2) acknowledge feedback as a potent behavioural regulator and a prerequisite for learning. However, the role and function of feedback differ depending on the theoretical framework used. Similarly, underlying theoretical perspectives help determine what is studied (the feedback format, the student, or an entire group's social activities) and how. Thus, while constructivist learning paradigms generally concentrate on the students' acceptance, understanding, and processing of feedback (Butler & Winne, 1998; Kluger and DeNisi, 1996), a more behaviourist perspective would be to focus on the format, granularity, and frequency of the feedback, and evaluate if and how it can be used as reinforcement (for example, Gagné, 1962; Kulhavy, 1977). In these lines of inquiry, VLEs are often used both to deliver feedback and assess its effectiveness. By tracing students' digital behaviour and relating it to performance outcomes, it becomes possible to model how different types of feedback may affect students' inner and outer states.

It is also possible to study feedback in a more qualitative sense, though. According to sociocultural ideas of teaching and learning, feedback is preferably delivered in dialogue between teachers and students. Here the core concept of learning is that teachers (and peers) 'mediate' children's experiences via social interaction and language use (Vygotsky, 1972). Even if Vygotskian ideas have influenced the design of VLEs – by, for example, emphasising the students' need for adapted feedback or showing how virtual characters can be used as social buddies – much of this line of research looks at how learning conversations evolve and may lead to common ground and mutual understanding (for example, Steen-Utheim & Wittek, 2017).

In this thesis, feedback is investigated in several ways. PAPER II addresses the difference between receiving feedback from an educational game and receiving it from an instructor – both by analysing student data and by giving examples of student–instructor dialogues. PAPERS IV and V instead evaluate how collaboration and LBT techniques affect students' engagement with automatically delivered feedback from an educational game. As will be seen, all this speaks to the delicate relationship between feedback acceptance, task performance, and students' general achievement level.

7.2.1 Possible drawbacks of negative feedback – and how to mitigate them

As mentioned earlier, feedback – especially if its critical – may evoke negative emotions. This leaves students inclined to ignore feedback, even though it is supposed to help them (Chase et al., 2009; Segedy et al., 2012; Tärning et al., 2020). Avoiding critical constructive feedback is especially frequent amongst lower achievers, and even more among students with low self-efficacy (Gan et al., 2021). The students in most need of feedback are also the ones fleeing from it. This problem is even more pronounced when looking at critical constructive feedback in VLEs. And even though there have been several attempts to automatically adapt such feedback, by, for example, student modelling and AI, there is still little agreement on how to optimise feedback uptake in each learning situation – for all types of students.

Studies about how to affect students' emotions by using different types of feedback are also contradictory. In a study on 11–12-year-old students by Hwang et al. (2020), for example, it was shown that using data logs to model students' affective states and thereafter adding emotional content to feedback messages and prompts (jokes, encouragements, questions, etc.) helped students to learn more and perform better. These adaptations were especially beneficial for lower-achieving students, reducing anxiety and making them more resilient. However, trying to influence students' emotions can be a risky business, as shown by Cabestrero et al. (2018), who took 15-year-old students' self-reported emotional states and combined this data with performance measures in a VLE. They then added encouraging content to feedback messages – 'Very Good! From now on you'll receive more complicated challenges', or 'Don't worry! We've only just started'. It was found that including affective content in the critical feedback message did influence progression, but *negatively*, and that hints were only effective when they were *not* accompanied by this type of emotional feedback.

How best to navigate telling someone they have misunderstood something, that they need to revise a task, or that they simply need to study more? Well, first, the interpersonal closeness between the feedback provider and the learner is important. In a study by Madaio et al. (2017), 12 to 15-year-old students were paired together in an online learning environment. In one group the pairs consisted of friends, in the other of total strangers. Results showed that tutors with high self-efficacy and low interpersonal closeness with their fellow students used significantly more indirect instructions, which had a significant positive correlation with their learning. A common feature in indirect instructions is hedges – words such as 'just' and 'actually' that are used to reduce the intensity or certainty of an utterance. Hedges, together with subjectivisers ('I guess that') and apologies ('Sorry'), are often used to mitigate face threat, and in Madaio et al. (2017) hedges were the most common indirect tutoring move.

