Universität Bayreuth

Lehrstuhl Didaktik der Biologie

Kreatives Modellieren im Lernort Labor

Eine vergleichende Studie zu Wissenserwerb, Modellverständnis und dem Einfluss individueller Kreativität

DISSERTATION

zur Erlangung des akademischen Grades einer
Doktorin der Naturwissenschaften (Dr. rer. nat.)
an der Fakultät für Biologie, Chemie und Geowissenschaften
der Universität Bayreuth

vorgelegt von

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Bayreuth, 2019

Die vorliegende Arbeit wurde in der Zeit von September 2016 bis Mai 2019 am Lehrstuhl Didaktik der Biologie der Universität Bayreuth unter Betreuung von Herrn Professor Dr. Franz X. Bogner angefertigt.

Dissertation eingereicht am:	16.05.2019
Zulassung durch die Promotionskommission:	22.05.2019
Wissenschaftliches Kolloquium:	26.07.2019

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INHALTSVERZEICHNIS

Hinweis auf Geschlechtsneutralität

Im Sinne eines guten Leseflusses wird in der folgenden Arbeit auf Doppelnennungen verzichtet (z.B. Schüler und Schülerinnen) und im Text nur die Form „Schüler“ verwendet. Wenn nicht anders dargestellt, ist keine spezifische Zuordnung zu einem Geschlecht gemeint. In Abschnitten, die sich explizit mit Geschlechterunterschieden befassen, werden die geschlechtsspezifischen Bezeichnungen der Personengruppen verwendet.

1 SUMMARY

Models and modelling occupy a key position in research processes as they may help to explain experimental observations by extracting essential parameters and bridging theoretical knowledge to provide a basis for further scientific predictions. Within the framework of sound scientific education, models and modelling contribute significantly to illustrate abstract phenomena, to reduce complex molecular processes or to test certain hypotheses in biology lessons. Genetics, in particular, is a topic characterized by high complexity that typically can lead to misconceptions and learning difficulties due to invisible molecular structures and processes. In addition to the application of models and modelling, previous studies have shown benefits of student-centred learning in outreach labs. By performing experiments on their own, students can achieve a deeper understanding of genetic concepts. As modelling and experimental investigations go hand in hand in the scientific research process, suitable educational programs should also combine both aspects.

The present study integrates these two methods on learning about DNA structure within an inquiry-based, out-of-school laboratory module for secondary school students (study A). Herein, hands-on experiments were combined with model-based learning in order to promote cognitive achievement and students' understanding of scientific models. The sample was divided in order to allow comparison of the effectiveness of two different model-based approaches: while all participants were subjected to the experimental part of the module, only the 'modellers' (I) were required to creatively generate a DNA-model using assorted handcrafting materials, whereas the 'model viewers' (II) worked with a commercially available school model of the DNA structure.

All further substudies are based on data from about 290 ninth graders (highest secondary school level) who participated in the laboratory module with different methodological model-based approaches (I: *modelling*; II: *model viewing*). Initially, the focus was on the evaluation of the modelling approach (I), where cognitive achievement, creativity, and model quality was assessed (study B). As a major result, girls were shown to produce significantly better structured models and were able to close prior knowledge deficits. Additionally, significant positive correlations were unveiled between girls' cognitive achievement and the model quality as well as the creativity subscale 'flow'. In contrast, neither creativity nor model quality were decisive for boys' cognitive achievement. However, no relations were found between individual creativity levels and model quality for both genders.

Due to the fact that teachers can use models for different purposes in science lessons, another major aim was to observe the instructional efficiency (*i.e.,* the standardized difference between mental effort and performance) of the implemented approaches (study C). Both approaches showed similar results with regard to cognitive load during the different model phases.

However, the 'model viewers' (II) achieved a significant higher mid-term knowledge increase than the 'modellers' (I). This means that with comparable mental effort of the implemented approaches, the 'model viewers' (II) achieved a higher performance. Subsequently, model viewing (II) can be evaluated as an instructionally more efficient learning method.

As effective methods to foster students' understanding of models in science education are needed, increased reflection on thinking about models is regarded as a relevant competence associated with scientific literacy. Therefore, another main objective of the study was to investigate the impact of both model-based approaches on students' understanding of models (study D). Three subsections of the construct were examined: (1) students' reasoning about multiple models in science, (2) students' understanding of models as exact replicas, and (3) students' understanding of the changing nature of models. Students' argumentations about 'multiple models' provided a typical cross-section for the age group surveyed and showed that a majority justified model differences with varying properties of the original (DNA) or referred to the model design. This corresponds to a lower understanding and emphasizes the common interpretation of models mainly regarded as teaching tools. Despite the lack of differences between the two approaches, a positive impact of model-based learning on students' understanding of scientific models was observed. This was associated with a reduced understanding of 'models as exact replicas' and an increased perception of 'the changing nature of scientific models'.

In summary, the combination of model-based learning with experimental observations had a significant positive effect on knowledge acquisition and model understanding. Although model viewing was found to be more instructionally efficient, creative modelling offered female students the opportunity to close knowledge gaps through successful model building and 'flow' experiences. In attempting to attract girls to science, model elaboration may further support hands-on experimentation and thus balance gender differences. In addition, the implemented learning methods are not limited to the use in out-of-school laboratories but can also enrich conventional science classrooms.

2 ZUSAMMENFASSUNG

Modelle und Modellbildung nehmen eine zentrale Position im naturwissenschaftlichen Forschungsprozess ein: Sie präzisieren wesentliche Aussagen experimenteller Beobachtungen und verknüpfen theoretische Hintergründe miteinander, um so eine Grundlage für wissenschaftliche Vorhersagen zu bilden. Im Rahmen einer fundierten naturwissenschaftlichen Ausbildung tragen Modelle und Modellierung maßgeblich zur Veranschaulichung abstrakter Phänomene, zur didaktischen Reduktion komplexer Vorgänge und zur Hypothesenüberprüfung im Biologieunterricht bei. Gerade der Fachbereich Genetik weist eine hohe Komplexität auf und führt aufgrund unsichtbarer Strukturen molekulargenetischer Abläufe typischerweise zu Fehlvorstellungen und Lernschwierigkeiten bei Schülern. Neben dem Einsatz von Modellen und Modellbildung zum Verständnis genetischer Fachinhalte zeigten frühere Studien, dass schülerzentriertes Experimentieren in authentischen Lernumgebungen zu einem langfristigen Wissenszuwachs führen kann. Im naturwissenschaftlichen Forschungsprozess gehen Modellentwicklung und die Deutung experimenteller Untersuchungen Hand in Hand, daher sollten auch geeignete Unterrichtsprogramme beide Aspekte vereinen.

Vor diesem Hintergrund integriert die vorliegende Studie beide naturwissenschaftlichen Arbeitsmethoden in einem schülerzentrierten, forschend-entdeckenden Unterrichtsmodul für die Sekundarstufe am außerschulischen Lernort Labor im Kontext der Erarbeitung der DNA-Struktur (Teilstudie A). Die Kombination von Hands-on Experimenten mit modellbasiertem Lernen hatte zum Ziel, den Aufbau von Fachwissen zu fördern und das Modellverständnis der Schüler zu steigern. Es wurden zwei unterschiedliche Unterrichtsansätze implementiert und bezüglich ihrer Effektivität verglichen: Während die experimentellen Einheiten für alle Schüler identisch waren, arbeiteten in der Modell-Phase die ‚Modellierer' (I) kreativ und konstruierten selbstständig ein DNA-Modell, wohingegen die ‚Modellbetrachter' (II) Bausteine der DNA anhand eines herkömmlichen Schulmodells untersuchten und identifizierten.

Das Unterrichtsmodul mit den beiden beschriebenen modellgestützten Ansätzen bildete die Grundlage für drei Teilstudien, an denen insgesamt rund 290 Schüler der neunten Jahrgangsstufe (Gymnasium) teilnahmen. Zunächst lag der Fokus auf der Evaluation des Ansatzes zum Modellieren (I), wobei Wissen, Kreativität und Modellqualität erfasst wurden (Teilstudie B). Im Hinblick auf geschlechtsspezifische Wissensunterschiede konnte gezeigt werden, dass die Mädchen Vorwissensdefizite gegenüber den Jungen nach dem Unterricht ausgleichen konnten und der Wissenszuwachs der Schülerinnen positiv mit einer höheren Modellqualität und kreativen ‚Flow'-Erfahrungen einherging. Allerdings wurden für beide Geschlechter keine Zusammenhänge zwischen der individuellen Kreativität und der Modellqualität festgestellt.

Vor dem Hintergrund unterschiedlicher Einsatzmöglichkeiten von Modellarbeit im Unterricht sollten die implementierten Ansätze hinsichtlich ihrer instruktionalen Effizienz, d.h. der standardisierten Differenz von geistiger Anstrengung und der Lernleistung, überprüft werden (Teilstudie C). Beide Unterrichtsansätze zeigten ähnliche Ergebnisse bezogen auf die kognitive Belastung während der verschiedenen Modell-Phasen. Jedoch erreichten die ‚Modellbetrachter' (II) mittelfristig einen höheren Wissenszuwachs gegenüber den ‚Modellierern' (I). Das bedeutet, dass bei vergleichbarer geistiger Anstrengung im Unterricht die ‚Modellbetrachter' (II) eine höhere Lernleistung erreichten. In der Folge lässt sich das untersuchende Modellbetrachten (II) als instruktional effizientere Lernmethode bewerten.

