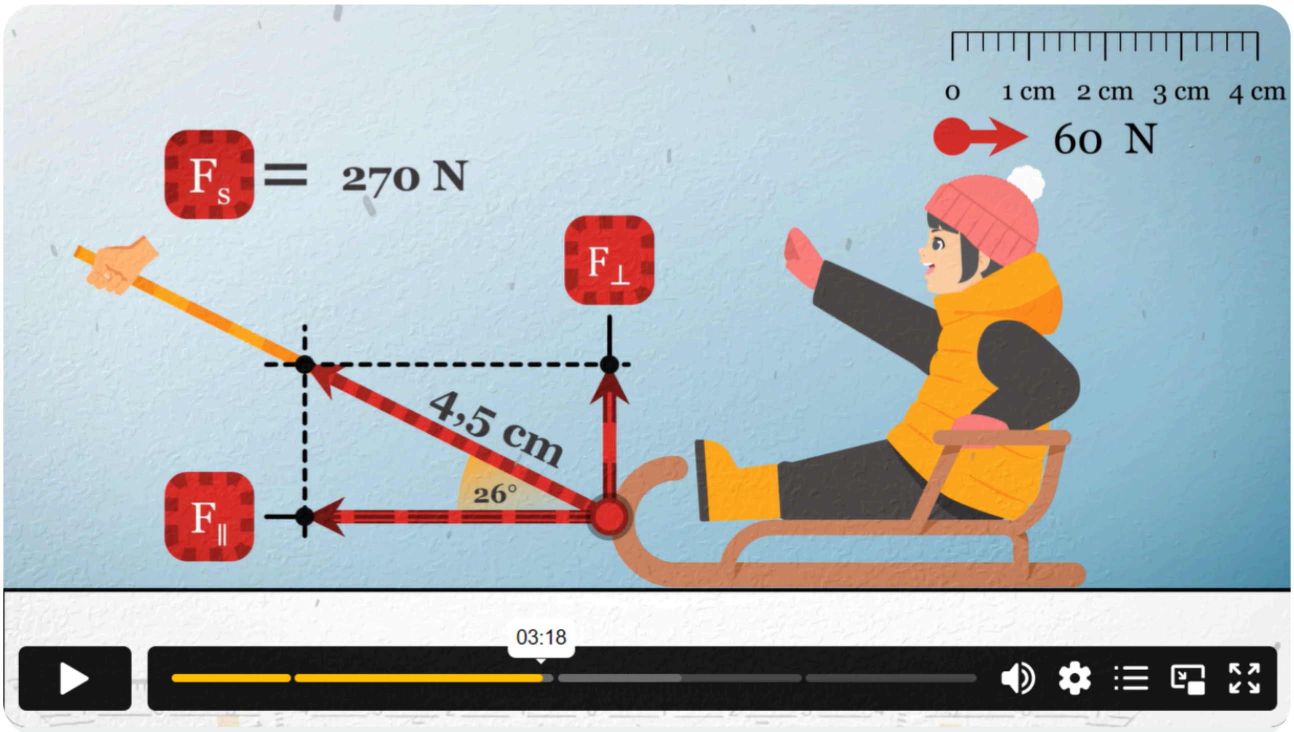
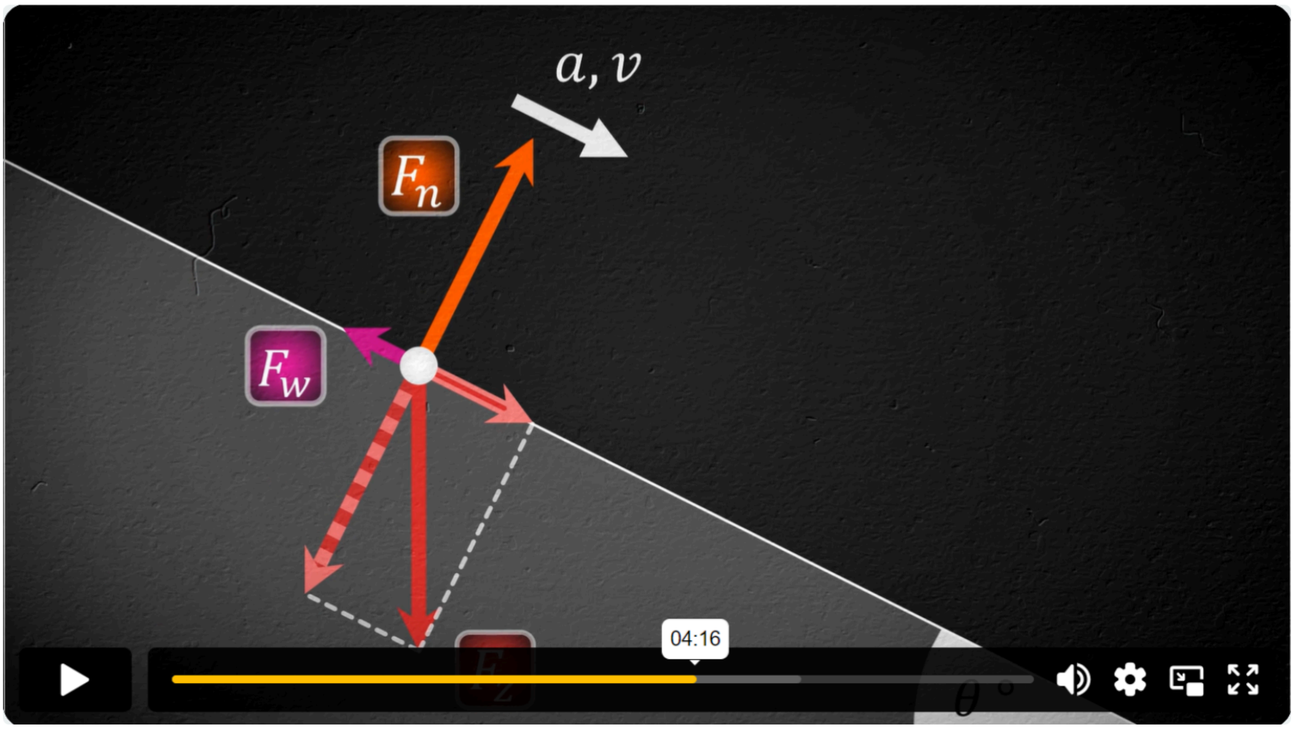
Optimizing and evaluating the design of animated explainer video for higher education physics and engineering





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Abstract

This thesis investigates the optimization and evaluation of animated explainer videos tailored for higher education students in physics and engineering, using principles derived from cognitive load theory and educational psychology. The core objective was to formulate and test clear, empirically-backed design guidelines for such videos, specifically focusing on the congruence and apprehension principles which will be reviewed with much detail. These guidelines were applied to develop three distinct animated videos, each designed to target specific educational outcomes within the disciplines. A case study with quasi-experimental elements was utilized to measure the videos' effectiveness, combining quantitative assessments and qualitative feedback from students. While the study revealed no statistically significant improvement in student test scores, qualitative insights suggest that the videos were valued for their clarity and instructional design. Students reported that the videos facilitated a deeper understanding of complex concepts, although they also highlighted areas for improvement in terms of integration into course structures and pacing. These findings underscore the potential of well-designed educational videos to enhance learning, while also pointing to the necessity for ongoing refinement to fully exploit their educational benefits.

1 Introduction

The use of educational videos in any discipline of higher education in today's educational landscape has become common practice. Moreover, the digitalization of education, accelerated by the COVID-19 pandemic, has made video a central tool in online and blended learning environments like universities and online courses. According to Wijnker (2021), video’s capacity for preservation, sharing, and replaying offers substantial opportunities for self-paced and differentiated learning, which are hot topics in the 21st century (Bonk & Graham, 2012; Şad, 2012).

One of the primary known benefits of video-based learning is its ability to engage and motivate students. Videos can evoke emotions such as interest, which are beneficial for effective learning (Meeter et al., 2020). Furthermore, generative AI-based software make it nowadays more easy to develop video's. For example, in this study I used Elevenlabs to generate natural sounding narration for the video about thermodynamics which only took a matter of seconds instead of recording for hours.

When effectively implemented, engaging students through video can foster deeper knowledge processing and create more enjoyable learning experiences (Wijnker, 2021; Mayer and Clark, 2016). This is particularly beneficial for subjects demanding conceptual understanding, ranging from the emission spectra in physics to the complexities of collateralized debt obligations in economics. These abstract topics often present a challenge in maintaining student interest (Wijnker, 2021). Streaming platforms such as YouTube and Nebula demonstrate the success of science explanation channels like Veritasium and Kurzgesagt in captivating millions of hobbyist viewers.

But how much do students actually learn from videos? Can they remember the content, and apply these concepts in different contexts? Research on the effectiveness of videos in education presents mixed results (Zhang et al., 2005; Brame, 2016). However, it is evident that videos can significantly enhance learning outcomes when specific conditions are met (Höffler & Leutner, 2007). These conditions are often domain-specific and can sometimes conflict with one another (Tversky, Morrison, & Betrancourt, 2002).

Tversky, Morrison, and Betrancourt (2002) propose a framework that relates all educational features in videos and animations to two core principles: the congruence principle and the apprehension principle. The apprehension principle encompasses all features that enhance the viewer's perception and accurate reception of the information. This involves ensuring that the visual and auditory elements are clear, unambiguous, and easily processed by the viewer. Within the context of cognitive load theory, this can be characterized as managing extraneous cognitive load, ensuring that unnecessary or confusing details do not overwhelm the viewer (Brame, 2016).

The second principle, the congruence principle, pertains to processing information and developing cognitive schemas of concepts and procedures. This principle ensures that the structure and content of the visual representation align with the cognitive processes they aim to support, facilitating a deeper understanding of the material. Unlike the apprehension principle, the embodiment of the congruence principle is discipline-specific, meaning that its application varies depending on the subject matter being taught (Tversky et al., 2002).

The aim of this study is to design videos and evaluate explainer videos. The design of the videos involve a literature study. These videos will then be evaluated in higher educational courses. It is important to note that many empirical studies have shown that the learning outcomes of videos can be significantly enhanced by implementing them in the right educational environment. For example, equipping them with interactive features that provides self pacing and stimulate active learning (Moreno & Mayer, 2009; Zhang et al., 2005). However, this study focuses on the inherent design of the video content itself—such as the use of representations and animations—as an independent feature. The aim of this study is hereby to design videos optimized by adhering to two core principles.

2 Theoretical background

Two main principles, apprehension and congruence, are essential for ensuring that videos are clear, engaging, and educationally valuable. Before delving into our video design, we will discuss these principles in greater detail.

2.1 Apprehension principle

The purpose of adhering the apprehension principle is to enhance the viewer's perception and accurate reception of information. This principle ensures that the visual and auditory elements are clear, unambiguous, and easily processed by the viewer, thereby minimizing cognitive load and preventing unnecessary confusion. Several key methods and strategies have been identified to achieve this principle effectively.

1. **Highlighting**
   Highlighting involves directing the viewer's attention to specific elements of the visual content. This can be achieved through the use of color, contrast, or motion to emphasize important information. According to De Koning et al. (2009), effective attention cueing through highlighting helps learners focus on critical parts of the animation, thereby enhancing comprehension and retention.
2. **Spatial proximity**
   Ensuring spatial proximity means placing related visual and textual information close together on the screen. This method reduces the cognitive effort required to integrate separate pieces of information, facilitating easier cognitive processing. Brame (2016) emphasizes that when visual and textual elements are spatially closely aligned, it helps learners to form a coherent mental representation of the material. An integrative view is important here, as it ensures that all relevant elements are seen as part of a unified whole, thereby enhancing the overall comprehension and retention of the information presented.
3. **Temporal proximity**
   Temporal proximity involves presenting related visual and auditory information simultaneously or in close succession. This approach ensures that learners can process the information together, making it easier to integrate and understand. According to Brame (2016), aligning the timing of animations with accompanying narration or text helps reduce cognitive load and prevents the disconnection that can occur when related information is presented too far apart in time.
4. **Absence of extraneous content**
   Removing unnecessary information that does not contribute to the learning objectives helps to minimize extraneous cognitive load. This principle, discussed by Tversky, Morrison, and Betrancourt (2002), suggests that simpler and cleaner visuals are more effective as they prevent cognitive overload and allow the viewer to focus on the essential elements of the content.
5. **Use of conversational language**
   Employing conversational language rather than formal or complex language in the narration of educational

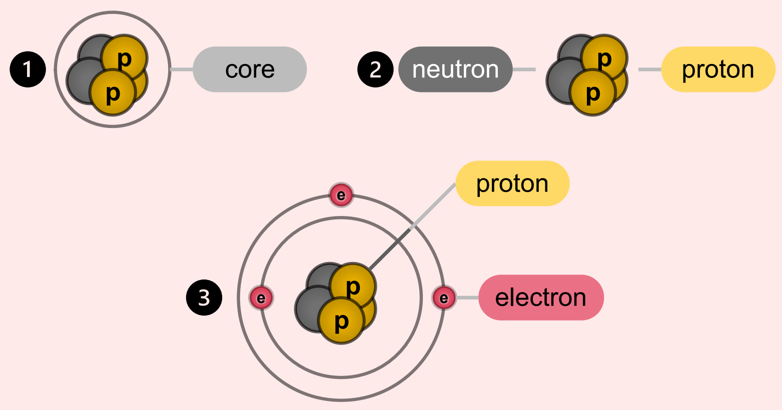
videos makes the content more relatable and easier to understand. This approach is supported by Mayer's multimedia principles, which advocate for a more engaging and accessible presentation style to enhance learning (Clark & Mayer, 2016; Brame, 2016).