These findings say something about the difference between human-to-human interaction and human–computer interaction. Even though we might be entertained or encouraged by a system (within limits), when such a system (by its design) 'tries' too hard to make us feel at ease, this may be counterproductive. This became obvious when conducting the study in PAPER II, where the students playing the digital number line game were sometimes frustrated by the automated feedback – mostly the negative, but also the positive. Even though we tried to design and vary the feedback messages, some students still thought them repetitive. When annoyed with the game, students might respond by deliberately giving incorrect answers, arguing with the virtual characters, or simply disengaging and stopping learning. On the other hand, the researchers supporting the students when playing did their best to compensate for these flaws. They not only spontaneously tailored their own feedback to the student's achievement level, they also often mitigated negative feedback and used hedges. However, the timeframes and automaticity in the virtual game limited the researchers' opportunities to actively engage and talk with students. In contrast, the researcher in charge of the physical game gave more elaborate instructions for how to do better next time. This feedback was also more dialectic – just as suggested by Vygotsky (1972). Regardless of how advanced the intelligent techniques used to tailor critical constructive feedback may be, such reciprocal delivery and uptake of feedback is hard to achieve in artificial systems. Perhaps it would be better to avoid pretending this is the case?

7.2.2 The importance of success and resilience for engaging in feedback

There are far better ways to help students engage in automated digital feedback than to spice it with emotional content or try to mimic friendly utterances. Namely (*i*) to deliver clear, concise feedback messages of an appropriate length so students can easily read and understand them; (*ii*) to make students more resilient to failure and criticism by using specific strategies; and (*iii*) to ensure the actual tasks are in line with the student's level of expertise (so that the student does not fail completely).

It has been proven countless times that engagement with feedback will result in better academic performance. Whether students' achievements (in a VLE or outside it) affect feedback acceptance, has, however, not been extensively studied. Some studies have found that task difficulty in relation to student performance can be important for feedback uptake (for example Cabestrero et al., 2018). It would be fair to suspect, for example, that as soon as students start being convinced that they cannot succeed, they also stop trying to do so. The cost for engaging in feedback then might become too high, and it may be easier to just guess or try to find loopholes so they can progress with less effort.

The importance of succeeding for engaging in critical constructive feedback is discussed in PAPER IV, where students used an educational history game with and without a TA. As hypothesised, the students using a TA accepted feedback more often. Evidently, making the TA 'take the blame' when failing, protected the students from refusing feedback (see Chapter 3). However, feedback acceptance decreased significantly with lower test scores and repeated failure.

The matter of feedback acceptance is also discussed in PAPER V, where students played the same game (although without a TA present), either singlehandedly or in pairs. We postulated that collaboration would make the students more inclined to attend to feedback, since, just as with the TA, they could share the burden of criticism and failure. It is also often argued that collaboration can strengthen self-regulated learning, since students working together may help one another to self-regulate (Schoor et al., 2015). However, it turned out that higher- and lower-achieving students were affected differently. Thus, collaboration seemed most beneficial for feedback acceptance when the tasks were too difficult for one person to handle. More competent students were actually less likely to attend to feedback when working in pairs, perhaps because they thought they did not need it.

8 Closing remarks

This thesis work covers a number of aspects of students' use of virtual learning environments. It highlights differences between virtual and physical interaction and gives examples of how VLEs can scaffold or hinder learning, depending on their design. My intention has been to capture the core aspects of what happens when learning materials are put on-screen. What opportunities emerge and what limitations may follow? And how do they relate to what students learn?

Naturally, adding intelligence and important information to a VLE should increase the opportunities to learn. This is highlighted by Zhai et al. (2019), who emphasise that for VLEs to be beneficial, they need to *augment* the learning experience. This could be done by using teachable agents – as described in PAPERS III and IV. However, VLEs may also easily *diminish* the learning experience, for example, by reducing or eliminating haptic information and 'unnecessary' practical exercises (such as creating representations by hand, as in PAPER I), by automatically providing feedback in a limited timeframe, or by constraining the students' physical interactions (as in PAPER II).