Effektive Methoden zur Förderung des Modellverständnisses sind gefragt, da eine verstärkte Reflexion über die Bedeutung von Modellen als ein relevanter Bestandteil naturwissenschaftlicher Grundbildung angesehen wird. Deshalb war ein weiteres Ziel der Studie, Einflüsse beider modellbasierter Ansätze auf das Modellverständnis der Schüler zu vergleichen (Teilstudie D). Drei Teilaspekte des Konstrukts wurden erfasst: (1) alternative Modelle, (2) Modelle als exakte Nachbildungen und (3) veränderlicher Charakter naturwissenschaftlicher Modelle. Die Argumentationen der Schüler über ‚alternative Modelle' (1) lieferten einen typischen Querschnitt zum Modellverständnis der untersuchten Altersgruppe. Die Mehrheit der Schüler begründete Modellunterschiede mit variierenden Eigenschaften des Originals (DNA) oder bezog sich auf das gewählte Modelldesign. Dies entspricht einem niedrigeren Verständnisniveau und stützt die geläufige Auffassung von Modellen als Lehrmittel. Im Gegensatz dazu konnte kurz- und mittelfristig sowohl durch das kreative Modellieren (I), als auch durch das untersuchende Modellbetrachten (II) eine Annäherung an ein naturwissenschaftlich anerkanntes Modellverständnis erreicht werden. Damit verbunden war die verringerte Auffassung von Modellen als ‚exakte Nachbildungen eines Originals' und die gesteigerte Wahrnehmung vom ‚veränderlichen Charakter naturwissenschaftlicher Modelle'.

Zusammengefasst zeigte die Kombination von modellgestütztem Lernen mit experimentellen Untersuchungen signifikant positiven Einfluss auf Wissenserwerb und Modellverständnis. Obwohl das untersuchende Modellbetrachten (II) als instruktional effizienter bewertet wurde, bot der Zugang des kreativen Modellierens den Schülerinnen die Möglichkeit, durch erfolgreiche Modellbildung und ‚Flow'-Erfahrungen, Lücken im Vorwissen zu schließen und somit Geschlechterunterschiede auszugleichen. Darüber hinaus sind die implementierten Lernmethoden nicht auf den isolierten Einsatz am außerschulischen Lernort Labor beschränkt und lassen sich fächerübergreifend in den naturwissenschaftlichen Unterricht integrieren.

3 SYNOPSIS

3.1 Einleitung

In der modernen Biologie nimmt die Genetik eine Schlüsselposition ein, sie bietet Zugang zu vielen Arbeitsbereichen wie der Zellbiologie, der Systematik, der Verhaltensbiologie oder der Medizin und Pharmazie (Graw 2015). Seit im Rahmen des Humangenomprojekts (1990-2003) die Abfolge der Basenpaare der menschlichen DNA durch Sequenzierung vollständig entschlüsselt wurde, konnten besonders in der Molekulargenetik mit zunehmender Geschwindigkeit Fortschritte erzielt werden (Collins *et al.* 2003). Folgeprojekte ermöglichen nun neue Wege bei der Erforschung komplexer biologischer Zusammenhänge, so werden beispielsweise im ‚Krebsatlas', die für bestimmte Krebsarten verantwortlichen Mutationen einzeln kartiert (Green *et al.* 2015). Ausgelöst durch Forschungsergebnisse über genetische Einflüsse auf Lernvorgänge, Gedächtnisleistungen und Intelligenz (Matynia *et al.* 2002; Roubertoux *et al.* 2017), wurden darüber hinaus Diskussionen über Veränderungen in der Bildung bei Psychologen und Pädagogen angestoßen (Plomin & Walker 2003; Plucker & Shelton 2015). So konnten bereits zahlreiche Zusammenhänge zwischen Lernschwierigkeiten und genetischen Veränderungen, besonders im Bereich der Leseentwicklung, beschrieben werden (Plomin & Walker 2003; Plomin *et al.* 2007).

Eine aktuelle Forschungsstudie zeigte, dass Lehrer im Allgemeinen ein geringes Wissen über Genetik besitzen. Dennoch schätzen sie für die kognitive Entwicklung angeborene und umweltbedingte Faktoren als gleichermaßen bedeutsam ein (Crosswaite & Asbury 2019). Dabei decken sich Lehreransichten mit Ergebnissen der Zwillingsforschung, die ebenfalls von einem ausgewogenen Verhältnis von Genotyp- und Umwelteinflüssen auf die Entwicklung kognitiver Fähigkeiten berichten (Polderman *et al.* 2015). In der Folge ergeben sich wichtige Erkenntnisse für bildungspolitische Anstöße. Das Wissen um genetisch bedingte individuelle Unterschiede der Schüler hilft individualisierte Bildungsangebote zu schaffen und Lernschwierigkeiten zu begegnen (Asbury 2015). Neben einer sensiblen und kompetenten Lehrtätigkeit und einem Unterricht, der Kreativität und individuelle Entwicklung fördert, ist die Kenntnis über genetische Einflüsse auf Lernen und Verhalten der Schlüssel für personalisierte Lernangebote (Asbury & Plomin 2013; Asbury 2015).

Aus Schülerperspektive ist der Erwerb von genetischem Fachwissen ebenfalls von hohem Stellenwert und eine wichtige Komponente zum Aufbau naturwissenschaftlicher Grundbildung. „Genetische Grundbildung" soll junge Menschen dazu befähigen, ihre Meinung und Entscheidungsfindung mit wissenschaftlich fundierten Argumentationen stützen zu können, um an bedeutsamen gesellschaftlichen Diskussionen aktiv teilhaben zu können (Bowling *et al.* 2008; Boerwinkel *et al.* 2017). Im Hinblick auf die persönliche Gesundheit der Schüler

kristallisieren sich schon heute medizinische Standards zur frühzeitigen Diagnose von Krankheiten durch Gentests heraus, deren Verwendung mit bioethischen Fragestellungen verbunden sein kann (Abrams *et al.* 2015). Nationale wie internationale Richtlinien für den naturwissenschaftlichen Unterricht verweisen daher auf die Verankerung der Genetik in den Lehrplänen, wobei das Verständnis von Struktur und Funktion der DNA einen der wichtigsten Bausteine genetischer Grundbildung ausmacht (KMK 2005; NGSS Lead States 2013).

Genetische Konzepte gelten jedoch aufgrund zahlreicher zellulärer und molekularer Charakteristika und Prozesse als besonders schwer zu vermitteln (Marbach-Ad & Stavy 2000; Lewis & Kattmann 2004). Frühere Studien berichten über Lernerfolge durch schülerzentrierten und experimentell gestützten Unterricht am außerschulischen Lernort Labor, in dem diese Lernschwierigkeiten verringern und Schülerfehlvorstellungen korrigieren können (Scharfenberg *et al.* 2007; Langheinrich & Bogner 2015). Damit einhergehend bietet der Einsatz von Modellen und Modellbildung im Unterricht einen praxisorientierten und forschungsnahen Zugang zum anschaulichen Verständnis molekulargenetischer Inhalte (Rotbain *et al.* 2006).

Vor dem Hintergrund authentischer Primärerfahrungen im Biologieunterricht soll in der vorliegenden Studie untersucht werden, in wie weit die Kopplung von Experimenten und kreativem Modellieren im Schülerlabor einen geeigneten Zugang zur effektiven Vermittlung von Genetik haben könnte.

3.2 Theoretischer Hintergrund

3.2.1 Lernen am außerschulischen Lernort Schülerlabor

Das Angebot im naturwissenschaftlichen Unterricht gilt viel zu häufig als langweilig, irrelevant oder gar als veraltet. Dabei sollte im Vordergrund die Vermittlung einer wissenschaftlichen Grundbildung und einem ebensolchen Weltverständnis stehen, um mündige Bürger mit eigenständiger Urteilskraft heranzuziehen (Osborne & Collins 2001; Rennie *et al.* 2001; Lyons 2006). Um diesen typisch anhaftenden Stigmen angemessen begegnen zu können, untersucht die fachdidaktische Forschung seit vielen Jahren die Effektivität außerschulischer Lernorte und charakterisiert diese als besonders authentische und schülerzentrierte Lernumgebungen (Bryce & Robertson 1985; Franke & Bogner 2011). Die Verbindung von neu erworbenem Wissen mit autonomen, praxisbezogenen Lernerfahrungen wurde wiederholt erforscht und mit traditionellen lehrerzentrierten Unterrichtsansätzen verglichen (Randler & Bogner 2006; Gerstner & Bogner 2010). Das Erleben der Naturwissenschaft und die Art und Weise, wie über sie an Orten außerhalb der Schulen kommuniziert wird (z.B. Nationalparks, Museen, Zoos, botanische Gärten) wird oft als aufregend, herausfordernd und inspirierend empfunden

(Braund & Reiss 2006). Darüber hinaus konnte ein positiver Effekt auf das Wohlbefinden der Schüler bestätigt werden (Meissner & Bogner 2011).