6. **Signaling**
   Signaling involves using cues to indicate the structure of the content, such as headings, arrows, or other visual markers that guide the viewer through the material. This method helps in organizing information and making the logical flow of the content more apparent (De Koning et al., 2009).
7. **Segmenting**
   Breaking down information into smaller, manageable segments allows learners to process and understand one part before moving on to the next. This approach aligns with the principle of managing cognitive load by preventing information overload (Brame, 2016).

Lets discuss some examples. Example 1 (see image below) illustrates the segmentation principle through temporal sequencing by building up a representation of an atom. The image uses colors (yellow for protons and ruby for electrons) and symbols ("p" for protons and "e" for electrons) to make the elements easily distinguishable, adhering to the signaling principle.

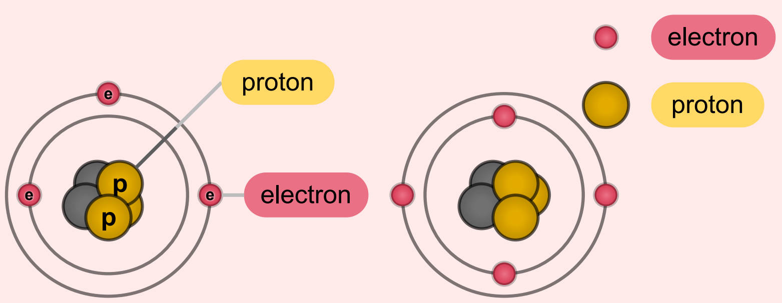
The goal of this image was to explain protons and electrons. Including the caption for the neutron initially helped to avoid confusion, but it was eventually removed to maintain a minimalistic representation, adhering to the principle of the absence of extraneous content.

Example 1: Applying the segmentation principle by temporal sequencing



Example 2 compares two similar representations. The left image is easier to perceive than the right image because it uses letters and visual markers, adhering to the signaling principle. The right image lacks these markers and violates the spatial proximity principle by placing captions too far from the subatomic particles, making it harder to integrate the information.

Example 2: signalling (left) versus no signalling (right)



2.2 Congruence principle

The congruence principle, as mentioned earlier, asserts that the structure and content of instructional materials should closely match the mental representations they aim to evoke in learners. Unlike the more straightforward apprehension principle, which primarily deals with enhancing perception and managing cognitive load, the congruence principle is more nuanced and discipline-specific.

The congruence principle involves aligning instructional materials with learners' cognitive processes, ensuring that the way information is presented matches how learners should process and understand that information. This alignment helps in building accurate and robust mental models, which are essential for understanding complex systems and processes in science and engineering (Tversky, Morrison, & Betrancourt, 2002).

The effectiveness of congruence-based strategies can vary significantly across different disciplines, necessitating tailored approaches. For instance, what works well for teaching mechanical processes in physics might not be as effective for conveying biological systems in life sciences (Tversky et al., 2002).

Representations

An effective method in video-creation that aligns with the congruence principle is the effective use of different representations. Representations both- static and dynamic should facilitate the construction of accurate mental models by making abstract concepts more concrete and visually accessible (Hegarty, 2003).

This is in accordance with contemporary discipline-based educational research in physics and engineering. The interplay of multiple representations helps students grasp complex concepts by providing various perspectives and ways of understanding the same information (Docktor & Mestre, 2014).

The use of representations, such as graphical, schematic, or realistic, should balance dynamic and realistic features appropriately to achieve optimal learning outcomes.

The role of realism in instructional (dynamical) representation is particularly remarkable. The meta-analysis by Höffler and Leutner (2007) highlights that highly realistic animations are significantly more effective in conveying procedural knowledge compared to more abstract representations. Realism helps learners relate the instructional content to real-world scenarios, enhancing their ability to form accurate mental models. However, realism must be balanced with simplicity to avoid violating the apprehension principle and causing cognitive overload (Höffler & Leutner, 2007).

Dynamic representations, such as animations or simulations, are not inherently superior to static ones; their effectiveness depends largely on the instructional context and the nature of the content being taught. Tversky, Morrison, and Betrancourt (2002) suggest that dynamic visualizations are particularly beneficial when depicting processes that involve temporal changes, such as the movement of electrons in a chemical reaction or the operation of a mechanical system. However, they also highlight that animations often do not provide additional benefits over static representations, as they can introduce excessive complexity or present information too quickly, which may hinder accurate perception and comprehension (Tversky, Morrison, & Betrancourt, 2002).

Moreover, Höffler and Leutner (2007) emphasize that static representations can be equally effective, if not more so, for certain types of content. They argue that static images, when designed well and incorporating methods traditionally used in dynamic representations, can enhance learning effectively. For example, static visuals might employ progressive disclosure, where information is revealed in a sequence that learners follow at their own pace, or use multiple diagrams to simulate interactive exploration of a topic—techniques that manage cognitive load by focusing attention on one part of the content at a time, thus facilitating deeper understanding (Höffler & Leutner, 2007).

To illustrate the congruence principle, let's examine schematic representations of a simple electric circuit in the provided example (figure 2.2.1). The context of this image is a worked-out problem where the electric current is calculated using Ohm's law. Both representations show the necessary information to solve the problem, but the representation on the right significantly enhances the development of a mental model of electricity.

Example of two representations of an electric circuit

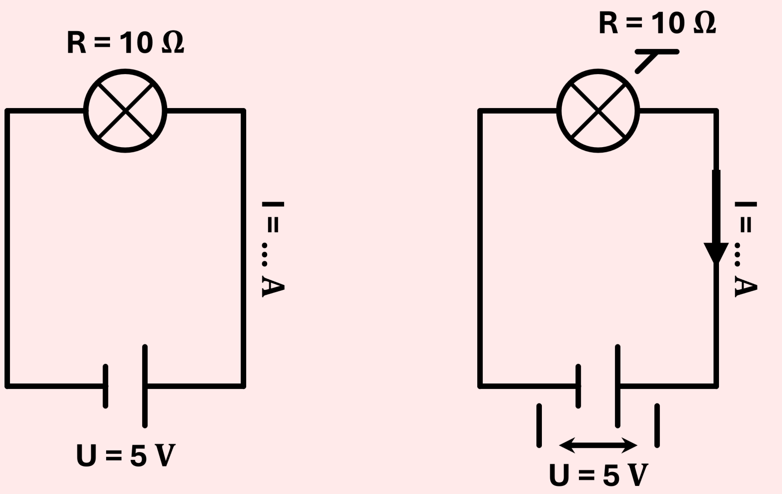


figure 2.2.1: congruence principle is being applied in the circuit on the right

In the illustration on the right contains the following cues:

- **Voltage:** A clear visual cue highlights that voltage is property between two points in the circuit.
- **Current:** An arrow within the circuit wire represents the current, helping learners grasp that this quantity signifies the flow of charge through a wire or component.
- **Resistance:** Resistance is depicted as a property of an electric component, emphasizing that it is typically a constant value found written on the resistor.

These depictions align closely with the desired cognitive scheme of how electric circuits work, making it easier for students to form accurate mental models.

2.3 Research questions

This study aims to design and evaluate instructional videos for higher education engineering. Although substantial research has been conducted on video-based learning in general, there remains a lack of clearly defined and empirically tested embodiments of theoretical principles, particularly the congruence principle, due to its domain and context-specific nature.

The primary research question guiding this study is:
"How can the design of instructional videos, utilizing the congruence and apprehension principles, enhance student learning outcome in a higher education context?"

The first objective is to optimize the video design using the congruence and apprehension principles. This means ensuring the content aligns with learners' cognitive processes (congruence) and enhances perceptual clarity (apprehension). An important part of this research is maintaining transparency in the design process, as many studies often lack clarity about the specific content used in their empirical work which makes there result quite hard to compare. Small details, such as background music being too loud or a poorly articulated speaker, can significantly affect the results and make it challenging to compare videos accurately.

The second objective of this study is to accurately evaluate the videos and link those results to their underlying design principles. We have chosen a higher educational setting, as video-based learning fits well into the blended learning environment that has become common practice in many universities. It is also beneficial to investigate the relationship between students' perceived usefulness of the videos, based on their subjective evaluations, and their actual learning outcomes. This exploration can reveal whether students' perceptions align with their performance. By analysing the interdependence of these indicators, we can better understand the distinction between the core principles and our specific interpretation and implementation of their embodiment.

These two objectives can be translated into two partial research questions:

1. How can videos be systematically designed adhering the congruence and apprehension principle in classical mechanics?
2. Does empirical evidence in higher educational setting validate our conjecture-based design?

3 design of the videos

3.1 Design process

In this section we discuss the first part of the research objective.
Three videos were designed by the main author, Luuk van der Togt. In order to create a firm workflow, we used storyboarding. Storyboarding is systematic approach of video production to analyse scenes.

The main principles, apprehension and especially the congruence principle, might seem purely theoretical at first glance. In appendix A2 we have provided an storyboard analysis of a renowned explainer video to exemplify these principles through a storyboard analysis. By doing so, we aim to illustrate the practical application of these principles and provide a systematic approach to developing and evaluating educational videos transparently.

Storyboarding is a method used to visually organize, plan, and evaluate the content of a video project. It involves creating a sequence of drawings or images that represent scenes in a video, helping to ensure that the final product effectively conveys the intended information. By constructing a storyboard, we can systematically design videos that make optimal use of the apprehension and congruence principles.

Storyboarding is a method used to visually organize and plan or evaluate the content of a video project. It involves creating a series of drawings or images displayed in sequence to represent the scenes in a video. Because constructing a systematic and transparent way of video production and evaluation is part of the research aim. I will provide a brief overview of how video's can be specifically designed to make optimal use of the apprehension and congruence principle.

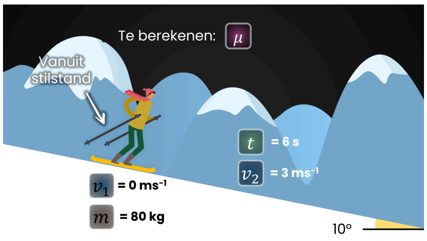
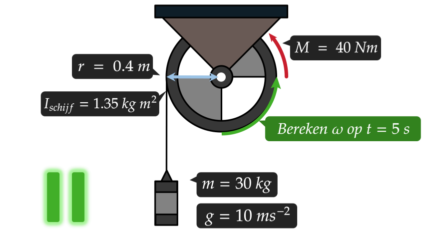
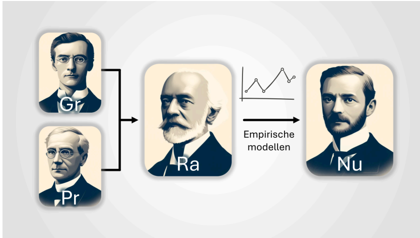
In Appendix A1, you can find a storyboard analysis of a famous video by Grant Sanderson, a famous educational creator who contributed a lot into the area of research regarding multimedia learning in math and physics education.