Where conventional physical learning environments are often messy, clumsy, inaccurate, time-consuming, and demanding, VLEs can be perfect, smooth, quick, effortless, and automatic. However, if raw intelligent automation replaces the human aspects of teaching and learning (social interaction and teacher-led instruction, sensorimotor interaction, getting in touch with the real world, performing actions that others can observe and relate to, sharing materials in a way that is fruitful, etc.), there is a risk of reducing rich learning experiences to a pure mechanistic activity. This does not mean that virtual interfaces or educational games cannot be used for repetition and drill practice – only that they cannot totally replace physical learning materials without creating a significant void.

Solving tasks on-screen using a VLE means that students, as long as they stay within the bounds of the correct app, can only perform the actions which the app allows. You cannot fold a tablet into an aeroplane and throw it at your classmate, for example. By constantly providing feedback on the student's actions – as educational games often do – an app may hold their attention and keep them on track. We may think this is good for learning, since we know that to learn you need to concentrate and maintain focus. Yet, there are several problems with the 'framing' and 'attention-grabbing' abilities of intelligent software. First, attention is not the same as understanding. Clicking – and especially clicking as fast as possible – is not the same thing as understanding either. Second, one thing that students need to learn in school is to maintain their attention *by themselves*. They need to train this ability and learn to persevere in solving problems and processing information, also without instant rewards or feedback.

Still, technology is here to stay. And virtual interfaces do have strong potential – if properly designed. Even if children need rich embodied experiences of real-world phenomena, sooner or later such experiences need to be translated to symbols, formulas, and rules – especially in STEM subjects. Many researchers and educators thus state that the advantage of virtual interfaces is that they can be a bridge between the physical world and the abstract concepts that the students are expected to learn (Brinson, 2015; Wörner et al., 2022). No surprise that it was recently concluded that a combination of hands-on materials and VLEs probably is what is needed to optimise learning – especially in higher grades where students have sufficient prior knowledge of real-world phenomena and experience with physical tools and objects (Wörner et al., 2022).

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Summary of the papers and the author’s contribution

Paper I: Mediating an understanding of areas of parallelograms: Exploring middle-school students’ learning from virtual or physical representations

The first paper presents a study on middle-school students’ interaction with physical or virtual representations when learning about areas of parallelograms, with the underlying hypothesis that different types of learning materials would lead to different learning outcomes. 94 students worked during two lessons either with a physical deck of cards and a plastic frame (physical condition), or with virtual and screen-based representations of these objects (virtual condition). The lessons took place during two consecutive weeks, during which the students created parallel shapes, discussed the height, base, and area of those shapes, and solved a series of tasks. The students who used the physical materials drew figures by hand and answered questions on paper, while the students who used the virtual representations solved all tasks on a tablet and saved the shapes on the screen. The students worked in pairs. Thus, we complemented data logs and paper-based answers and drawings with observation notes of the students’ conversations. One week after the second lesson, the students took a test. The study was inspired by the work of Sayeki et al. (1996), who used a similar physical material (a pile of papers and a paper frame) in an intervention that had a significant impact on students’ learning.

Result: When it comes to the students’ understanding of the formula of areas of parallelograms (*Area* = *Base* × *Height*), we found no significant differences between conditions. However, the students who used the physical materials reached a better understanding of the concept of height, and even if they created significantly fewer parallel shapes, they discussed the properties of the parallelograms (base, height, and area) more than the students working on the tablets. We suggest that this is due to that the students in the physical condition were asked to explicitly mark the base and height in their drawn figures, while the students in the virtual condition only attended to these concepts on screen. The conclusion is that the creation of very simple representations by hand can be important for being able to understand geometric properties and formulas.