Im Schulalltag führen zeitliche Engpässe häufig dazu, dass das Erlernen naturwissenschaftlicher Arbeitspraktiken, z.B. das selbstständige Experimentieren, gegenüber der lehrerzentrierten Vermittlung theoretischen Fachwissens zurücktreten muss (Euler 2004). Um dem entgegenzuwirken bieten Schülerlabore realistische Lernumgebungen, in denen Schüler die Rolle junger Wissenschaftler einnehmen und durch Hands-on Experimente Bezüge zu aktuellen Forschungsthemen herstellen können (Scharfenberg *et al.* 2007; Goldschmidt *et al.* 2016). Speziell zu molekularbiologischen und gentechnologischen Inhalten ermöglicht der Lernort Labor besondere Primärerfahrungen. Die Lernenden können spezifische praktische Kompetenzen erwerben (z.B. Umgang mit Mikropipetten) und haben Zugang zu Geräten (z.B. Thermocycler), die in Schulen nicht verfügbar sind (Scharfenberg *et al.* 2007). Die Kopplung von autonomen praktischem Arbeiten mit positiven Auswirkungen auf den Wissenserwerb und auf das konzeptuelle Verständnis konnten mehrfach belegt werden (Franke & Bogner 2011; Scharfenberg & Bogner 2013; Langheinrich & Bogner 2016). Ergänzend zeigte die Arbeit von Ben-Nun und Yarden (2009), dass praktische molekularbiologische Experimente am Lernort Labor zu einer Verbesserung der mentalen Modelle der DNA sowie zu einem gesteigerten prozeduralen Verständnis von DNA-Manipulationen führen können.

3.2.2 Modelle und Modellbildung im naturwissenschaftlichen Unterricht

Modelle und Modellbildung sind als weiterer Ansatzpunkt für authentische naturwissenschaftliche Bildung Forschungsgegenstand zahlreicher Studien (Buckley 2000; Gilbert 2004; Chittleborough & Treagust 2009). Grosslight und Kollegen (1991) definierten Modelle als konstruierte Repräsentationen mit variierenden theoretischen Fokussen zu verschiedenen Aspekten eines Originals, um komplexe oder unbekannte Zusammenhänge zu erklären. Ergänzend wurden Modelle als externe Repräsentationen mentaler Konzepte charakterisiert (Krajcik & Merritt 2012). Ausgehend von der Beobachtung naturwissenschaftlicher Phänomene wurde die Modellbildung als Konstruktionsprozess konkreter Repräsentationen abstrakter Ideen unter Berücksichtigung zugrundeliegender theoretischer Mechanismen beschrieben (Windschitl *et al.* 2008; Sins *et al.* 2009).

Im Unterricht sind Modelle und Modellierungen unerlässlich für die Vermittlung von Fachwissen und die Entwicklung eines naturwissenschaftlichen Verständnisses (Giere 1988; Henze & van Driel 2011). Als Brücke zwischen experimentellen Beobachtungen und abstrakter naturwissenschaftlicher Theorie helfen sie komplexe Zusammenhänge zu erklären und zu vereinfachen sowie die Grundlage für wissenschaftliche Prognosen zu bilden (Gilbert *et al.*

1998). Um im Biologieunterricht eine anregende Lernumgebung in der Genetik zu schaffen, empfehlen mehrere Studien dringend das Einbeziehen von Modellen (Malacinski 1996; Templin & Fetters 2002). Rotbain und Kollegen (2006) verglichen bei der Vermittlung molekulargenetischer Inhalte die Anwendung von zwei Arten von Modellen: einer Illustration und einem Kugelmodell. Obwohl beide den individuellen Wissensstand verbesserten, war die Verwendung des dreidimensionalen Kugelmodells deutlich effektiver.

Als ergänzende Strategie verweisen mehrere Studien auf das große Potential von Modellierungen zur Verbesserung des naturwissenschaftlichen Lehrens und Lernens (z.B. Barab *et al.* 2000; Maia & Justi 2009). Louca und Zacharia (2012) beschrieben die Modellbildung als unterstützende Methode, um ein tieferes Verständnis eines beobachteten wissenschaftlichen Phänomens zu erreichen. Die Konstruktion einer anschaulichen Darstellung erleichtert hierbei das Begreifen des abstrakten und unbekannten Mechanismus. Eine rein mentale Veränderung und Anpassung neuerworbener Konzepte würde zu einer geistigen (Über-)Beanspruchung führen (van Merriënboer & Ayers 2005). Hierbei helfen Modelle und Modellierungen wichtige Informationen zu erlernen, zu organisieren und in das Vorwissen zu integrieren (Stull & Hegarty 2016). Aktuelle Ergebnisse zur Vermittlung molekularchemischer Inhalte zeigten außerdem, dass der aktive Umgang und die Manipulation dreidimensionaler Molekülmodelle durch Schüler zu einer verringerten kognitiven Belastung führt gegenüber Schülern, die passiv der modellgestützten Demonstration einer Lehrkraft folgten (Stull *et al.* 2018).

Ein Paradigma erfolgreicher Modellbildung in der Forschung lieferte die Entschlüsselung der Doppelhelixstruktur der DNA (Watson & Crick 1953): James Watson und Francis Crick interpretierten als erste Wissenschaftler vorliegende experimentelle Daten korrekt zu einem geeigneten Modell. Auf Basis empirischer röntgenspektrographischer Untersuchungen der DNA von Rosalind Franklin und Raymond Gosling konstruierten sie zusammen ein adäquates Modell, das alle damalige experimentelle Befunde vereinte (Watson 1968). Wie die historische Entdeckung der DNA-Struktur deutlich macht, nimmt die Fähigkeit zu kreativem Denken einen einzigartigen Platz als Triebkraft für Innovationen in der Wissenschaft ein (Braben 2004). Besonders während Modellierungsprozessen scheint die individuelle Kreativität als Schlüsselfaktor zu fungieren (van Driel & Verloop 1999). Holm-Hadulla (2010) definierte Kreativität als eine Kombination aus Talent, Wissen, Können, Eigenmotivation und Persönlichkeitsmerkmalen, zusätzlich geprägt durch Umwelteinflüsse. Darüber hinaus wird ein psychischer Zustand namens ‚Flow' oft mit kreativem Schaffen verbunden. Dieser ist dadurch gekennzeichnet, dass eine beteiligte Person vollständig in eine Aktivität versinkt sowie fokussierte und enthusiastische Gefühle empfindet (Csikszentmihalyi 2000). In der Bildung kann eine Förderung individueller Kreativität zu einem tieferen Verständnis von Lerninhalten

beitragen, indem dadurch zielstrebiger Wissenslücken und Lernprobleme identifiziert und in der Folge Lösungswege gesucht werden (Chow 2010).

3.2.3 Modellverständnis als Teil naturwissenschaftlicher Grundbildung

Da Modelle und Modellbildung eine Schlüsselrolle in der naturwissenschaftlichen Forschung und Kommunikation spielen, fordern bildungspolitische Richtlinien den Einbezug einer Metaebene des Denkens über Modelle in den Lehrplänen (KMK 2005; NGSS Lead States 2013). Ziel ist dabei, als Bestandteil naturwissenschaftlicher Grundbildung, den Aufbau von Modellverständnis nachhaltig zu fördern (Halloun 2007).

Im Unterricht überwiegt häufig die Verwendung von Modellen als Medium für den Erwerb konzeptionellen und theoretischen Wissens, was die Rolle von Modellen und Modellbildung als Teil naturwissenschaftlicher Denk- und Arbeitsweisen vernachlässigt (Treagust *et al.* 2002). Weitere Studien bestätigten, dass sowohl Lehrer als auch Schüler Modelle hauptsächlich mit deskriptiven Eigenschaften und ihrer Rolle als Lehrmittel zur Visualisierung abstrakter Konzepte assoziieren (Grosslight *et al.* 1991; Justi & Gilbert 2003). In der Folge ist die Auffassung von Modellen bei Schülern häufig begrenzt und als naiv zu werten, wenn sie Modelle als physische Kopien beschreiben und ihre Rolle als Vermittler zwischen Theorie und Beobachtung nicht verstehen (Grosslight *et al.* 1991; Grünkorn *et al.* 2014). Aus wissenschaftspropädeutischer Sicht sollten die Lernenden Modelle schon frühzeitig als Werkzeuge zur Interpretation und Vorhersage wissenschaftlicher Phänomene begreifen. Dazu sollte der passive, lehrerzentrierte Modelleinsatz zurücktreten gegenüber der aktiven und schülerzentrierten Handhabung von Modellen und Modellbildung im Unterricht (Chittleborough & Treagust 2009; Stull *et al.* 2018). Ergänzend forderten Krell und Kollegen (2012) eine exaktere Untersuchung des Modellverständnisses in Abhängigkeit von der Jahrgangsstufe und spezifischen biologischen Kontexten. Um das Metawissen der Schüler über Modelle und Modellbildung gezielt fördern zu können, sollten daher spezifische Unterrichtsansätze entwickelt und begleitend das Modellverständnis der Schüler erfasst werden.

Die empirische Forschung zum Modellverständnis ist weitgefächert und bietet verschiedene Rahmenkonzepte und Evaluationsinstrumente (z.B. Treagust *et al.* 2002; Krell *et al.* 2014; Wen-Yu Lee *et al.* 2017). Dabei gilt die Studie von Grosslight und Kollegen (1991) als Grundlage für die Erforschung des Verständnisses von Modellen und ihrer Anwendung in der Wissenschaft. Sie eruierten fünf Aspekte (*Arten von Modellen*, *mehrere Modelle für die gleiche Sache*, *Zweck der Modelle*, *Design und Erstellung von Modellen*, und *die Änderung eines Modells*) und beschrieben drei allgemeine Verständnislevel von Modellen (Niveau I bis III) und ihre Verwendung in der Wissenschaft.

Eine Förderung des Modellverständnisses kann im Hinblick auf drei Perspektiven erreicht werden: Aus der Betrachtungsperspektive sollten Modelle als Träger von Wissen und Ideen von dem ihm zugrundeliegenden Denkmodell abgegrenzt werden (Upmeier zu Belzen 2013). Die Herstellungsperspektive (Modell *von* etwas) berücksichtigt die Beziehung zwischen dem Denkmodell und dem Original bezüglich subjektiv ausgewählter Bereiche der Realität. Die Anwendungsperspektive (Modell *für* etwas) macht deutlich, dass durch Falsifizierung oder Verifizierung einer zu prüfenden Hypothese das Denkmodell abgelöst oder verändert werden kann (Upmeier zu Belzen & Krüger 2010; Upmeier zu Belzen 2013).