3.2 Video creation overview

In this section, we provide a brief overview of the videos:

- **Video 1:** This video explains how to calculate the coefficient of friction on a slope. It covers Newton's Second Law, the formula for kinetic friction, and the computation of the resultant force using vector components.
- **Video 2:** This video explains how to calculate the angular velocity of a rotating disk using Newton's Second Law for rotation. It covers rotational motion, Newton's Second Law for rotation, and the mass moment of inertia.
- **Video 3 (a, b, c):** This video is split into three parts:
  - **Part a:** Explains how empirical models are used to calculate spontaneous convection (heat transfer). (see appendix B1.1)
  - **Part b:** Discusses the Grashof and Prandtl numbers, which are important indicators in the field of heat transfer. (see appendix B1.2)
  - **Part c:** Discusses quantitative models used in various setups to calculate the coefficient of convection. (see appendix B1.3)
    A screenshot of each video can be found in tabel 3.1.1.

tabel 3.1.1: Overview of the thumbnails used in the videos designed during this study

<table>
<tr><th>Screenshot (video 1)</th><th>Screenshot (video 2)</th><th>Screenshot (video 3a)</th></tr>
<tr><td>
</td><td>
</td><td>
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4 Methods of Evaluation

This study employs a quasi-experimental design, executed over three distinct cycles of data collection at the University of Applied Sciences of Rotterdam, within the Faculty of Engineering. Initially prioritizing quantitative analysis, the scope expanded to include qualitative insights following the second iteration to elucidate specific outcomes.

4.1 Configuration of Iterations 1 & 2

Students participated in a controlled environment where they were given a paper-based test. This test included a link to either a video or a written explanation—depending on their group assignment—to ensure consistency with the intervention protocols. Validity of the test results was contingent upon students completing at least 15% of the test; correctness of answers was not a criterion for data inclusion.

Details of First Iteration

The first experimental phase involved 44 students, focusing on the dynamics of a point mass on an inclined plane, incorporating factors like gravity and friction. Detailed breakdowns of the concepts covered, the instructional video, and the test itself are available in Appendices B1.1, B2.1, and C, respectively.

Details of Second Iteration

The second iteration examined the kinetics of composite rigid bodies, a conceptually tougher subject, with 45 participants, 32 of whom provided valid results. Similar to the first iteration, comprehensive details about the video lesson and the test are accessible in Appendices B1.2, B2.2, and C.

Assessment Design

Due to logistical constraints and concerns about participant engagement, a full-scale pre-test was not implemented. To align the control and intervention groups comparably, two strategies were adopted: random assignment and the use of students' academic performances in related courses (e.g., Mathematics and Static Constructions) as covariates in an Analysis of Covariance (ANCOVA). These grades were hypothesized to predict outcomes on the post-test.

However, analysis indicated a low correlation ($r = 0.12$) between grades in these courses and post-test performance, suggesting that these metrics were insufficient predictors and thus unreliable for adjusting the ANCOVA. Consequently, random assignment was primarily relied upon to mitigate pre-existing knowledge differences and enhance the validity of the comparison between groups.

The test design followed five critical principles from Angelo & Cross (1988) to ensure the relevance and integrity of the assessment:

- **Consistency with Course Material:** The test mirrored the format and style of official course materials to avoid disorientation.

- **Independence of Questions:** Each question stood alone, ensuring that difficulty in one would not impede performance on subsequent items.
- **Balance of Application:** The test included questions directly reflecting video content and others requiring adaptive application, fostering knowledge transfer.
- **Incremental Difficulty:** Questions progressed from simpler to more complex, supporting confidence building and differentiation of student understanding levels.

The tests of the first and second iteration can be found in appendix B2.1 and B2.2.

4.2 Configuration of Iteration 3

Faced with the need for deeper insights after the second iteration's limited yield, a third iteration was introduced within a Thermodynamics course, engaging 40 students. This phase diverged from the previous ones by involving only an experimental group, which allowed a focused examination of the interplay among student performance, motivation, and perception. While the distinct curriculum of this course precluded the integration of its data with the first two iterations, the analysis was nonetheless useful in extending our understanding of the broader experimental objectives.

Assessment Design

This iteration introduced a comprehensive digital platform that housed the survey, test, instructional videos, and thermophysical property tables, significantly streamlining the user experience. This integration not only simplified the process for students but also ensured complete participation in the survey through compulsory response mechanisms.

In Figure 4.2.1-4.2.2, a screenshot is shown of the web application. The tabs are multiple subpages that allowed for easy navigation.

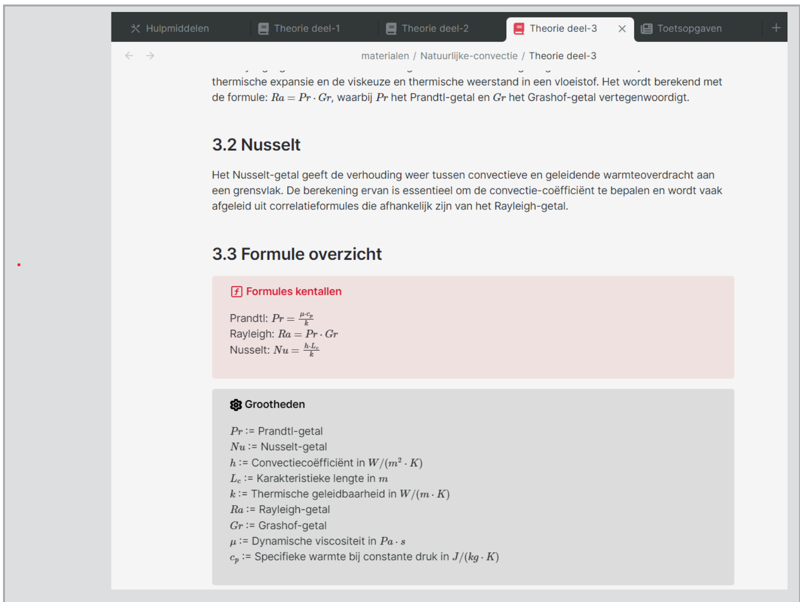

Figure 4.2.1: Screenshot of the web-based application

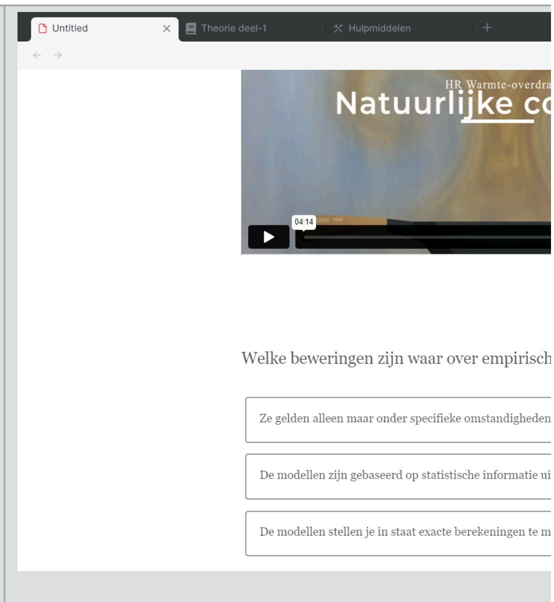

Figure 4.2.1: Screenshot of the test questions web application.

The video content delivery was meticulously controlled by the instructors to guarantee that all participants viewed the material, is it was observed that in the previous iterations not all students completely did.. Moreover, the division of the video into three segments—Part 1, Part 2, and Part 3—imposed structured pacing through interim deadlines, which was intended to enhance engagement and maintain consistent progress throughout the course.

To summarize, the deployment of this web-based application was an improvement of the research instruments by addressing the issues identified in earlier iterations, such as incomplete survey submissions and insufficient guidance between the different components (survey, assignments, videos and tools). By centralizing resources and controlling the instructional flow, the study aimed to produce a complete and more reliable dataset that could be more effectively analysed for correlations between performance, motivation and perception. This methodological shift highlights a proactive adaptation to the complexities encountered in educational research, particularly when exploring the efficacy of digital learning tools in a higher education setting.

4.3 Survey

Although the lay-out of the survey varied in the different iterations, the survey, which aimed to measure the motivation and perception of congruence and apprehension, comprises nine questions, each rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The questions are crafted to assess the impact of the congruence and apprehension principles, with each designed to measure one principle, while also reflecting aspects of the other.

Indicators for the Congruence Principle

The congruence principle addresses the alignment of instructional materials with learners' cognitive processes, facilitating comprehension and problem-solving abilities. This principle is evaluated through questions that probe the structural and contextual integrity of the video content:

- "The video provided valuable insights into the subject matter."
- "The design elements, such as illustrations and animations, were effectively integrated to enhance content understanding."
- "The video accurately emphasized the necessary procedural steps for solving the problems presented."
- "The logical structure of the video helped in understanding complex concepts."
- "Visual aids like diagrams and charts were directly relevant and supportive of the concepts explained."

These questions aim to assess whether the educational materials succeed in mirroring the cognitive structures that students use to understand and solve problems, a core aspect of the congruence principle.

Indicators for the Apprehension Principle

The apprehension principle focuses on the ease of perceiving and processing information presented in the videos. It aims to minimize cognitive overload by ensuring clarity and avoiding unnecessary distractions. This principle is measured through questions that examine the perceptual clarity of the instructional content:

- "The steps outlined in the video were presented clearly, making them easy to follow."
- "The use of visual aids like highlights and colors effectively facilitated comprehension of the material."
- "The verbal explanations were delivered in a clear and comprehensible manner."

Additionally, to address potential negative aspects of video presentation that could hinder learning, the survey includes:

- "The video avoided including unnecessary elements that do not contribute to learning."
- "The presentation was not overwhelming, maintaining a focus on key content."
- "The video was free from distracting features that could detract from the educational goals."

These questions focus on the perceptual clarity of the video and the avoidance of extraneous cognitive load, critical for maintaining learner engagement and facilitating effective information processing.

By evaluating responses to these questions, the survey aims to directly link student feedback to the theoretical principles underpinning the video content, providing a nuanced understanding of how well the educational interventions align with educational psychology theories on learning and cognition. This approach ensures a comprehensive assessment of each principle's impact on learning outcomes.

Motivation as covariate

Although this study does not investigate the direct impact of instructional videos on student motivation, it recognizes the influence of motivation on students' performance in the specific post-tests administered. To ensure the reliability of our statistical analyses, it is essential to control for motivation levels. Students rated their motivation on a 1 to 5 scale, which was then converted to a 0 to 100 scale for more granular analysis. This measure is referred to as the Motivation Index (MI) and is used as a covariate in our statistical models. Including the MI helps account for variations in test scores that may be attributed to differing levels of motivation among participants, thus providing clearer insights into the actual effectiveness of the videos. This approach acknowledges the expected linear relationship between motivation and performance on the post-tests, ensuring that our findings more accurately reflect the impact of the educational content.

5 Results & Analysis

5.1 Iteration 1 & 2 (quantitative)

This section presents the quantitative results of the first and second iterations, focusing on performance, motivation, apprehension, and congruence indices. We analyze the data using descriptive statistics, visualizations, and statistical tests to provide a comprehensive overview of the findings.

Descriptive Statistics

The descriptive statistics for both iterations are summarized in Table 5.1.1.

Table 5.1.1: Descriptive statistics (Iteration 1 & 2)

Group	Mean Motivation Index	Mean Test Score Percentage	Mean Apprehension Index	Mean Congruence Index	Participants
Control 1	52	44.34%	*non existent*	*non existent*	24
Video 1	63	53.57%	3.57	3.35	20
Control 2	56	38.89%	*non existent*	*non existent*	9
Video 2	47	26.40%	3.70	3.22	23

In Figure 5.1.1, bar plots for performance and motivation indices are presented. The bar plots indicate that the video groups had higher mean performance scores compared to the control groups in both iterations. Specifically, in Iteration 1, the video group had a mean performance score of 53.57% (SD = 18%) compared to the control group's mean score of 44.34% (SD = 15%). In Iteration 2, the video group had a mean performance score of 26.40% (SD = 12%) compared to the control group's mean score of 38.89% (SD = 10%). Additionally, the mean motivation scores were higher in the video group for Iteration 1 (63%) than in the control group (52%), while Iteration 2 showed the opposite trend, with lower motivation in the video group (47%) compared to the control group (56%).