Contribution: After having piloted a first version of the stimuli on 6th graders (Ternblad, 2022), and on adults (Ternblad, 2023), the study design was finally completed in 2022. I designed the experimental setup and the experimental stimuli but received invaluable help from Erik Anderberg (for implementing the virtual interface according to my instructions) and Birger Johansson (for 3D-printing). During the lessons – which were conducted in the students' ordinary classrooms – I had assistance from Betty Tärning and Tina Rastegar, who took notes while I helped students in need of support. The paper was written together with Betty Tärning, with me being responsible for all analyses and for the main part of the writing.

Paper II: Virtual versus physical number line training for 6-year-olds: Affordances matter!

The second paper presents a study that included 89 6-year-old children in Swedish grade 0, who played a number line game for 3 weeks during 3 lessons, in order to improve their numerical skills. In the game, the children were asked to help animals to search for food. They did this by estimating target numbers between 0 and 20 on an empty number line and receiving feedback on their estimations. For the study, two versions of an experimental stimulus were created: A virtual number line game, played on a tablet (virtual condition), and a paper-based version of the same game (physical condition). In the physical condition, the narrative, the target numbers, and the feedback were presented by a researcher. In the virtual condition, this information was delivered by the game. However, in both conditions the students were guided and supervised by a researcher who gave hints and commented on the students' progress. The researcher also took notes of the children's strategies (such as using different reference points on the number line, counting out loud, etc.). We hypothesised that the game play would improve the children's number estimations as well as increase their understanding of numerical magnitudes (such as that 8 is larger than 7 but smaller than 9) – measured through pre- and post-tests. We also hypothesised that the learning outcomes – as well as the used strategies – would differ between conditions due to the game formats' different constraints and affordances.

Result: By practicing the number line game, the children improved their numerical skills, with no significant differences between conditions. However, the children playing the physical game performed better *during play*, even though they estimated significantly fewer target numbers than the children who played the game on the tablet. The children in the physical condition also used more productive strategies – such as counting from different reference points along the number line instead of clicking directly on the line or counting from 0 – than the children in the virtual condition. We believe this was due to the following: First, the students in the physical condition received more tailored and elaborated feedback. Second, the physical material afforded the children to reconsider and change their estimations, and in this condition, it was also easier to point at the number line without accidentally responding. We conclude that constraints and affordances in the physical and virtual learning environments resulted in different learning experiences; one being fast and more repetitive, and the other being slower and more time consuming, but also more forgiving, and of higher quality.

Contribution: The study is a part of a larger study investigating if and how Number Line Estimation Task training (NLET-training) may strengthen children's numerical magnitude processing. The paper was written together with Maybí Morell Ruiz, who designed the comprehensive study and implemented a first version of the virtual number-line game. We then developed and refined the experimental setup and the physical and virtual stimuli together. Our colleagues Sonja Holmer, Betty Tärning, and Fanny Holmgren assisted us in conducting the study in 6 kindergarten classes. I am responsible for all the analyses in the paper and for the main part of the writing.

Paper III: I will help you, but will you help me? How the perception of a Teachable Agent may influence performance.

The third paper presents a study on students' attitudes towards a teachable agent (TA), hypothesising that the students' perception of the TA as being in greater or lesser need of help would affect their performance. 156 students played an educational history game during 3 lessons, either with one of the characters in the game, Timy, as a TA or with Timy as a narrator. The students then responded to an 'agent-opinion' questionnaire and took a post-test. By combining the post-test scores and in-game performance as a measure of learning outcomes, we explored the potential relation between these outcomes and the students' perception of the TA. Since TAs often have a more substantial positive effect on the learning of lower performing students (Silvervarg et al., 2021; Tärning et al., 2020), we assumed that such a relation might differ between students with different performance levels.

Result: As hypothesised, students who rated Timy as in greater need of help performed significantly better than students who rated him/her as in lesser need of help. The effect was similar across performance levels – a rather surprising result. We conclude that for TAs to be beneficial in educational software, their need for help should be clearly communicated and emphasized.

Contribution: The research data originates from a larger study on feedback engagement conducted in 2019 without my participation. The paper was written together with Betty Tärning and Magnus Haake, both being part of the original study. I am responsible for all analyses in the paper, while the writing was done in collaboration with my co-authors. The paper was presented by Betty Tärning and me at the *30th International Conference on Computers in Education (ICCE 2023)* in Kuala Lumpur, Malaysia, and was nominated for best student paper.