3.3 Ziele und Fragestellungen der Teilarbeiten

Die vorliegende Arbeit befasst sich mit modell-gestütztem Lernen zum Thema „DNA-Struktur“ im außerschulischen Lernort Labor mit der Intention im Rahmen eines exemplarischen Unterrichtsmoduls für die Sekundarstufe das Wissen und das Modellverständnis der Schüler zu steigern. Es werden hierbei zwei unterschiedliche methodische Ansätze hinsichtlich ihrer Effektivität untersucht: Das kreative und selbstständige Entwickeln eines DNA-Modells gegenüber dem Betrachten und Untersuchen eines handelsüblichen DNA-Schulmodells. Anhand des Vergleichs von Wissenserwerb und kognitiver Belastung lässt sich die instruktionale Effizienz beider Lernmethoden bestimmen. Zur Evaluation des eigenständigen Modellierens werden Kreativität und Modellqualität erfasst (s. Abb 1).

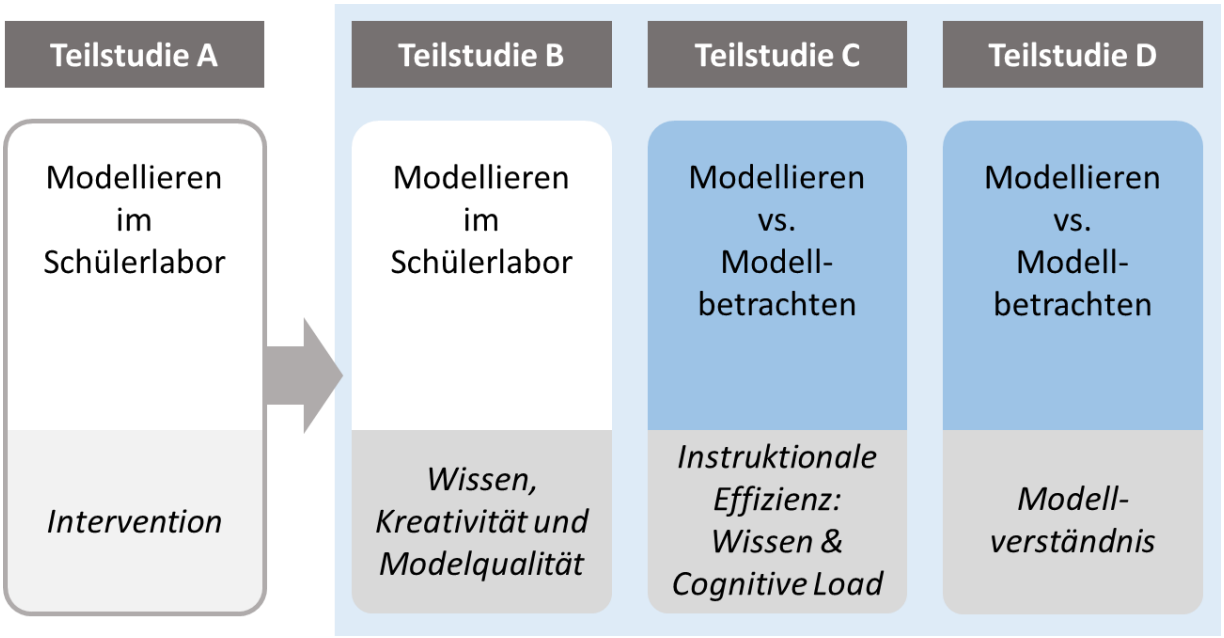

Abb. 1 Übersicht zu den Teilarbeiten der Gesamtstudie.

Teilstudie A: Unterrichtsmodul zum kreativen Modellieren im Schülerlabor

Der Fokus von Teilstudie A liegt auf der Entwicklung eines schülerzentrierten Unterrichtsmoduls für die 9. Jahrgangsstufe am außerschulischen Lernort Labor, welches an Inhalte des bayerischen Lehrplans anknüpft und diese vertieft behandelt (ISB 2007). Neben der Vermittlung von fachlichem Wissen zum Thema DNA-Struktur, führen die Schüler Experimente in einem authentischen Lernsetting durch, erstellen selbstständig Versuchsprotokolle und entwickeln mit Hilfe verschiedenster Materialien eigene Modelle der DNA-Struktur. Dabei soll die Verknüpfung experimenteller Beobachtungen mit theoretischem Fachwissen zum Aufbau der DNA über eine kreative Modellierungsphase einen wesentlichen Ansatzpunkt bieten, um Lernschwierigkeiten aus dem Fachbereich Genetik entgegenzuwirken. So ist bekannt, dass mangelndes Grundwissen über die Strukturen der verschiedenen Organisationsebenen (Gen, Chromosom, Zelle) zu Missverständnissen über die Prozesse zur Weitergabe genetischer Informationen führen können (Lewis & Wood-Robinson 2000). Weitere relevante Fehlvorstellungen sind aus dem Fach Chemie zu nennen: Schüler können Schwierigkeiten haben, Atome und Moleküle voneinander zu unterscheiden oder sie betrachten Atome grundsätzlich als gruppierte Einheiten (Harrison & Treagust 1996; Griffiths & Preston 1992). Die Kombination von experimentellen Untersuchungen und der Entwicklung eines Modells bietet dabei eine geeignete Möglichkeit, verschiedene Organisationsebenen zu verknüpfen sowie den naturwissenschaftlichen Weg der Erkenntnisgewinnung nachzuvollziehen. Dabei soll eine Wissenssteigerung und eine Förderung des Modellverständnisses erreicht werden. Positive Effekte auf den Wissenserwerb konnten bereits (Langheinrich & Bogner 2016) mit einem eLearning-gestütztem Unterrichtsmodul zur DNA für die 11.Jahrgangsstufe zeigen.

Teilstudie B: Wissen, Kreativität und Modellqualität beim Hands-on Modellieren

Die Modellbildung als typische naturwissenschaftliche Arbeitsweise nimmt bei der Forderung nach authentischen Zugängen in der naturwissenschaftlichen Ausbildung eine besondere Stellung ein (Gilbert 2004). Im Fachbereich Genetik bietet die Entwicklung von Modellen im Unterricht eine anspruchsvolle und effektive Möglichkeit um abstrakte Prozesse zu veranschaulichen und verstehen zu können (Rotbain *et al.* 2006). Nach Meinung von naturwissenschaftlichen Lehrern ist erfolgreiches Modellieren geprägt von Kreativität und Kommunikation (van Driel & Verloop 1999). Ausgehend von einem schülerzentrierten Lernsetting, dass Hands-on Experimente mit Modellierung verknüpft, befasst sich Teilstudie B mit der Rolle der Kreativität auf den Wissenserwerb sowie auf die Modellqualität. Zum Erfassen des komplexen Konstruktes der Kreativität wird eine Skala für Jugendliche verwendet, die zwischen den kreativen Teilaspekten ‚act' (bewusste und trainierbare kognitive Prozesse) und

‚Flow' (energiegeladene, fokussierte und enthusiastische Gefühle) unterscheidet (Conradty & Bogner 2018). Da Geschlechterunterschiede hinsichtlich kreativer Leistungen in der Literatur kontrovers diskutiert werden (Shin *et al.* 2002; Besançon & Lubart 2008), sollen auch diese untersucht werden.

Die konkreten Fragestellungen der Teilstudie B sind:

(1) Inwieweit beeinflusst selbstständiges Modellieren in einem experimentellen Hands-on Modul die kurz- und mittelfristigen kognitive Leistung der Schüler?
(2) Gibt es Zusammenhänge zwischen dem individuellen Kreativitätsniveau und der kognitiven Leistung, wenn Modelle in einem Hands-on Modul konstruiert werden?
(3) Wie hängt die Modellqualität mit dem individuellen Kreativitätsniveau und der kognitiven Leistung zusammen?
(4) Bestehen geschlechtsspezifische Unterschiede hinsichtlich der untersuchten Variablen (Wissen, Kreativität, Modellqualität)?

Teilstudie C: Vergleich der instruktionalen Effizienz

Modelle und Modellbildung nehmen eine wichtige Schlüsselrolle im Prozess der naturwissenschaftlichen Erkenntnisgewinnung ein, nationale Bildungsstandards unterstreichen ihre Bedeutung als feste Bestandteile in Lehrplänen zur Entwicklung von naturwissenschaftlicher Kompetenz (KMK 2005; NGSS Lead States 2013). Als geeignete Strategie für das Lehren und Lernen durch Modellierungsaktivitäten verweisen mehrere Studien auf das große Potential modellierungsbasierter Lernansätze, um ein tieferes Verständnis eines beobachteten wissenschaftlichen Phänomens zu erlangen (Barab *et al.* 2000; Maia & Justi 2009). Dennoch favorisieren viele Lehrer den unkomplizierten Einsatz von Modellen als reine Anschauungsobjekte, hauptsächlich um bestimmte Aspekte zu veranschaulichen und inhaltliches Wissen zu vermitteln (Gilbert *et al.* 2000; Upmeier zu Belzen 2013). Ziel von Teilstudie C ist der Vergleich von Wissenserwerb und kognitiver Belastung zwischen eigenständigem Modellieren und untersuchendem Modellbetrachten als Lernmethoden in einem experimentellen Unterrichtsmodul im Schülerlabor. Ausgehend von den erfassten Daten lassen sich die instruktionale Effizienz als standardisierte Differenz von geistiger Anstrengung und der Lernleistung für beiden Methoden ermitteln sowie Empfehlungen für die Arbeit mit Modellen im Biologieunterricht ableiten.