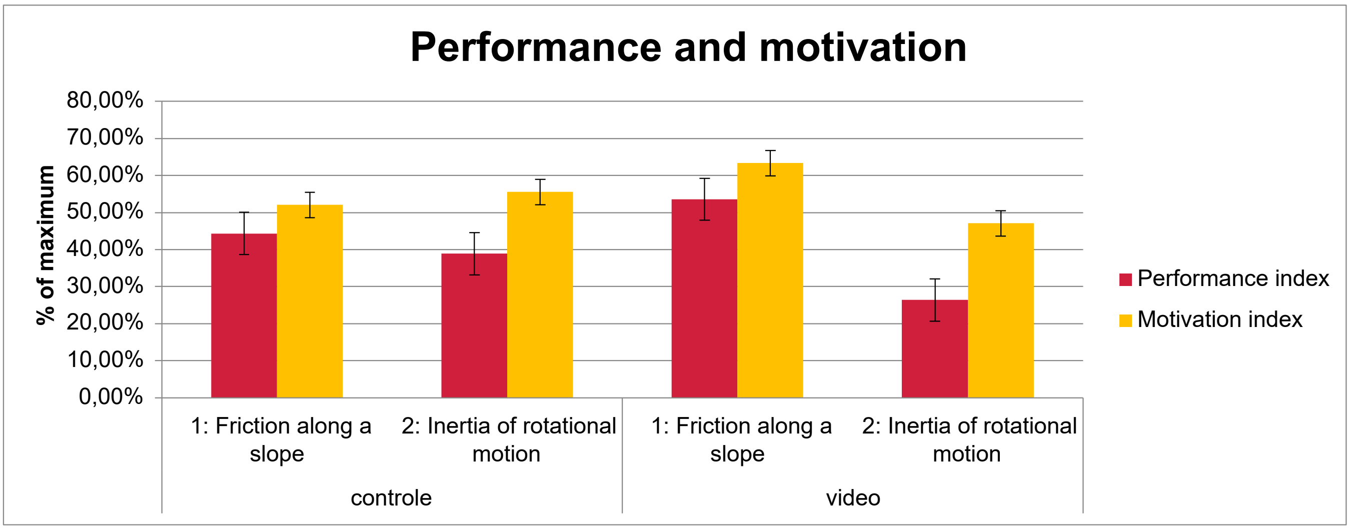

Figure 5.1.1: Bar plots for performance and motivation (1st and 2nd iteration)

Figures 5.1.2 and 5.1.3 present the distribution of performance and motivation indices among the different groups. In Figure 5.1.2, the boxplots for performance show a wider distribution of scores in the video groups compared to the control groups, indicating greater variability. The video group in Iteration 1 shows a median performance score higher than the control group, while Iteration 2 shows the control group outperforming the video group.

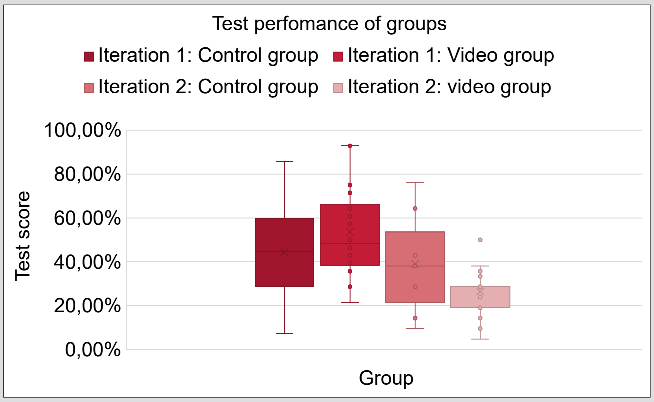

Figure 5.1.2: Distribution of performance in among the different groups

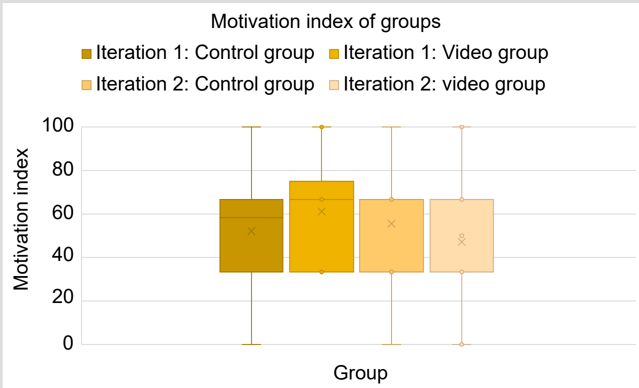

Figure 5.1.3 Distribution of performance in among the different groups

In Figure 5.1.3, the boxplots for motivation reveal that the video group in Iteration 1 had higher motivation scores, whereas in Iteration 2, the control group's motivation was higher. The variability in motivation scores was also greater in the video groups.

Figures 5.1.4 and 5.1.5 show the perception of congruence and apprehension among participants. In Iteration 1 (Figure 5.1.4), the majority of students rated both congruence and apprehension between 3.0 and 4.0, indicating moderate positive perceptions. In Iteration 2 (Figure 5.1.5), there is a noticeable shift, with more students rating apprehension higher (3.5 to 4.0) while congruence ratings are more dispersed.

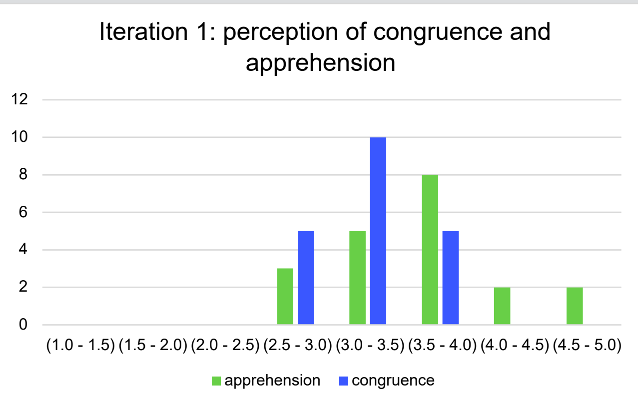

Figure 5.1.4: Histogram of perception of congruence and apprehension (iteration 1)

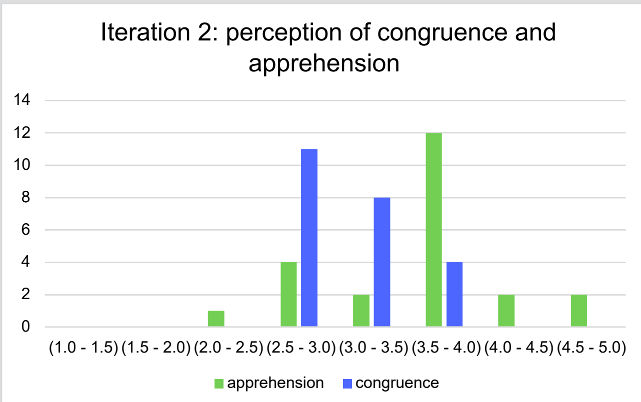

Figure 5.1.5: Histogram of perception of congruence and apprehension (iteration 2)

The low performance and the number of no-show participants in the second iteration made the results less valid. This issue will be discussed further in the discussion section. In the next section, we will perform an ANCOVA test and present a correlation matrix to explore the interdependencies of the parameters in the first iteration.

ANCOVA Test

Before conducting the ANCOVA analysis, we ensured linearity between the covariate (motivation index) and the dependent variable (test scores). In Figure 7, a scatter plot with a regression line shows this relationship. The linear regression analysis indicates a significant linear relationship between the motivation index and test scores (R^2 = 0.213, $p < 0.001$), confirming the appropriateness of using motivation as a covariate in the ANCOVA analysis.

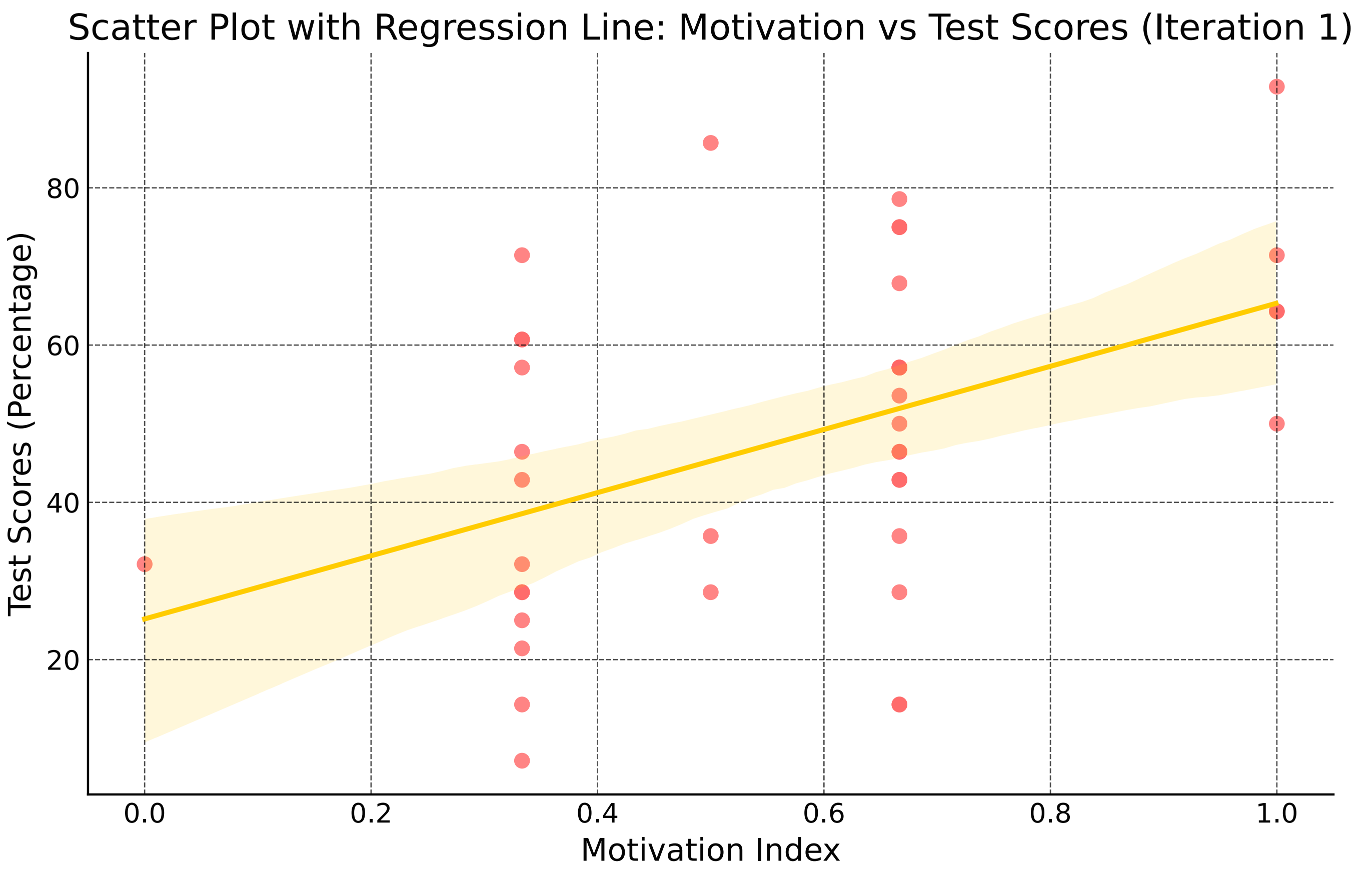

Figure 7: Scatterplot with Regression Line (Performance vs. motivation)

An Analysis of Covariance (ANCOVA) was performed to compare the test scores between the control and video groups, using the motivation index as a covariate. The results are summarized in Table 5.1.2.

Table 5.1.2: ANCOVA Results for Iteration 1

Source	Sum of Squares	df	Mean Square	F-value	p-value	Partial Eta Squared
Group (Version)	183.79	1	183.79	0.497	0.485	0.013
Motivation	2831.98	1	2831.98	7.651	0.009	0.171
Residual	13695.99	37	370.16			

The ANCOVA analysis for Iteration 1 shows no significant effect of the video intervention on test scores after accounting for motivation ($p = 0.485$). However, motivation had a significant effect on test scores ($p = 0.009$).

Interdependencies

In Table 5.1.3, a correlation matrix of the four parameters (performance, motivation, congruence, and apprehension) is shown. The matrix reveals the relationships between these variables, indicating how they interact and influence each other.

Table 5.1.3: Correlation Matrix (Iteration 1)

Parameter	Performance	Motivation	Congruence	Apprehension
Performance	---	---	---	---
Motivation	0.44	---	---	---
Congruence	-0.17	0.02	---	---
Apprehension	-0.06	-0.03	0.51	---

The correlation matrix indicates several notable relationships. There is a positive correlation between congruence and apprehension (r = 0.51). This suggests that students who found the videos congruent with their cognitive processes also perceived them as easier to apprehend. Conversely, it can also be interpreted that students who found the videos easier to apprehend were better at recognizing the cognitive processes expressed by the congruence principle.