Paper IV: Far from Success – Far from Feedback Acceptance? The Influence of Game Performance on Young Students' Willingness to Accept Critical Constructive Feedback During Play

The fourth paper, like the third, targets teachable agents and presents a study on how momentary performance levels may influence middle school students' willingness to accept critical constructive feedback (CCF) when they play an educational game in history – with or without a TA. In the game, the students solved a series of tasks, and when they failed, they were asked if they wanted feedback on their mistakes or not. Data logs from 121 students who played the game during 3 lessons in 3 consecutive weeks were gathered and analysed in detail, with respect to potential relations between failures on tasks, feedback (non-)acceptance, and the (no-)presence of a TA.

Result: The results showed that although both higher- and lower-achieving students were significantly less inclined to accept feedback after severe task failure, the presence of a TA mitigated this behaviour – and most for the lower-achieving students. This effect was found both if the students failed repeatedly on the same task, or if they had many errors on a single task. The fact that students tend to avoid feedback when they are most in need of it is problematic and needs to be addressed. Not least this is of importance for the design of educational software, since it very easy in a digital environment to dismiss unpleasant messages and avoid negative information regarding one's own performance.

Contribution: The study is a post-hoc analysis with data originating from the larger study on feedback engagement mentioned in the summary of PAPER III. The paper was written together with Betty Tärning, who also participated in the original study. I am responsible for all analyses in the paper, while the writing was done in collaboration with my co-author. The paper was presented by me at the *21st International Conference on Artificial Intelligence in Education (AIED 2020)*, and was awarded 'Best student paper runner up'.

Paper V: Are Pairs More Attentive Towards Feedback Than Individuals? A Glance Into Feedback Neglect for Middle-School Students Using an Educational Game in History

The fifth paper, like the fourth, concerns feedback neglect, but this time in a different context. In this study, we wanted to investigate whether collaborative learning could support feedback engagement and scaffold students to attend to critical feedback, instead of dismissing or neglecting it. 106 middle-school students played the same history game as in PAPER III and PAPER IV for two sessions, but without a teachable agent. At one of the two sessions, the students worked individually with one tablet (single condition), and at the other session they shared the tablet with a classmate (pair condition). The game had a slightly different configuration than in PAPER IV. For the analysis, we classified the feedback messages as 'attended to' or 'not attended to' depending on if the student clicked away the message shortly after it was displayed or not. We hypothesised that working in pairs would increase students' inclination to 'attend to' the feedback more often, finding it less threatening than if they played the game by themselves. The analysis was done in the same way as in PAPER IV, dividing the students into different groups depending on performance level.

Result: The results revealed that while medium/lower-performing students more often attended to the feedback when working in pairs (compared to working individually), the opposite was found for higher-performing students. However, if a pair of higher-performing students failed repeatedly on the same task, they were more inclined to attend to feedback than if they made the same mistakes playing by themselves. Evidently, the strength with collaboration is heavily dependent on the relation between task difficulty and the competence of the group members (Nokes-Malash et al., 2012). In this case, the combined competence for the higher-performing students seemed to be optimal for some of the more difficult tasks, leading to better learning strategies.

Contribution: The original research questions were proposed by me, after having observed students working in pairs in my pilot study on geometry (Ternblad, 2022). Me and Betty Tärning thereafter designed the experiment in cooperation with Sam Bagra, a master student in cognitive science. Since the study was conducted during the COVID-19-pandemic, it had to be supervised remotely, making the teachers responsible for distributing the software and assigning the students to specific log-in details etc. While Sam Bagra had the main responsibility for overseeing the students' game play, the paper was written by me and the other co-authors. However, I am responsible for all the analyses in the paper, as well as the main part of the writing. The paper was presented by me at the *16th International Conference on Computer-Supported Collaborative Learning (CSCL, 2023)* in Montréal, Canada, and was nominated for best student paper.