Die konkreten Fragestellungen der Teilstudie C sind:

(1) Wie beeinflussen modellbasierte Ansätze kurz- und mittelfristige kognitive Leistungen von Schülern, wenn selbstständiges Modellieren oder Modellbetrachtung in einem experimentellen Hands-on Modul angewendet werden?
(2) Inwiefern wirken sich die beiden modellbasierten Ansätze auf die kognitive Belastung der Schüler aus?
(3) Welchen Einfluss haben die beiden implementierten Lernmethoden hinsichtlich ihrer instruktionalen Effizienz, d.h. dem standardisierten Unterschied zwischen mentaler Anstrengung und (Wissens-)Leistung?

Teilstudie D: Vergleich des geförderten Modellverständnisses

Der Schwerpunkt der Teilarbeit D liegt auf der vergleichenden Untersuchung von Einflüssen auf das Modellverständnis der Schüler durch implementierte Lernmethoden. Die Wertschätzung der Schüler für Modelle ist oft begrenzt und kann häufig als naiv bewertet werden, wenn sie Modelle als physische Kopien eines biologischen Originals beschreiben (Grosslight *et al.* 1991). Darüber hinaus sind sich Schüler kaum über die Bedeutung der Modellbildung als wissenschaftliche Methode zum Verknüpfen theoretischen Wissens mit praktischen Beobachtungen bewusst (Grünkorn *et al.* 2014). Inwieweit modellbasierte Lernmethoden zu einer Förderung des Modellverständnisses beitragen können, soll durch den Einsatz geeigneter qualitativer und quantitativer Methoden hinsichtlich der Aspekte ‚Alternative Modelle', ‚Modelle als exakte Nachbildungen' und ‚Veränderlicher Charakter wissenschaftlicher Modelle' evaluiert werden.

Die konkreten Fragestellungen der Teilstudie D sind:

(1) Welchen Einfluss haben die beiden modellbasierten Ansätze auf die Argumentation der Schüler im Hinblick auf alternative Modelle in der Wissenschaft?
(2) Inwieweit kann durch die beiden Ansätze das Verständnis der Schüler von wissenschaftlichen Modellen als exakte Nachbildungen korrigiert werden?
(3) Lässt sich durch modellbasierte Aktivitäten das Verständnis der Schüler vom sich verändernden Charakter wissenschaftlicher Modelle fördern?

3.4 Methoden

3.4.1 Teilnehmer und Studiendesign

Im Frühjahr 2017 besuchten zwölf 9.Klassen aus acht bayerischen Gymnasien das Schülerlabor der Universität Bayreuth und nahmen am eintägigen Unterrichtsmodul „Einfach GENial! Die DNA als Träger der Erbinformation“ teil. Die Schüler wurden als Novizen betrachtet, da der Fachbereich Genetik erstmalig in der 9.Jahrgangsstufe im bayerischen Gymnasiallehrplan verankert ist (ISB 2007). Die betreuenden Lehrkräfte waren zusätzlich aufgefordert, vor und während des gesamten Zeitraums der Datenaufnahme keine fachlichen Inhalte zum Thema DNA-Struktur im Unterricht zu behandeln. Ausgehend von den unterschiedlichen Fragestellungen und Zielen der Teilstudien variiert die Anzahl der Studienteilnehmer sowie das Design innerhalb der Gesamtstudie. Geringfügige Abweichungen der Stichprobengröße bei der Beantwortung einzelner Fragestellungen der Teilarbeiten sind mit der unterschiedlichen Anzahl von vollständig ausgefüllten Instrumenten innerhalb der Gesamttests zu begründen.

Teilstudie A befasst sich mit der Konzeption des experimentellen Unterrichtsmoduls in Kombination mit kreativem Modellieren (s. 3.4.3) und bildet die Basis für die Folgeuntersuchungen von **Teilstudie B**: In der Teilstichprobe der ‚Modellierer‘ (n= 114; Alter M ± SD=14,45 ± 0,69; 40.87% weiblich) konstruierten die Schüler in der Modell-Phase selbstständig mit Hilfe einer Modellierungsbox ein eigenes Modell der DNA-Struktur.

Für die **Teilstudie C** und die **Teilstudie D** wurden in der Gesamtstichprobe insgesamt Daten von 254 Schülern erhoben (Alter M ± SD= 14,48 ± 0,70; 52,8% weiblich). Diese wurden nach Klassen zufällig auf zwei Treatments aufgeteilt: 120 Schüler wurden der bereits genannten Gruppe der ‚Modellierer‘ zugeordnet, wohingegen in der Gruppe der ‚Modellbetrachter‘ 134 Schüler ein handelsübliches Schulmodell der DNA-Struktur untersuchten.

Über einen ‚*Mixed-method*‘ Ansatz werden in **Teilstudie B** und **Teilstudie D** qualitative und quantitative Methoden kombiniert. **Teilstudien C** weist ein rein quantitatives Messdesign auf. Die Datenerhebung erfolgte im Rahmen eines quasi-experimentelle Studiendesigns über drei Testzeitpunkte mittels eines schriftlichen Testbogens (‚*paper-and-pencil*‘): Die Schüler füllten die Fragebögen zwei Wochen vor dem Besuch des Schülerlabors aus (T0), direkt im Anschluss an das Unterrichtsmodul (T1) und sechs Wochen später (T2). Damit die Testbögen untereinander zugeordnet werden können, kennzeichneten die Schüler diese mit einem vertraulichen Code, der sich aus Geschlecht, Geburtsmonat und –jahr, dem Vornamen der Mutter und der Hausnummer zusammensetzt.

Zur Kontrolle von Effekten wiederholter Messungen beantworteten zwei weitere 9.Klassen am Gymnasium als Test-Retest-Gruppe die eingesetzten Fragebögen ohne Teilnahme am

Unterricht (*n*=39; Alter *M* ± SD= 14,69 ± 0,57; 100.0% weiblich). Die Test-Retest-Gruppe wurde ebenfalls zu drei Testzeitpunkten befragt.

3.4.2 Erhebungsinstrumente und Datenauswertung

Die Genehmigung zur Befragung der Schüler wurde am 16.02.2017 erteilt (X.7-BO5106/149/10). Die eingesetzten Fragebögen umfassten mehrere Messinstrumente, die nach den Fragestellungen der einzelnen Teilarbeiten spezifisch untersucht wurden. Die zufällige Rotation von Items und Antwortoptionen wurden genutzt, um Reihenstellungseffekten zu begegnen, wenn die Instrumente von den Schülern wiederholt über mehrere Testzeitpunkte beantwortet wurden (Rost 2004).

Die statistische Datenauswertung erfolgt über das Programm *IBM SPSS Statistics* (Versionen 23.0 und 24.0), soweit nicht anders angegeben. **Teilstudie A** beschreibt die Entwicklung und den Aufbau des Unterrichtsmoduls, der Einsatz von Erhebungsinstrumenten zur Überprüfung der Effektivität der implementierten Lernmethode erfolgte über die **Teilstudien B bis D**. In den **Teilstudien B und C** wurden aufgrund von nicht-normalverteilten Werten einiger Variablen nicht-parametrische Analysemethoden zur Hypothesenüberprüfung verwendet. In der **Teilstudie D** wurde ausgehend von normalverteilten Daten parametrische Tests durchgeführt (Field 2013).

Teilstudie B konzentrierte sich auf die Teilstichprobe der ‚Modellierer' und evaluierte den Wissenserwerb, die individuelle Kreativität und die Qualität der konstruierten DNA-Modelle. Weitere Ziele waren die Erforschung der Abhängigkeiten dieser Variablen untereinander sowie die Untersuchung von Geschlechterunterschieden. Zur Erfassung des Wissensstandes zu den drei Testzeitpunkten wurde ein Multiple-Choice-Wissenstest verwendet (in Teilen adaptiert von (Langheinrich & Bogner 2016). Der Fragebogen umfasste dreißig Items von variierendem Schwierigkeitsgrad, wobei zwölf Items das projektorientierte Wissen über die Laboraktivitäten und achtzehn Items das inhaltliche Wissen der Modellphase untersuchten (s. Anhang IV). Den Schüler wurden vier Antwortmöglichkeiten geboten, von den jeweils nur eine korrekt war. Zur statistischen Auswertung wurden richtige Antworten mit ‚1' und falsche Antworten mit ‚0' gewertet, maximal konnten 30 Punkte erreicht werden. Zusätzlich wurde die Kreativität im Vortest (T0) mit dem modifizierten Fragebogen von Conradty und Bogner (2018) über eine vierstufige Likert-Skala von ‚1' (nie) bis ‚4' (sehr häufig) gemessen (s. Anhang IX). Dabei untersuchte das Messinstrument zwei Subskalen: ‚act' umfasst bewusste und trainierbare kognitive Prozesse und ‚Flow' beschreibt Elemente von Flow-Erfahrungen, einem mentalen Zustand der Kreativität. Zur Bewertung der Qualität der DNA-Modelle wurde das bestehende Kategoriensystem von (Langheinrich & Bogner 2015) für die 9. Jahrgangsstufe im Hinblick auf die erwartete Leistung und den Inhalt des Unterrichtsmoduls angepasst. Ausgehend von den