Furthermore, the correlations between performance and the other indices (congruence and apprehension) are is very small, implying that the perception of the educational value of the video did not per se translate to actual learning outcomes.

5.2 Iteration 3 (quantitative results)

In this iteration, we examined the effectiveness of the educational video intervention within a single group of 30 participants. We focused on four main parameters: performance, motivation, apprehension, and congruence. The results are presented in the following sections.

Descriptive Statistics

In iteration 3, there was only a single group of 30 participants. The descriptive statistics are shown in Table 5.2.1.

table 5.2.1: descriptive statistics	M	SD
Participants	30	-
Performance (%)	70	18
Motivation (scale: 0-100)	45	20
Apprehension (scale: 1-5)	3.2	0.54
Congruence (scale: 1-5)	3.3	0.70

The performance index had a mean of 70% with a standard deviation of 18%, indicating a reasonably high level of achievement among the participants. Motivation was somewhat lower, with a mean of 45% and a standard deviation of 20%, suggesting a wide range of motivational levels within the group. The mean scores for apprehension and congruence were 3.3 (SD = 0.54) and 3.2 (SD = 0.70), respectively, on a 5-point Likert scale.

Visualization of Results

The boxplot in Figure 3.2.1 illustrates the distribution of performance and motivation indices. The performance index is represented by the red boxplot, which shows a concentration of scores around the 70% mark, with a few outliers below 50%. The motivation index, depicted in yellow, shows a broader distribution with a median around 45% and several outliers, indicating varying levels of motivation among participants.

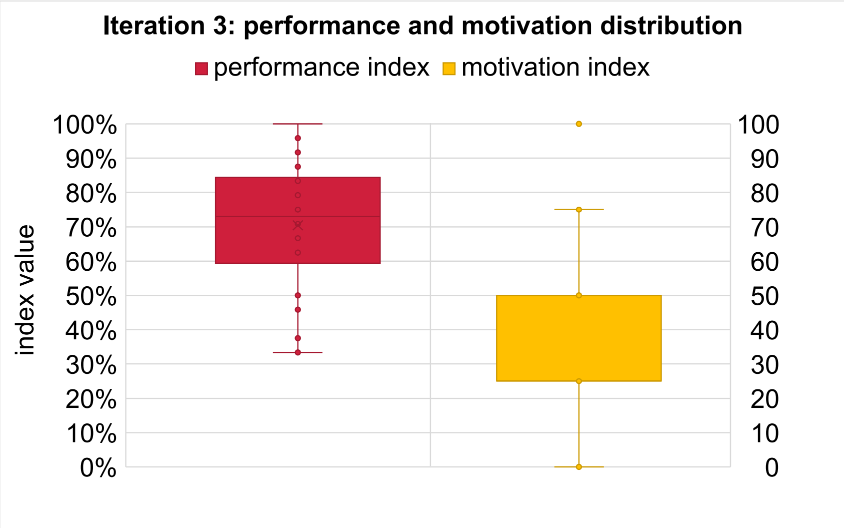

Figure 3.2.1: Boxplot of performance and motivation index on a scale from 0 to 100.

The histogram in Figure 3.2.2 displays the perception of congruence and apprehension among participants. The majority of responses for both parameters clustered around the midpoints of the scale, with a noticeable peak in the 3.0 to 3.5 range for both apprehension and congruence. This suggests that most participants found the videos moderately congruent with their cognitive processes and moderately easy to apprehend.

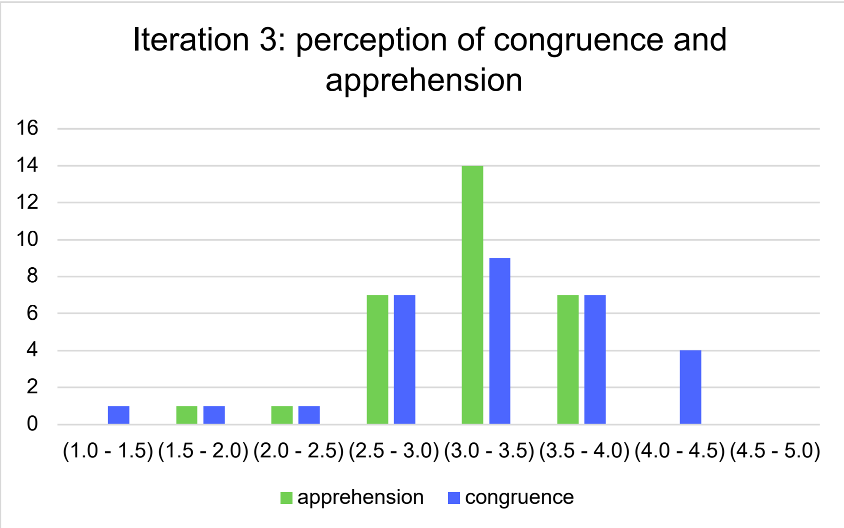

Figure 3.2.2: Histogram of perception and congruence in iteration 3 on a 5-point Likert scale.

Interdependencies

Table 5.2.2 presents the correlation matrix for performance, motivation, congruence, and apprehension. The matrix reveals a moderate positive correlation (r = 0.48) between performance and motivation, indicating that higher motivation is associated with better performance which makes perfectly sense. There is also a positive correlation between congruence and apprehension (r = 0.46), suggesting that students who perceived the videos as congruent with their cognitive processes also found them easier to apprehend or the other way around. Interestingly, there are no significant correlations between performance and the other indices (congruence and apprehension), implying that while the educational value of the video was perceived positively, it did not directly translate into better performance in this iteration.

table 5.2.2: correlation matrix	Performance	Motivation	Congruence	Apprehension
Performance	---	0.48	-0.06	0.06
Motivation	0.48	---	-0.19	-0.03
Congruence	-0.06	-0.19	---	0.46
Apprehension	0.06	-0.03	0.46	---

5.3 Qualitative findings

To clarify some findings from the quantitative analysis, unstructured interviews were conducted with students during the third iteration. This shallow qualitative data provided further insight into students' experiences and perceptions, which helped explain some of the quantitative outcomes. This feedback was useful in linking our findings to established theories on educational video design and student engagement in order to improve especially the methodology in further research.

Directly related to the research questions, students noted that the high information density, particularly in procedural animations and equations, made the videos overwhelming, hindering their ability to follow without pauses. Also, videos that combined complex conceptual explanations with procedural methods proved challenging, especially as they assumed prior knowledge from the viewers.

Additionally, the interviews revealed several factors that, while not central to the primary research questions, could inform future improvements to the research instruments. The type of device used for viewing significantly affected the students' experiences; despite recommendations to use laptops, some accessed the content via mobile phones and reported suboptimal viewing experiences. Many students expressed a preference for traditional, interactive lessons over video lectures, suggesting videos might be more effective in a different contextual setting. Variations in narration quality were also noted; particularly, the AI-driven narration in the third video was favored for its consistent pacing. Opinions on aesthetics varied, with some students favoring decorative elements while others preferred minimalism. Additionally, not all students immediately grasped the significance of color-coded cues in equations, pointing to a need for clearer visual signals. These insights are valuable for refining the educational materials used in future studies. For detailed quotes and observations, please see Appendix D.

6 Discussion & conclusion

6.1 General discussion

This study aimed to design and evaluate explainer videos as instructional tools for engineering subjects, hypothesizing that these videos should enhance learning by helping students acquire firm schemas and aiding in their visual attention. Despite employing carefully designed videos, quantitative analysis revealed no significant improvement in test scores for the video groups compared to the control groups. This finding aligns with mixed results in existing literature on educational videos (Zhang et al., 2005; Brame, 2016). The first iteration showed no significant effect on learning outcomes after conducting an ANCOVA test using motivation as a covariate. The second iteration's data was invalid due to extremely low average test scores caused by a general lack of motivation and numerous no-shows in the control group. Overall, student motivation during the tests was considerably low, impacting the data's validity and accuracy.

A notable correlation between perceived apprehension and congruence suggests an interdependence between these principles, partly due to the collinearity of survey questions. We hypothesize a causal relationship where developing an effective cognitive model (congruence) depends on the viewer's capacity to process information without cognitive overload (apprehension). To appreciate the educational value of a model, students must first perceive it clearly without excessive cognitive load.

Furthermore, there was no correlation between motivation and perceived congruence or apprehension, indicating that motivated students did not necessarily perceive the videos as more valuable. This suggests that motivated students evaluated the videos just as critically.

Qualitative feedback provided deeper insights into student experiences, revealing issues such as information density and the need for pacing adjustments. Students highlighted the importance of interactive and contextualized learning environments, consistent with findings from Moreno and Mayer (2009) about the benefits of interactive features in educational videos. The third iteration had consistent results regarding motivation, congruence, and apprehension. The average score was much higher, suggesting that a different approach to controlling their viewing experience had a positive effect, though the lack of a control group makes this difficult to contextualize.

In summary, our study focused on two partial research questions. The first question explored the systematic design of videos using the apprehension and congruence principles, extensively documented through our storyboard analyses detailed in Appendix A. The second question sought empirical evidence to validate our design approach. While our findings highlighted several beneficial aspects of explainer videos for higher education students, we were unable to uncover statistically significant evidence that supports our primary conjecture regarding the impact of these videos on learning outcomes.

6.2 Limitations

Several limitations should be considered when interpreting the results. Firstly, the relatively small sample size may have limited the statistical power to detect significant effects, suggesting that future studies should include larger samples. Secondly, participant motivation was a significant factor, with many students considering the entire test a large burden, likely affecting their engagement and performance. This was particularly evident in the second iteration, where low participation and performance were noted. Thirdly, the second iteration had a high number of no-shows in the control group, leading to invalid data, indicating that the testing conditions and timing might need adjustment to ensure higher participation. Fourthly, the videos were relatively high-paced and included a lot of new content, potentially overwhelming students. Lastly, the integration of the videos into the course may not have been optimal, suggesting that future research should explore different contexts and methods of embedding videos into the curriculum.

6.3 Implications for further research

Synthesizing that the test-results, the data of the survey and some additional open-interviews with literature we identified a few deficiencies in the intervention. These deficiencies seem in accordance with findings of other studies, in this section we provide some solutions that might be interesting for future empirical testing.

Firstly, the designed videos are likely to require a certain level of meta-cognition and self-regulation. The videos contain many novel concepts and are relatively high-paced if you compare it with traditional lectures. Therefore it is important that students pause, reflect, and sometimes rewind the video in order to process all the information effectively. During data collection, we observed that many students watched the video from start to finish without pausing or rewinding, despite later commenting that there were too many concepts and procedures presented in one video. This observation aligns with findings from the study "Does Training on Self-Regulated Learning Facilitate Students' Learning With Hypermedia?" by Azevedo and Cromley (2004), which demonstrated that without explicit training in self-regulated learning (SRL), students often fail to employ strategies such as pausing and reflecting. The study found that SRL training significantly improves students' ability to manage their learning, suggesting that incorporating SRL training could enhance the effectiveness of our explainer videos by encouraging students to engage more actively with the content and use self-regulatory strategies to better understand and retain the material.

Furthermore, a more recent study by Tuysuzoglu and Greene (2014) reinforces these findings, highlighting the critical role of metacognitive monitoring and control in learning. Their study revealed that students who adaptively adjusted their learning strategies based on their metacognitive judgments achieved better learning outcomes. Conversely, students who did not change their strategies in response to recognizing a lack of understanding struggled more. This suggests that fostering metacognitive skills and adaptive learning behaviors is essential in digital learning environments. Therefore, integrating both SRL training and metacognitive support into our video-based learning materials could help students manage the cognitive load more effectively, leading to improved schema acquisition and overall learning outcomes.

"Secondly, our videos may have inadvertently deviated from the congruence principle. Although they were ideally structured for imparting conceptual schemas, the development of procedural schemas was perhaps insufficiently addressed. The methods for solving problems in our videos, which utilized digital tools for mathematical manipulations and graph drawing, offered flexibility not available with traditional pen and paper—the tools that students typically use during tests. This discrepancy between digital and traditional problem-solving methods could explain why many students find traditional tutorial videos, such as those by MathwithMenno[1], more effective. Such videos often directly mimic the problem-solving steps students are expected to use in examinations, thereby aligning closely with the real-world tasks students face."

Footnote[1]: *Math with Menno is a Dutch YouTube channel featuring a teacher who focuses on the procedural steps of mathematics, rather than underlying concepts. Critics however argue Menno's explanations rely on shallow learning approaches that do not develop any conceptual understanding in the long run*

7 Generative AI disclaimer

In the preparation of this thesis, several generative AI tools were employed to enhance both the efficiency of the research process and the quality of the final document. These tools have been used in accordance with university guidelines, which allow for the integration of artificial intelligence in academic work. This section describes how each tool was utilized.

Grammarly (grammarly.com)

Grammarly, an AI-powered writing assistant, was extensively used to refine the language and presentation of this thesis. This tool was set to generate text in a style reminiscent of The New York Times, known for its rigorous yet accessible academic writing. This style choice ensured that the thesis maintained high academic standards while being clear and comprehensible, making the research accessible to both academic peers and informed readers outside the academic community.

Connected Papers (connectedpapers.com)

Connected Papers was another pivotal tool in the research phase of this thesis. It expedited the research process by automatically generating summaries of related papers, which allowed for a rapid assimilation of the current research landscape and helped in identifying key papers that are foundational to the topics discussed. Additionally, Connected Papers provided tools to evaluate the content quality of each paper, ensuring that only credible and relevant research informed the insights and conclusions presented in this thesis.

ChatGPT (chat.openai.com)

ChatGPT was employed for several tasks, primarily involving the creation and execution of Python code for statistical analysis. The AI was instructed to generate scripts tailored to the specific analytical needs of the thesis, thereby streamlining the data analysis process and generating tailored data visualisations. ChatGPT was also used to create summaries from PDFs of research papers. These summaries provided quick insights into the papers, aiding in a more efficient review and integration of literature into the research. The use of ChatGPT was carefully monitored to ensure that the outputs were accurate and relevant, and any code or summaries generated were thoroughly reviewed and edited as necessary by the author to ensure they met the research requirements and standards.

Furthermore, Chat GPT was used to generate most of the appendix B as those documents where originally made in Dutch. ChatGPT was used to generate telegram-style overviews.

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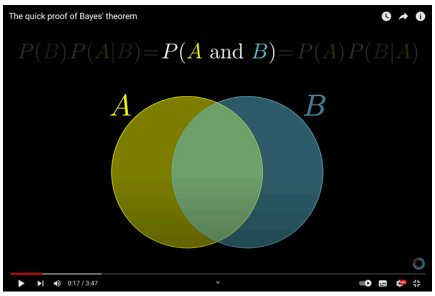
9 Appendix

Appendix A1: analysis of storyboard of a well-established video creator (Grant Sanderson)

To illustrate the utility of storyboarding as an evaluative tool and demonstrate how embodiment of the established principle looks like, we analyzed a video by 1blue1brown, a renowned channel known for its sophisticated mathematical explanations. By creating a storyboard of one of his videos, we aimed to examine how effectively the video adheres to the identified principles.

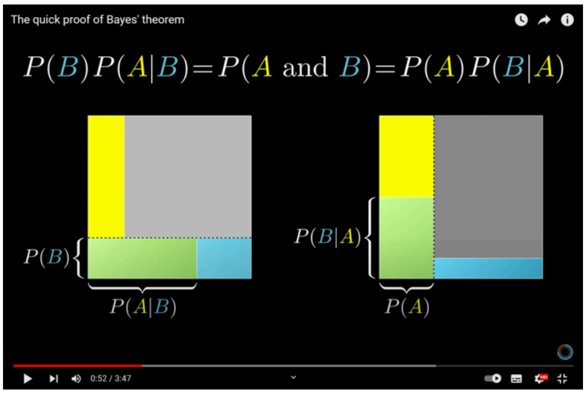
Scene 1: Introduction of Joint Probability

Screenshot scene 1	Description
	In this scene, the video introduces the concept of joint probability using a Venn diagram. The diagram visually represents events A and B as two overlapping circles, with the intersection highlighting $P(A \cap B)$.

Congruence Principle in scene 1: The use of a Venn diagram is a classic abstract representation that effectively conveys the idea of joint probability. By overlapping the circles, the visual aligns well with the mental model of intersecting sets, making the concept of $P(A \cap B)$ intuitive.

Apprehension Principle in scene 1: The clear, static image of the Venn diagram with highlighted overlapping areas minimizes cognitive load, allowing viewers to easily perceive and understand the relationship between A and B. The use of distinct colors for A and B further aids in distinguishing the two events.

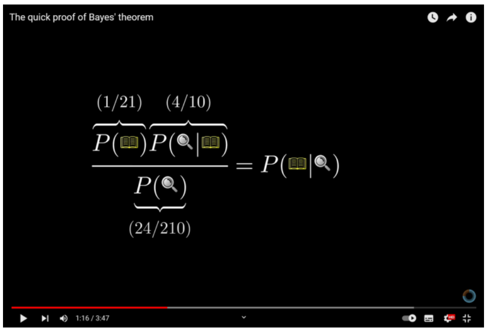
Scene 2: Conditional Probability Formula

Screenshot scene 2	Description
	The scene presents the formula for conditional probability $P(A\ and\ B) = \frac{P(A \cap B)}{P(B)}$ alongside the area model.

Congruence Principle in scene 2: The formula is dynamically connected to the area model, helping viewers see the mathematical relationship in a visual context. This dual representation solidifies the conceptual understanding.

Apprehension Principle in scene 2: Highlighting each part of the formula sequentially while relating it to the areas of the rectangles helps in reducing cognitive overload. Viewers can follow the logical flow without being overwhelmed by the entire formula at once.

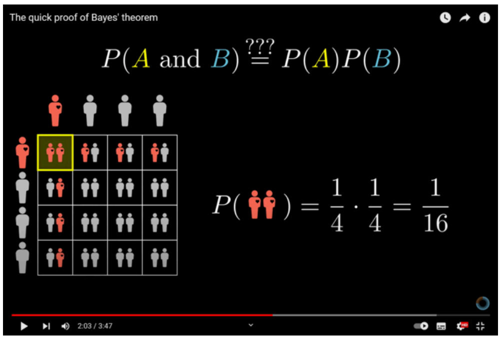
Scene 3: Application of Bayes' Theorem

Screenshot scene 3	Description
	This scene uses an example involving real-world symbols (books and magnifying glasses) to apply Bayes' theorem, reducing cognitive load by providing familiar icons.

Congruence Principle: The icons and simple numbers make the abstract formula more concrete and relatable. By using symbols that viewers can immediately recognize, the video helps bridge the gap between abstract mathematical concepts and real-world applications.

Apprehension Principle: The use of familiar icons and straightforward numbers simplifies the complex concept, minimizing cognitive load. This clarity ensures that viewers can focus on understanding the application of Bayes' theorem without being distracted by complex details.

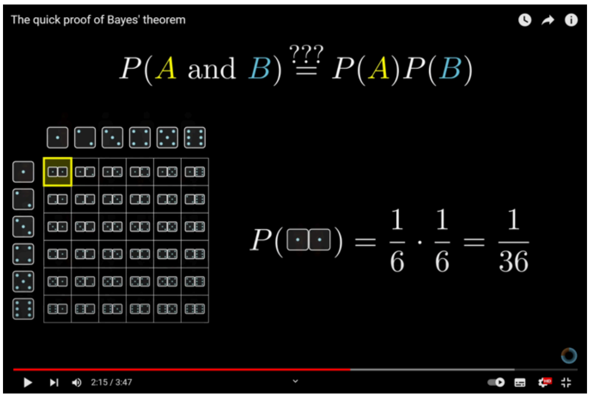
Scene 4: Joint Probability with People Icons

Screenshot scene 4	Description
	In this scene, a grid of people icons is used to explain joint probability, serving as a bridge between abstract and real-world representations.

Congruence Principle in scene 4: The grid layout with people icons helps viewers understand the analogy between individual probabilities and joint probabilities in a concrete, visual manner. The minimalistic color scheme and detail prevent cognitive overload while maintaining the analogy.

Apprehension Principle in scene 4: The colors and simplicity of the icons ensure that the viewer's attention is focused on the key concept. This use of minimalistic design avoids unnecessary distractions, aiding in comprehension.

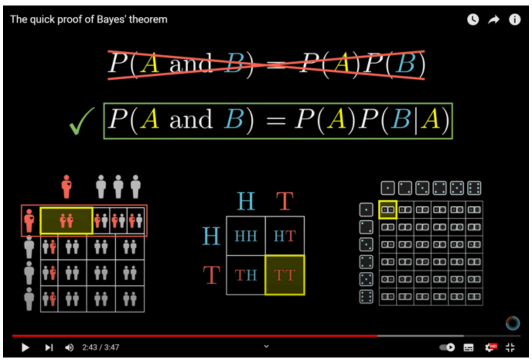
Scene 5: Independent and Dependent Probabilities with Dice

Screenshot scene 5	Description
	This frame elucidates the difference between independent and dependent probabilities using dice illustrations.

Congruence Principle in scene 5: Using dice instead of abstract symbols like A and B makes it easier for viewers to perceive the concept. The visual of dice helps in understanding the difference between independent and dependent events, which is crucial for grasping the underlying mechanics of Bayes' theorem.

Apprehension Principle in scene 5: The combination of the dice illustration and the abstract formula aids in understanding. The viewer can connect the tangible example of dice with the abstract mathematical notation, ensuring a better grasp of the concept.

Scene 6: Integrative View of Probabilities

Screenshot scene 6	Description
	This frame provides an integrative view to help viewers see the difference between scenarios with independent and dependent chances.

Congruence Principle in scene 6: By presenting multiple representations side by side, the video helps viewers make cognitive connections between different scenarios. This integrative view reinforces the understanding of how independence affects probability calculations.

Apprehension Principle in scene 6: The simultaneous display of various scenarios ensures that viewers can compare and contrast them directly. This clear organization of information aids in understanding and retention.

Appendix A2: Storyboard of video in first iteration

Scene 1: Problem introduction

<table>
<tr><th>Screenshot scene 1</th><th>Description</th></tr>
<tr><td>
</td><td>The scene explains the initial situation and the objective of the question. All properties of the situation are verbally and visually presented step by step. A pause and reflect moment is provided to allow viewers to scan the information.</td></tr>
</table>

Congruence Principle in scene 1: The stepwise presentation of information aligns with the learners' cognitive processes by gradually building up the complexity of the problem. This approach helps in constructing a mental model of the situation, ensuring that viewers understand each component before moving to the next.

Apprehension Principle in scene 1: The pause and reflect moment adheres to the apprehension principle by minimizing cognitive load. Viewers have the opportunity to absorb the information at their own pace, reducing the risk of being overwhelmed. The visual elements, such as the skier and the mountain, are simple yet effective, focusing attention on the relevant parts of the problem.

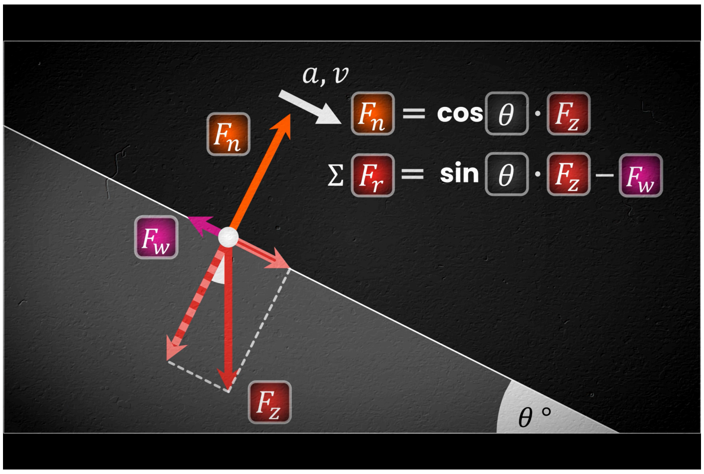
Scene 2: Problem analysis

<table>
<tr><th>Screenshot scene 2</th><th>Description</th></tr>
<tr><td>
</td><td>A clear overview is provided to help students document the problem. Colors are used to distinguish different quantities: forces in warm colors, motion-related quantities in cold colors, and properties like mass and geometry in low saturated colors.</td></tr>
</table>

Congruence Principle in scene 2: The use of color coding helps align the instructional materials with the learners' cognitive processes. By categorizing quantities visually, learners can easily differentiate and relate them to the relevant physical concepts.

Apprehension Principle in scene 2: The stepwise verbal and visual presentation prevents cognitive overload. Each quantity is introduced sequentially, allowing viewers to process and understand the information without being overwhelmed.