DNA-Modellen und dazugehörigen, beschrifteten Skizzen konnten fünf Kategorien analysiert werden (z.B. Kategorie BA1 ‚*Basen*'). Die DNA-Modelle und Zeichnungen wurden mit Hilfe eines Punktesystems (max. 19 Punkte) entsprechend den dargestellten strukturellen Eigenschaften der DNA bewertet (z.B. Kategorie BA1 ‚*Basen*': *symbolisierte Basen* - 1 Punkt, *symbolisierte und beschriftete Basen* - 2 Punkte, *symbolisierte Basenpaare* - 3 Punkte, *symbolisierte und beschriftete Basenpaare* - 4 Punkte). Die Objektivität des Kategoriensystems wurde durch Intra- und Interraterreliabilität überprüft und eine substantielle Übereinstimmung festgestellt (Cohens *kappa* > 0,693; (Landis & Koch 1977). Die ermittelten Werte für den Wissenserwerb, die Kreativität und die Modellqualität bildeten die Grundlage für den Geschlechtervergleich und die Berechnung von Korrelationen. Die Änderungen des Wissens innerhalb der drei Testpunkte wurden mithilfe von Friedmans ANOVA und Wilcoxons *post-hoc*-Tests analysiert. Um Geschlechterunterschiede zu testen, wurden Mann-Whitney-*U*-Tests (MWU) durchgeführt. Abhängigkeiten der Variablen untereinander wurden durch Spearman's Rho Korrelationen untersucht.

Der Fokus von **Teilstudie C** lag auf dem Vergleich der instruktionalen Effizienz der beiden Lernmethoden, ermittelt aus der kognitiven Leistung (Wissenszuwachs) und der geistigen Anstrengung. Zur Bestimmung des kurz- und mittelfristigen Wissenserwerbs wurde der bereits beschriebene Multiple-Choice-Wissenstest über drei Testzeitpunkte eingesetzt und Unterschiede zwischen den Treatmentgruppen untersucht. Die statistischen Analysen zum Wissenserwerb waren vergleichbar mit denen zu **Teilstudie B**. Darüber hinaus wurde die kognitive Belastung (Cognitive Load; Paas *et al.* 2003) durch Messung der mentalen Anstrengung als Index des Cognitive Loads gemessen (van Gog & Paas 2008). Basierend auf einer eindimensionalen neunstufigen Likert-Skala gaben die Schüler ihre geistige Anstrengung während des Unterrichtsmoduls über acht Zeitpunkte an (s. Anhang XI). Für die vier Phasen des Unterrichtsmoduls (PreLab-Phase, experimentelle Phasen, Modell-Phase, Interpretations-Phase) wurde jeweils ein Wert erfasst, basierend auf einer Skala von ‚1' (sehr, sehr geringe geistige Anstrengung mentaler Aufwand) bis ‚9' (sehr, sehr hohe geistige Anstrengung). Der Mittelpunkt der Skala wurde definiert als durchschnittliche geistige Anstrengung im regulären Biologieunterricht, um mögliche individuelle Abweichungen zu minimieren (Scharfenberg & Bogner 2011). Die instruktionale Effizienz ist definiert als standardisierter Unterschied zwischen mentaler Anstrengung und (Wissens-)Leistung (s. Abb. 2). Zur Berechnung der instruktionalen Effizienz der beiden modellgestützten Lernsettings wurden die Daten der mittelfristigen Wissenssteigerung in der Modell-Phase (T2-T1; achtzehn Items) mit den Daten zur geistigen Anstrengung bei der Arbeit mit den Modellen kombiniert. Dabei wurden die Daten auf z-Werte normiert und in zwei orthogonalen Achsen dargestellt (Sweller *et al.* 2011). Zusätzlich wurden die Erfahrungen mit Modellen und mit der Entwicklung eigener Modelle im

naturwissenschaftlichen Unterricht über eine fünfstufige Likert-Skala von ‚1' (niemals) bis ‚5' (immer) erfasst (s. Anhang X).

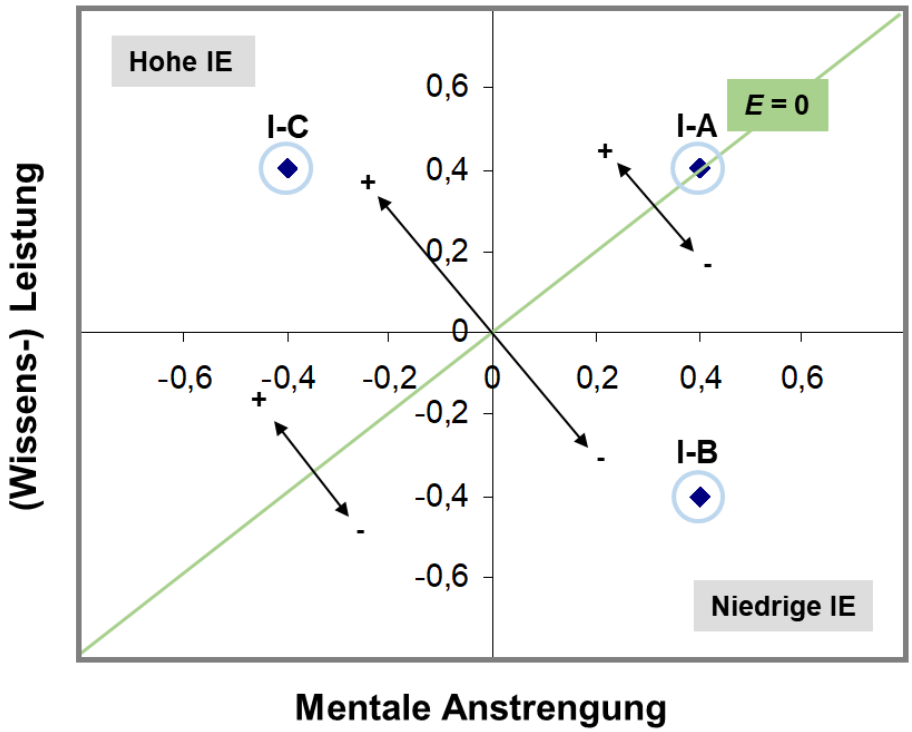

Abb. 2 Durch die Berechnung der instruktionale Effizienz (IE) ist es möglich, Aussagen über die relative Effizienz ($E = (z_{performance} - z_{mental\ effort})/\sqrt{2}$; (Paas & van Merriënboer 1993) verschiedener Unterrichtsbedingungen einzuholen. IE ist der berechnete senkrechte Abstand zur Referenzlinie ($E = 0$), der die durchschnittliche IE darstellt, d.h. ein Gleichgewicht zwischen mentaler Anstrengung und (Wissens-) Leistung liegt vor.
IE für drei exemplarische Lernsettings: I-A: durchschnittlich; I-B: niedrig; I-C: hoch

In **Teilstudie C** wurde die Entwicklung des Modellverständnisses unter dem Einfluss der beiden Unterrichtsbedingungen verglichen. Zur qualitativen Evaluation des Verständnisses über alternative Modelle beantworteten die Schüler eine offene Frage direkt nach dem Unterrichtsmodul (T1) und sollten dabei erklären, warum es zu einem biologischen Original (wie der DNA-Struktur) verschiedene Modelle geben kann (s. Anhang XII). Die Schülerantworten wurden mittels der qualitativen Inhaltsanalyse induktiv kategorisiert (Mayring 2015). Das entwickelte System umfasste fünf verschiedene Kategorien (MM1: *unterschiedliche Ideen und Konzepte*, MM2: *Individualität der DNA*; MM3: *unterschiedliches Modeldesign*; MM4: *unterschiedlicher Fokus* und MM5: *unterschiedliche Forschungsstände)*. Die Objektivitätsprüfung durch Intra- und Interraterreliabilität bestätigte eine substantielle Übereinstimmung des Kategoriensystems (Cohens *kappa* > 0,651; Landis & Koch 1977). In der Folge wurden die Antworthäufigkeiten zwischen den Treatmentgruppen verglichen, d.h. die relativen Häufigkeiten bei der Nennung der Kategorien. Zur quantitativen Untersuchung des Modellverständnisses über drei Testzeitpunkte wurden die beiden Subskalen ‚Modelle als

exakte Nachbildungen‘ (ER) und ‚Veränderlicher Charakter wissenschaftlicher Modelle‘ (CNM) des *SUMS* Fragebogens eingesetzt (*Students’ understanding of models*; (Treagust *et al.* 2002). Die Schüler konnten aus einer fünfstufigen Likert-Skala Antwortmöglichkeiten von ‚1‘ (stimme absolut nicht zu) bis ‚5‘ (stimme stark zu) wählen (s. Anhang VIII). Zur Bestätigung der Skala als geeignetes Messinstrument wurden die sieben Items beider Subskalen einer Faktorenanalyse unterzogen (Hauptachsenanalyse, *Varimax*-Rotation). Für den Vergleich der beiden Subskalen zwischen den Treatmentgruppen wurde jeweils eine Varianzanalyse (ANOVA) mit anschließendem *post-hoc*-Tests mit Bonferroni-Korrektur für jeden Testzeitpunkt durchgeführt. Die Analysen innerhalb einer Gruppe über verschiedene Testzeitpunkt hinweg wurden mit einer ANOVA mit Messwiederholung untersucht.

3.4.3 Unterrichtsmodul

Das eintägige Unterrichtsmodul „Einfach GENial! Die DNA als Träger der Erbinformationen“ (270 min ≙ 6 Schulstunden) wurde am außerschulischen Lernort Labor an der Universität Bayreuth für Schüler der 9.Jahrgangsstufe angeboten. Die Inhalte des Moduls knüpfen eng an den bayerischen Lehrplan des Gymnasiums an und bieten durch schülerzentrierte Hands-on Erfahrungen im Schülerlabor einen besonderen Zugang zum Thema DNA-Struktur (ISB 2007). Das Unterrichtsmaterial und der Ablauf der Hands-on Phasen wurden zuvor in einer Pilotstudie getestet und optimiert. Die entwickelten Lernmaterialien bauen auf der Arbeit von Langheinrich (2015) auf und wurden für die 9.Jahrgangsstufe adaptiert (s. Anhang Unterrichtsmaterialien).

Der Labortag war in fünf Phasen gegliedert: eine PreLab-Phase, zwei experimentelle Phasen, eine Modell-Phase und eine Interpretations-Phase (s. Tab. 1). Während der gesamten Intervention leitete die selbe Lehrkraft die schüleraktiven Unterrichtsabschnitte jeweils über eine kurze theoretische Hinführung an und diskutierte im Anschluss die entsprechenden Teilergebnisse im Plenum. Die Schüler arbeiteten größtenteils selbstständig in Partnerarbeit und wurden anhand ein speziell konzipierten Arbeitshefts mit Informationen zu Arbeitstechniken, Versuchsanleitungen und Aufgabenstellungen durch die einzelnen Phasen des Projekttages geführt.

Tab. 1. Ablauf, Unterrichtsinhalte und ausgewählte Schüleraktivitäten der einzelnen Phasen des Hands-on Moduls „Einfach GENial! Die DNA als Träger der Erbinformationen".

Zeit [min]	*Phase*	*Unterrichtsinhalt*	*ausgewählte Schüleraktivitäten*
50	PreLab-Phase	Seid vorbereitet! So arbeiten Forscher im Genlabor	• Umgang mit der Mikropipette • Bedienen einer Zentrifuge • Dekantieren
60	experimentelle Phase 1	Spinnt eure DNA! Der stoffliche Charakter der DNA	• Hypothesenbildung zur Überführung eines Straftäters mittels DNA-Spur • Isolierung eigener DNA aus Mundschleimhautzellen • Unterscheidung zwischen Stoff- und Teilchenebene am Beispiel der DNA
60	experimentelle Phase 2.1	Macht das Unsichtbare sichtbar! (Teil 1) Die Agarose-Gelelektrophorese – eine wichtige Methode im Genlabor	• Einführung in die Methode der Agarose-Gelelektrophorese • Aufarbeiten der Probe der eigens isolierten DNA
60	Modell-Phase	Auf den Fußspuren zweier GENies! So lösten Watson & Crick das molekulare Puzzle der DNA-Struktur	• Beantworten von Verständnisfragen zum Informationstext • Entwicklung eines eigenen DNA-Modells (Modellierer) oder Überprüfen der beantworteten Fragen anhand eines DNA-Schulmodells (Modellbetrachter) • Anfertigen einer beschrifteten Skizze der DNA-Struktur
25	experimentelle Phase 2.2	Macht das Unsichtbare sichtbar! (Teil 2) Ergebnisse der Agarose-Gelelektrophorese	• Betrachten und Analysieren der Ergebnisse der Agarose-Gelelektrophorese
15	Interpretations-Phase	DNA – Ein Makromolekül des Lebens: Zusammenfassung des Projekttages	• Gruppendiskussion zu den experimentellen Ergebnissen • Verknüpfung mit den gebauten DNA-Modellen bzw. dem Schulmodell der DNA-Struktur.

Um Lernschwierigkeiten aufgrund fehlender experimenteller Fähigkeiten vorzubeugen, begann das Unterrichtsmodul mit einer einführenden PreLab-Phase, in der die Schüler mit wichtigen Geräten und Arbeitstechniken im Schülerlabor vertraut gemacht wurden (Scharfenberg & Bogner 2011). Ausgehend von der Fahndungsmeldung zu einem ungeklärten Mordfall bildeten die Schüler im Anschluss Hypothesen, wie ein Täter einwandfrei anhand

seiner DNA-Spuren überführt werden könnte. Die Lehrkraft leitete anhand der verschiedenen genetischen Organisationsebenen (Chromosom, DNA, Gen) zum ersten Versuch über, in welchem die Schüler ihre eigene DNA aus Mundschleimhautzellen isolierten. Um die DNA auf molekularer Ebene sichtbar zu machen, führten die Schüler in der zweiten experimentellen Phase eine Agarose-Gelelektrophorese mit der aufgearbeiteten Probe ihrer zuvor isolierten, eigenen DNA durch.

Die Modell-Phase nahm eine Schlüsselrolle im Unterrichtsmodul ein, indem sie den Schülern wichtige theoretischen Informationen zum Aufbau der DNA-Struktur vermittelte und die beiden experimentellen Phasen hinsichtlich der Stoff- und Teilchenebene der DNA inhaltlich verknüpfte (z.B. „Welche Komponente ist für die Migration der DNA im elektrischen Feld verantwortlich?"). Dabei folgten die Schüler den Spuren von Watson und Crick beim Lösen des molekularen Puzzles anhand eines didaktisch reduzierten Informationstextes. Dieser bezog sich auf einen originalen Brief, den Francis Crick 1953 seinem damals zwölf Jahre alten Sohn geschrieben hatte. Als zentrale Bestandteile des DNA-Moleküls wurden im Text u.a. die Phosphat-Zuckerketten als DNA-Rückgrat, Namen und Anordnung der Basen, mögliche Basenpaarungen und die rechtshändige Doppelhelix-Struktur genannt. Nach dem Lesen beantworteten die Schüler Verständnisfragen im Arbeitsheft (z.B. „Benenne die Basen der DNA und gib mögliche Basenpaarungen an!“). Bei der Formulierung ihrer Antworten sollten sie sich wesentliche Hintergrundinformationen zur DNA-Struktur bewusstmachen und mit der Entwicklung eines gedanklichen Modells beginnen.

In der Folge wurden die beiden unterschiedlichen Ansätze zur Arbeit mit Modellen im Unterricht realisiert: Die ‚Modellierer‘ konstruierten selbstständig mit Hilfe von DNA-Modellierungsboxen, die eine Vielzahl von Materialien enthalten (z.B. Klebstoff, Schere, Strohhalme, Pfeifenreiniger, Perlen, Pappkärtchen, Filzstifte), ein eigenes Modell der DNA. Wohingegen die ‚Modellbetrachter‘ ein handelsübliches Schulmodell der DNA-Struktur betrachteten und untersuchten, indem sie die Substrukturen des Modells ihren mentalen Modellbildern gegenüberstellten. Abschließend mussten sowohl ‚Modellierer‘ als auch ‚Modellbetrachter‘ eine beschriftete Skizze der DNA-Struktur erstellen und in einer Modellevaluation die Grenzen der Modelle analysieren. In beiden Treatmentgruppen sollte die Arbeit in Tandems die Kommunikations- und Problemlösefähigkeiten der Schüler stärken, die auch von den Bildungsstandards im Fach Biologie neben der bloßen Vermittlung von Fachwissen gefordert werden (KMK 2005).

In der abschließenden Interpretations-Phase wurden die experimentellen Ergebnisse unter zu Hilfenahme der DNA-Modelle diskutiert und mit den eingangs formulierten Hypothesen verglichen. Zusätzlich wurde eine Fotografie des originalen Modells von Watson und Crick

präsentiert, um Unterschiede und Gemeinsamkeiten mit den gebauten DNA-Modellen bzw. den DNA-Schulmodellen im Plenum zu erarbeiten und zu diskutieren.

3.5 Ergebnisse und Diskussion

Der Leitgedanke der Gesamtstudie basiert auf einer erfolgreichen Implementierung von Hands-on Experimenten mit modellbasiertem Lernen. Im authentischen Lernsetting eines Schülerlabors sollen die Schüler den naturwissenschaftlichen Weg der Erkenntnisgewinnung anhand eines Zusammenspiels von experimentellen Beobachtungen und modellgestütztem Lernen zum Thema „DNA-Struktur“ erfahren. Dazu beschäftigte sich **Teilstudie A** mit der Entwicklung eines Unterrichtsmoduls zum kreativen Modellieren im Lernort Labor. Die Überprüfung hinsichtlich der Effektivität sowie die Erforschung von Geschlechter-unterschieden erfolgte in **Teilstudie B** unter den Aspekten Wissen, Kreativität und Modellqualität. In **Teilstudie C** wurden die instruktionale Effizienz von ‚Modellieren‘ und ‚Modellbetrachten‘ gegenübergestellt und in **Teilstudie D** ausgewählte Aspekte zur Steigerung des Modellverständnisses zwischen den Gruppen verglichen.