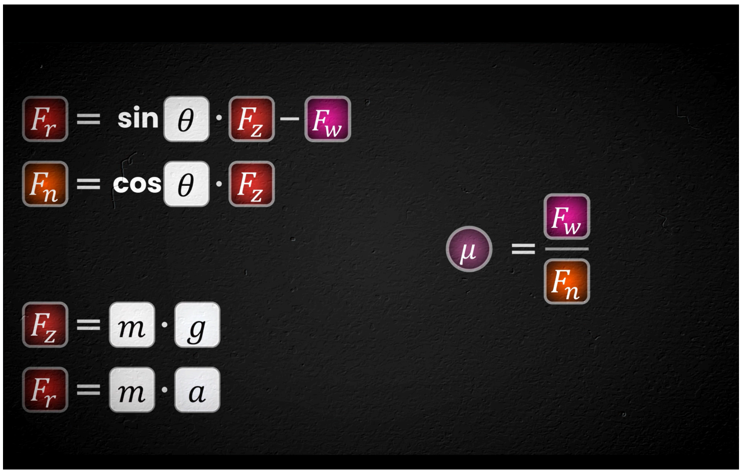
Scene 3: Visual Scheme of the Forces

Screenshot scene 3	Description
	A visual scheme of the forces is constructed gradually. The direction of motion, friction force, and resultant force are displayed to help viewers understand the dynamics of the problem. Highlights draw attention to relevant parts of the picture.

Congruence Principle: The gradual construction of the force diagram aligns with learners' cognitive processes by sequentially introducing each force. This method helps learners build an accurate mental model of how forces interact.

Apprehension Principle: Highlighting specific parts of the diagram reduces cognitive load by directing attention to the most important elements. This focus prevents viewers from being overwhelmed by too much information at once.

Scene 4: Algebraic Procedures

Screenshot scene 4	Description
	The algebraic procedures are visually demonstrated. Known quantities are in white, while quantities to be computed are colored. The manipulations are visualized by moving letters to different spots.

Congruence Principle in scene 4: The use of color coding and visual movement aligns with learners' cognitive processes by clearly distinguishing between known and unknown quantities. This visual differentiation helps in understanding the steps involved in solving the equations.

Apprehension Principle in scene 4: Visualizing algebraic manipulations reduces cognitive load by making the process explicit. Moving the letters to different spots helps viewers follow the logical flow of the algebraic transformations.

The clear distinction between known and unknown quantities, combined with the step-by-step visual manipulation, aids in schema acquisition. Viewers can see how each step contributes to the solution, reinforcing their understanding of the algebraic process.

B1.1 Description video 1: Newton's Laws on a Slope with Friction

Introduction

- **Central problem**: Explanation of kinetic concepts through a skier moving down a slope.
- **Main Concepts**:
  1. Newton's Second Law: $F = m \cdot a$
  2. Gravitational Force: $F_z = m \cdot g$
  3. Vector components of forces

Problem Setup

- **Scenario**: An 80 kg skier descends a 10-degree slope, accelerating for 6 seconds until reaching a speed of 3 m/s.
- **Key Question**: What is the frictional force?

Steps to Solution

1. **Initial Analysis**:
   - Identify known values: mass $m = 80$ kg, slope angle $\theta = 10^\circ$, time $t = 6$ s, final velocity $v_f = 3$ m/s.
   - Draw a free-body diagram showing forces: gravitational force, normal force, frictional force, and the force due to acceleration.
2. **Force Breakdown**:
   - Gravitational force components:
     - Parallel to slope: $F_{g,\parallel} = m \cdot g \cdot \sin(\theta)$
     - Perpendicular to slope: $F_{g,\perp} = m \cdot g \cdot \cos(\theta)$
   - Normal force $F_N = F_{g,\perp}$
   - Frictional force $F_f = \mu \cdot F_N$
3. **Acceleration Calculation**:
   - Use kinematic equation: $a = \frac{v_f}{t}$
   - Resulting acceleration $a = \frac{3\,\mathrm{m/s}}{6\,\mathrm{s}} = 0.5\,\mathrm{m/s}^2$
4. **Force Analysis Along Slope**:
   - Net force along slope: $F_{net} = m \cdot a$
   - $F_{net} = F_{g,\parallel} - F_f$
5. **Solve for Friction Coefficient**:
   - $F_f = m \cdot g \cdot \sin(\theta) - m \cdot a$
   - $\mu = \frac{F_f}{F_N} = \frac{m \cdot g \cdot \sin(\theta) - m \cdot a}{m \cdot g \cdot \cos(\theta)}$
   - Simplify: $\mu = \frac{\tan(\theta) - \frac{a}{g}}{1}$
   - Substitute known values: $\mu \approx 0.13$

Note: This telegram-style summary of the video script is provided by ChatGPT.

B1.2 Description Video 2: Rotational Movements with Inertia

Introduction

- **Context**: This section analyzes rotational motion in a system involving multiple rigid bodies interacting through a pulley system.
- **Main Concepts**:
  1. Newton's Law for Rotation: $\sum M = I \cdot \alpha$
  2. Moment of Inertia (I)
  3. Angular Acceleration (α)
  4. Interaction and analysis of motion between multiple rigid bodies

Problem Setup

- **Scenario**: A pulley with a moment of inertia $I = 1.35$ kg·m² is subjected to an external torque of 40 Nm, with a 30 kg mass attached. The system starts from rest, with a gravitational acceleration $g = 10$ m/s² and a pulley radius of 0.40 m.
- **Key Question**: What is the angular velocity ω at $t = 5$ seconds?

Steps to Solution

1. **Initial Analysis**:
   - **Known Values**:
     - Moment of Inertia: $I = 1.35$ kg·m²
     - External Torque: $M = 40$ Nm
     - Mass: $m = 30$ kg
     - Radius: $r = 0.40$ m
     - Gravitational Acceleration: $g = 10$ m/s²
   - **Diagram**: A free-body diagram should be drawn showing the forces acting on the mass and the pulley, including gravitational force, tension in the rope, and the torque acting on the pulley.
2. **Force and Torque Analysis**:
   - **Gravitational Force on Mass**: $F_z = m \cdot g = 30\,\text{kg} \cdot 10\,\text{m/s}^2 = 300\,\text{N}$
   - **Tension in the Rope**: Denote the tension as T
   - **Net Torque on Pulley**: $\Sigma M = M_{external} - T \cdot r$
3. **Kinematic Analysis**:
   - **Torque and Angular Acceleration Relationship**: $\Sigma M = I \cdot \alpha$
   - **Vertical Force Balance for the Mass**: $T = m \cdot (g - a_y)$
   - **Relationship Between Linear and Angular Acceleration**: $a_y = r \cdot \alpha$
4. **Solving for Angular Acceleration**:
   - Substitute the expression for T into the net torque equation: $\Sigma M = M_{external} - (m \cdot (g - r \cdot \alpha)) \cdot r$
   - Rearrange to solve for α: $\alpha = \frac{M_{external} - m \cdot g \cdot r}{I + m \cdot r^2}$
   - Plug in the known values to calculate α.
5. **Angular Velocity Calculation**:
   - Using the relationship $\omega = \alpha \cdot t$:
   - $\omega = \left(\frac{40\,\text{Nm} - 30\,\text{kg} \cdot 10\,\text{m/s}^2 \cdot 0.40\,\text{m}}{1.35\,\text{kg} \cdot \text{m}^2 + 30\,\text{kg} \cdot (0.40\,\text{m})^2} \right) \cdot 5\,\text{s}$
   - Calculate ω to find the angular velocity at $t = 5$ s.
   - $\omega(5) = 130\ rad/s$

Conclusion

- **Importance**: Understanding the interplay between forces and motion in rotational dynamics is crucial for accurately analyzing and predicting the behavior of complex mechanical systems.

Note: This telegram-style summary of the video script is provided by ChatGPT.

Appendix B1.3a: Description thermodynamics video 1

Natural convection occurs when heat transfer within a fluid creates local density differences, leading to fluid movements. This process facilitates heat distribution not only through conduction but also via mass transport, significantly impacting the thermal dynamics of the system.

The primary formula used to calculate the heat transfer per second via the convection coefficient is $\dot{Q} = hA(T_s - T_\infty)$, where:

- $\dot{Q}$ represents the heat flow in watts,
- h is the convection coefficient in $W/(m^2 \cdot K)$,
- A is the surface area in square meters,
- T_s is the surface temperature,

- T_∞ is the ambient temperature.

Convection dynamics depend significantly on subtle environmental differences, leading to diverse flow patterns. The analysis typically utilizes dimensionless numbers like the Grashof number, Prandtl number, Rayleigh number, and Nusselt number. These numbers quantify different physical properties of the system, facilitating the application of empirical models derived from experimental data.

Note: This telegram-style summary of the video script is provided by ChatGPT.

Appendix B1.3b: Description thermodynamics video 2

The Grashof number is pivotal in the calculation of the convection coefficient, as it epitomizes the relationship between the buoyancy forces that stimulate movement within a medium and the viscous forces that attempt to maintain it at rest. In mediums like air, a high Grashof number indicates significant fluid motion, which enhances overall convection, promoting effective heat transfer.

The Grashof number metaphorically compares the viscous frictional force to the driving force in a medium. A high Grashof number signifies that buoyancy forces overcome viscous forces, leading to vigorous fluid motion and increased convective heat transfer.

Factors influencing the Grashof number

Stimulating Factors:

- **Gravity (g):** Enhances convective flow in mediums with a temperature gradient by increasing the buoyancy force. This force arises as warmer, less dense areas of the fluid rise while cooler, denser areas sink.
- **Expansion coefficient (β):** Indicates how much a fluid expands when heated. A higher coefficient results in greater density differences for a given temperature difference, enhancing the buoyant forces.
- **Temperature difference ($T_s - T_\infty$):** The greater the temperature difference, the larger the local density variations, which further stimulates movement within the medium.
- **Characteristic length (L_c^3):** Represents the total volume of fluid in motion. Larger volumes allow particles to move more freely, achieving higher velocities with less resistance.

Inhibiting Factors:

- **Kinematic viscosity (ν):** Reflects the internal friction within the fluid. Higher viscosity impedes fluid movement, resulting in a lower Grashof number. Kinematic viscosity is often sourced from tables and is temperature-dependent, requiring adjustments for accurate calculations.

Calculating the Grashof Number

The formula for the Grashof number is given by:

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2}$$

where:

- g is the acceleration due to gravity in m/s^2,
- β is the cubic expansion coefficient in K^{-1},
- T_s is the surface temperature,
- T_∞ is the ambient temperature,
- ν is the kinematic viscosity in m^2/s.

The values of ν and β are temperature-dependent and must be adjusted based on the average temperature of the medium being analyzed.

Example Calculation: A Hot Pan in the Open Air

Consider a scenario where a hot pan is exposed to outdoor conditions:

- **Given data:**
  - Diameter of the pan: 25 cm
  - Surface temperature of the pan (T_s): 150°C
  - Ambient temperature (T_∞): 20°C
  - Average temperature: 85°C (358 K)
- **Parameters to determine or lookup:**
  - Cubic expansion coefficient (β): 0.0028 (1/K) (calculated as $\beta = 1/T_{avg}$)
  - Kinematic viscosity (ν): 2.17×10^{-5} m²/s (from a chart at 360K)
- **Characteristic length calculation for a horizontal plate (L_c):**
  - For a plate with diameter (d) of 25 cm:

$$L_c = \frac{A}{p} \text{ where } A = \pi\left(\frac{d}{2}\right)^2 \text{ and } p = \pi d$$

$$L_c = \frac{\pi\left(\frac{0.25}{2}\right)^2}{\pi \cdot 0.25} = 0.0625 \text{ m}$$

- **Temperature difference (ΔT):**

$$\Delta T = T_s - T_\infty = 150^\circ C - 20^\circ C = 130^\circ C$$

- **Grashof number calculation (Gr):**

$$Gr = \frac{9.81 \cdot 0.0028 \cdot 130 \cdot (0.0625)^3}{(2.17 \times 10^{-5})^2}$$

$$Gr \approx 1.85 \times 10^6$$

Note: This telegram-style summary of the video script is provided by ChatGPT.

Appendix B1.3c: Description thermodynamics video 3

Introduction

Understanding the comprehensive approach to analysing natural convection requires an appreciation of the sequence in which dimensionless numbers and empirical models are employed. This sequence facilitates a systematic estimation of the convection coefficient necessary for practical engineering applications.

Overview of total procedure:

1. **Initial Calculations**: Begin by determining the Grashof and Prandtl numbers using the available data. These numbers provide a foundational understanding of the buoyancy and thermal properties of the fluid.
2. **Rayleigh Number Calculation**: Combine the Grashof and Prandtl numbers to compute the Rayleigh number, which integrates both thermal and fluid dynamic characteristics.
3. **Empirical Modeling**: Utilize empirical models to approximate the Nusselt number based on the calculated Rayleigh number. This step is crucial as it links the theoretical understanding of fluid dynamics with practical heat transfer coefficients.
4. **Convection Coefficient**: Finally, convert the Nusselt number into a convection coefficient, which quantitatively describes the rate of heat transfer from a surface to a fluid.

Prandtl Number

The Prandtl number is a dimensionless quantity expressing the ratio of momentum diffusivity (viscous diffusion) to thermal diffusivity. It is essential in characterizing how quickly temperature gradients are smoothed out in a fluid compared to velocity gradients.

- **High Prandtl Numbers**: Substances like motor oil, with high Prandtl numbers, exhibit slow thermal diffusion due to low thermal conductivity but high viscosity, which quickly damps out fluid motion.
- **Low Prandtl Numbers**: Conversely, substances like liquid mercury, with low Prandtl numbers, facilitate rapid thermal diffusion coupled with low viscosity.

Typically, the Prandtl number is not computed but looked up in tables as it depends heavily on temperature and pressure but not on the system's configuration.

Rayleigh number:

The Rayleigh number (Ra) is a dimensionless number that quantifies the force driving convection (thermal expansion) against forces resisting it (viscosity and thermal diffusion). It is calculated using the formula:

$$Ra = Pr \cdot Gr$$

where Pr is the Prandtl number and Gr is the Grashof number.

Nusselt number:

The Nusselt number (Nu) represents the ratio of convective to conductive heat transfer at a boundary in a fluid. Calculating this number is crucial for determining the convection coefficient and is typically derived from empirical formulas dependent on the Rayleigh number.

Formulas and definitions

- **Prandtl Number**: $Pr = \frac{\mu \cdot c_p}{k}$
- **Rayleigh Number**: $Ra = Pr \cdot Gr$
- **Nusselt Number**: $Nu = \frac{h \cdot L_c}{k}$

Where:

- Pr := Prandtl number
- Nu := Nusselt number
- h := Convection coefficient in $W/(m^2 \cdot K)$
- L_c := Characteristic length in meters
- k := Thermal conductivity in $W/(m \cdot K)$
- Ra := Rayleigh number
- Gr := Grashof number
- μ := Dynamic viscosity in $Pa \cdot s$
- c_p := Specific heat at constant pressure in $J/(kg \cdot K)$

Empirical models for Nusselt number

Empirical models are essential tools for approximating the Nusselt number, where the Rayleigh number serves as a critical indicator. Various models exist, typically expressed as power functions, and are applied depending on the configuration of the system (horizontal, vertical, or inclined plates).

Models for Horizontal Plates

For horizontal plates, the correlation typically follows the form:

$$Nu = a \cdot Ra^b$$

This relationship is graphically represented on a logarithmic scale to cover a broad range of Rayleigh numbers, thereby simplifying the analysis as power functions appear as straight lines.

Rayleigh Ranges:

- $Ra < 10^4$: Heat convection is negligible.
- $10^4 \leq Ra < 10^7$: Use $a = 0.59$ and $b = \frac{1}{4}$.
- $Ra \geq 10^7$: The best approximation is given by $a = 0.1$ and $b = \frac{1}{3}$.

The above synthesis ensures that the sequence from the initial calculation of dimensionless numbers through to the application of empirical models is clear, providing a structured approach to estimating the convection coefficient for various practical applications in thermal engineering.

Note: This telegram-style summary of the video script is provided by ChatGPT.

B2.1 Test questions iteration 1

1. **Draw and Analyze Forces**
   - **Task**: Draw a clear free-body diagram (FBD) on the provided worksheet showing all forces acting on the box.
   - **Information Provided**: Diagram of the setup, including the direction of motion and applied forces.
   - **Approach**: Identify and label all forces, including gravitational force, frictional force, normal force, and the pulling force. Choose and indicate an appropriate coordinate system.
2. **Calculate Time to Stop**
   - **Task**: Calculate the time it takes for the box to come to a complete stop from point A to point B using the given information and formulas.
   - **Information Provided**: Initial speed, mass, angle, pulling force, and friction coefficient.
   - **Approach**: Use kinematic equations and Newton's second law to determine the deceleration and then calculate the time to stop.
3. **Calculate Additional Pulling Force**
   - **Task**: Calculate the additional pulling force required to move the box at a constant speed.
   - **Information Provided**: Mass of the box, angle, pulling force, friction coefficient, and gravitational force.
   - **Approach**: Use the force balance equation to find the net force required for constant velocity, accounting for friction and the component of the pulling force.
4. **Effect of Weight on Distance**
   - **Task**: Determine whether the distance from point A to point B will increase, decrease, or remain the same if the box is replaced with a heavier version.
   - **Information Provided**: Mass of the heavier box.
   - **Approach**: Analyze the relationship between mass, frictional force, and distance traveled using Newton's second law and kinematic equations.
5. **Theoretical Consideration for Infinite Mass**
   - **Task**: Evaluate the claim that as the mass of the box increases, the time to stop decreases, with a theoretical minimum.
   - **Information Provided**: Initial mass, friction coefficient, and the theoretical minimum time.
   - **Approach**: Perform calculations to test the validity of the claim, considering the relationship between mass, frictional force, and stopping time.

B2.2 Test-questions (iteration 2)

General Information

- **Time Allotted**: 60 minutes
- **Permitted Tools**: Calculator, explanatory video, no textbook

Questions and Answers Overview

1. **Sketch Angular Velocity**
   - **Task**: Sketch the angular velocity of the disk in the given coordinate system.
   - **Information Provided**: Diagram showing the initial conditions of the disk's motion.
   - **Approach**: Use the given conditions and the concept of constant angular acceleration to sketch the graph of angular velocity versus time.
2. **Comparison of Tension in the Cable**
   - **Task**: Determine which statement about the tension in the cable at points C and D is correct.
   - **Information Provided**: Diagram showing the cable and its points of interaction.
   - **Approach**: Compare the tensions using the concepts of force equilibrium and the effects of different forces acting on the points.
3. **Free-Body Diagram**
   - **Task**: Draw a free-body diagram (FBD) for all individual bodies in the system, showing all relevant forces and moments.
   - **Information Provided**: Diagram showing the system setup.
   - **Approach**: Identify and label all forces and moments acting on each body, and indicate the direction of motion.
4. **Calculate Tension at $t = 0$**
   - **Task**: Calculate the tension in the cable at point C at $t = 0$.
   - **Information Provided**: Diagram of the system, initial conditions, and relevant equations.
   - **Approach**: Use motion equations and Newton's laws to determine the tension in the cable.
5. **Calculate Mass of Box A**
   - **Task**: Calculate the mass of box A to two decimal places.
   - **Information Provided**: Initial conditions, kinematic equations, and system parameters.
   - **Approach**: Use the given data and relevant equations to solve for the mass of box A.
6. **Determine Number of Rotations**
   - **Task**: Calculate the number of rotations of the wheel to two decimal places.
   - **Information Provided**: Average angular velocity and time duration.
   - **Approach**: Calculate the angular displacement and convert it to the number of rotations.

B2.3 Test-questions (iteration 3)

Appendix B2.3: Overview of Posttest Questions

1. **Which statements are true about empirical quantitative models?** (multiple choice)
   - This question tests understanding of the nature and limitations of empirical models. It is crucial for students to recognize that these models are based on experimental data and only valid under specific conditions, and not capable of delivering 100% accurate calculations due to their reliance on observational data.
2. **What is a dimensionless number?** (multiple choice)
   - The question aims to assess students' understanding of dimensionless numbers, which are crucial in engineering and physics for simplifying the analysis by removing unit dependencies. Students need to identify that dimensionless numbers, such as the Reynolds or Prandtl number, are pure numbers without any physical units.
3. **True or False: The characteristic length for heat convection, which describes the heat flow along a plate, is larger in a vertical setup than in a horizontal setup with the same dimensions.** (true/false)
   - This question tests the student's comprehension of how fluid dynamics differ between vertical and horizontal convection processes due to the direction and effects of buoyancy forces.
4. **A horizontal rectangular plate has a length of 35 centimeters and a width of 25 centimeters. Calculate the characteristic length.** (numerical answer)
   - Here, students must apply geometric relations and the definition of characteristic length for convection over a flat plate, which involves the area-to-perimeter ratio of the plate to determine how the flow conditions affect heat transfer.
5. **Calculate the kinematic viscosity of air at an average temperature using the data provided.**

    - This question challenges students to use thermophysical property tables or equations to find the kinematic viscosity of air, which varies with temperature and significantly affects fluid flow and heat transfer characteristics. (numerical answer)

6. **Calculate the Grashof number for a cooling plate based on given properties and conditions.**
    - Students are expected to integrate their knowledge of thermodynamics and fluid mechanics to calculate the Grashof number, which describes the ratio of buoyancy to viscous forces in the context of convection. (numerical answer)
7. **Erik argues that air under high pressure has more active convection than air under low pressure due to increased density, while Janna claims this is incorrect as density does not appear in the Grashof number formula. Who is correct, explain why?**
    - This question is designed to evaluate students' understanding of the factors influencing convection and the role of density and pressure in fluid dynamics, focusing on the correct application and interpretation of the Grashof number. (text answer)
8. **Predict which of the following substances has the highest Prandtl number based on their properties and the Prandtl number formula.** (multiple choice)
    - This question challenges students to apply their knowledge of fluid properties—specifically, viscosity and thermal conductivity—to determine which substance (syrup, water, or air) has the highest Prandtl number. The Prandtl number is significant in heat transfer and fluid flow studies as it indicates the ratio of momentum diffusivity to thermal diffusivity.
9. **Calculate the Nusselt number for a cooling plate using the given Grashof number and properties.**
    - Students must use the provided Grashof number and temperature conditions to determine the Nusselt number, which is a dimensionless number critical for assessing the convective heat transfer relative to conductive heat transfer. This calculation involves applying empirical correlations or formulas that relate the Grashof and Prandtl numbers to the Nusselt number. (numerical answer)
10. **Calculate the convection coefficient using the Nusselt number.**

- Here, students need to convert the previously calculated Nusselt number into the convection coefficient. This coefficient quantifies the convective heat transfer per unit area per unit temperature difference between the surface and the fluid. This practical application solidifies understanding of how theoretical concepts are used to solve real-world engineering problems. (numerical answer)

Appendix C: Links to video's

Dynamics: Newton's laws on a slope with friction	Dynamics: Rotational motion with inertia
Thermodynamics: Convection part I	**Thermodynamics: Convection part II**
Thermodynamics: Convection part III	

Dynamics: Newton's laws on a slope with friction	Dynamics: Rotational motion with inertia

Appendix D: Qualitative data report

Student Engagement and Information Density:

- *"The information in the video was super dense, this video should be great to watch back at home, but for now it was a bit overwhelming."*
- Observation: Students tended to watch the video from beginning to end without pausing, which may have contributed to the feeling of being overwhelmed.

Effectiveness and Necessity of Visual Aids:

- *"The animations were looking fancy, however, they were not always necessary and sometimes a bit annoying."*
- *"The color theme and the icons were at the beginning a bit confusing because I didn't know the structure behind it. When I watched the second video, it was way easier to understand as I was more used to it."*

Narration Quality:

- *"I would find someone that would be more suitable for narrating. The speaker spoke at an irregular tempo and used a lot of 'uhm' 'ah'."*

Content Overload and Structure:

- *"The explanation of the concept and the worked-out example together were, in my opinion, too many learning goals for one video. That was too overwhelming for me as the concepts and procedures of the second session were totally novel."*
- *"Maybe you could also show a neat overview of the calculation at the end?"*
- *"I miss a step-by-step plan."*

Technology and Viewing Conditions:

- *"I forgot to bring my laptop and used my phone. My phone had a small screen which made it very hard to see the highlighting, captions, and more."*
- *"I used my phone, and I was constantly getting distracted by messages."*

Preference for Interactive Learning:

- *"Although I see the potential of these videos, I think this lesson was wasted as normally I can discuss and ask for feedback. Videos are more suitable as a complementary tool."*

Additional Observations:

- *"The speaker was speaking inconsistently, sometimes very enthusiastic and fast, and sometimes very irregular and sudden."*
- *"The backgrounds could be calmer."*

- *"The morphing of the formulas (moving letters) was insightful in that it showed how the math works. But if you miss a second, you lose track. Maybe you could also show a neat overview of the calculation at the end?"*