3.5.1 Teilstudie A

Zeitgemäßer Biologie-Unterricht sollte neben dem bloßen Erwerb von fachlichen Inhalten verstärkt diverse naturwissenschaftliche Kompetenzen fördern (KMK 2005): Im Kompetenzbereich Erkenntnisgewinnung sollen Schüler u.a. das eigenständige Formulieren von Fragen und Hypothesen zu naturwissenschaftlichen Phänomenen lernen, Experimente durchführen und deuten oder die Entwicklung und den Umgang mit Modellen lernen. Im Kompetenzbereich Kommunikation ist die Darstellung von Methoden und die Argumentation über Ergebnisse biologischer Untersuchungen zu nennen. Darüber hinaus ist in den letzten Jahren verstärkt die Nachfrage an sogenannten STEAM-Ansätzen gestiegen (STE**A**M: Science, Technology, Engineering, **A**rts, Math) mit dem Ziel durch die Integration künstlerisch-kreativer Elemente in den naturwissenschaftlichen Unterricht Enthusiasmus zu vermitteln, Selbstständigkeit zu fördern und dadurch kreative, problemlösende Denkweisen anzustoßen (Henriksen 2014). Um der Vielfalt dieser Forderungen nachzukommen, wurde ein entsprechendes Unterrichtsmodul entwickelt, das kreatives Modellieren mit Hands-on Experimenten in einem schülerzentrierten Lernsetting im Schülerlabor zum Thema „DNA-Struktur“ vereint. Die einzelnen Phasen und Schüleraktivtäten für die 9.Jahrgangsstufe (Gymnasium) werden detailliert unter 3.4.3 beschrieben. Die Intervention bildete die Basis für die Untersuchungen der Teilstudien B bis D, welche u.a. die Effektivität der Lernmethodik hinsichtlich Wissenserwerb und Modellverständnis bestätigten. Eine Realisierbarkeit ausgewählter Inhalte des außerschulischen Moduls im regulären Biologieunterricht war

besonders im Hinblick auf die DNA-Modellierung angestrebtes Ziel von Teilstudie A. Darüber hinaus wurden Möglichkeiten für eine Adaption in höheren Jahrgangsstufen aufgezeigt, z.B. durch eine Fokussierung auf die atomare Ebene des DNA-Moleküls.

3.5.2 Teilstudie B

Teilstudie B beschäftigte sich mit dem kurz- und mittelfristen Wissenserwerb durch das experimentelle Unterrichtsmodul mit kreativer Modellierungs-Phase. Die Untersuchung der Qualität des Messinstruments ergab ein akzeptable bis gute Item-Reliabilität für die Gesamtskala (T1/T2/T3: 0,74/0,87/0,86) sowie für die Items der Modell-Phase (T1/T2/T3: 0,74/0,85/0,84) (Kline 2000). Eine Wissensänderung konnte über alle drei Testzeitpunkte festgestellt werden, wobei der niedrigste Wissenstand im Vortest (T0) gemessen wurde, gefolgt von einem Wissensanstieg im Nachtest (T1). Im Behaltenstest (T2) erfolgt eine Wissensabnahme, jedoch lagen die ermittelten Werte signifikant höher als das Vortestlevel. Demgegenüber zeigten die konstant niedrigen Wissensstände für die Test-Retest-Gruppe über den gesamten Testzeitraum keinen Lerneffekt allein durch das Beantworten der Wissensfragebögen. Die Reliabilität des Messinstrumentes für die drei Testzeitpunkte war akzeptabel bis gut. Die Ergebnisse früherer Studien bestätigen einen positiven Effekt auf die kognitive Leistung durch den Besuch von Schülerlaboren im Fachbereich Genetik (Franke & Bogner 2011; Goldschmidt *et al.* 2016; Langheinrich & Bogner 2016). Rotbain und Kollegen (2006) konnten durch den Einsatz dreidimensionaler Modelle gegenüber von Abbildungen ebenfalls einen Wissenszuwachs bei der Vermittlung genetischer Fachinhalte feststellen.

Die Untersuchung von Geschlechterunterschieden beim Erwerb von Wissen ergab einen signifikant niedrigeren Wissenstand der Mädchen im Vortest, wohingegen keine Abweichungen hinsichtlich der Nach- und Behaltenstestlevel zwischen den Geschlechtern festzustellen waren. Folglich gab es einen geschlechtsabhängigen Unterschied im Wissenszuwachs (T1-T0) gegenüber einer geschlechtsunabhängigen Wissensabnahme sechs Wochen nach Besuch des Unterrichtsmoduls (T2-T1).

Die Reliabilität der Skala zur Bestimmung der Kreativität war hinreichend gut (0,74; Kline 2000). Die im Vortest gemessenen individuellen Kreativitätslevel für die Subskalen ‚Act' und ‚Flow' wiesen keine Unterschiede zwischen Schülerinnen und Schülern auf. In der Literatur wird die Abhängigkeit der Kreativität vom Geschlecht kontrovers diskutiert; während einige Studien Frauen als kreativer einschätzen (Ülger & Morsünbül 2016), geben andere dies für Männer an (Shin *et al*. 2002) oder es werden keinerlei geschlechtsspezifische Unterschiede identifiziert (Besançon & Lubart 2008).

Die DNA-Modellierung fand in Partnerarbeit statt, weshalb die Geschlechteraufteilung sowie die Vorwissensunterschiede in den Tandems als mögliche Einflussfaktoren auf die

Modellqualität und den Wissenserwerb während der Modell-Phase geprüft wurden. Die Mehrheit der Schüler und Schülerinnen arbeitete in gleichgeschlechtlichen Paaren zusammen (89,6%), was eine geschlechtsspezifische Untersuchung der Modellqualität rechtfertigte. Darüber hinaus waren die Vorwissensdifferenzen zwischen Schüler- und Schülerinnenpaaren in der Gesamtheit vergleichbar.

Als Ergebnis der Modellierungs-Phase konstruierten die Teilnehmer vielfältige DNA-Modelle unterschiedlicher Qualität mit beschrifteten Skizzen. Die Bewertung der Modellqualität zeigte, dass Mädchen und gemischtgeschlechtliche Tandems (10,4%) signifikant besser strukturierte DNA-Modelle erstellten als die Jungen.

In weiteren Analysen wurden Zusammenhänge von Wissen, Kreativität und Modellqualität untersucht: Für Schüler ergaben sich keine Korrelationen der Wissenslevel zu den drei Testzeitpunkten mit den beiden Kreativitätssubskalen ‚act' (bewusste und trainierbare kognitive Prozesse) und ‚Flow' (mentaler kreativer Zustand: energiegeladene, fokussierte und enthusiastische Gefühle). Im Gegensatz dazu konnten bei Schülerinnen positive Beziehungen zwischen der Kreativitätssubskala ‚Flow' mit dem kurz- und mittelfristigen Wissensniveaus festgestellt werden (Spearman's correlation coefficient r_s ≥ ,34**). Zusätzlich korrelierten die Wissensstände in Nach- und Behaltenstests bei Mädchen deutlich positiv mit der Modellqualität, was bei Jungen nicht der Fall war. Aufgrund vergleichbarer Wissenslevel zwischen den Geschlechtern lag die Vermutung nahe, dass bei den Jungen andere Faktoren zur Wissenssteigerung beitragen, z.B. der Zugang zu einem naturwissenschaftlichen Arbeitsbereich in einem Universitätslabor oder die praktische Durchführung von Experimenten. Damit stellte die kreative und künstlerisch inspirierte Modellierungs-Phase ein geeignetes Beispiel für eine erfolgreichen STEAM-Ansatz dar, der eine ergänzende Förderung der Mädchen im experimentellen Lernsetting gewährleistete und die Gleichstellung der Geschlechter unterstützte (Burkam *et al.* 1997).

Van Driel und Verloop (1999) berichten von einer Schlüsselrolle der Kreativität und der Kommunikation bei der Modellbildung, da Modelle als Produkte menschlicher Gedanken häufig in inspirierendem sozialen Austausch entstehen. Entgegen der Vermutung, dass kreativere Schülerinnen und Schüler eine höhere Modellqualität erreichen könnten, ließen sich in Teilstudie B für beide Geschlechter keine Korrelationen zwischen der individuellen Kreativität und der Modellqualität beobachten. Genetik als abstraktes Thema könnte zu einer hohen Belastung des Arbeitsgedächtnisses geführt haben und in der Folge zu einer Einschränkung von Lernprozessen (Kirschner *et al.* 2006): Die Modellierer mussten sich insbesondere auf die korrekte Übertragung der Informationen aus dem Text in ein adäquates DNA-Modell konzentrieren, wobei ihre individuelle Kreativität durch Perfektionismus und strikte Zielorientierung blockiert gewesen sein könnte (Grant *et al.* 2012).

3.5.3 Teilstudie C

Ausgehend vom erworbenen Wissen und der kognitiven Belastung wurde in Teilstudie C die instruktionale Effizienz der zwei modellbasierten Lernansätze (Modellieren vs. Modellbetrachtung) verglichen.

In der Gesamtstichprobe war eine signifikante Änderung des Wissens über die drei Testzeitpunkte festzustellen: Der Vorwissensstand (T0) lag niedriger als die erfassten Wissenslevel direkt bzw. sechs Wochen nach dem Unterrichtsmodul. Der Wissenszuwachs ließ sich aufgrund steigender Werte im Nachtest (T1) bestätigen, gefolgt von einer leichten Wissensabnahme im Behaltenstest (T2). In der Literatur finden sich ähnliche positive Effekte auf den Wissenserwerb sowohl durch modellbasierte Lernansätze als auch durch den Besuch von Schülerlaboren (Henze & van Driel 2011; Scharfenberg & Bogner 2013). Demgegenüber war keine Änderung der Wissensstände für die Test-Retest-Gruppe festzustellen (vgl. 3.5.2).

Zwischengruppenanalysen untersuchten Unterschiede im Wissen über den Testzeitraum in Abhängigkeit vom Treatment: Das Vorwissen und der kurzfristige Wissenserwerb der Modellierer und der Modellbetrachter waren vergleichbar, jedoch wurden Abweichungen beim mittelfristigen Wissenserwerb beobachtet. Im Behaltenstest erreichten die Modellbetrachter signifikant höhere Werte, wobei der Unterschied zu den Modellierern noch deutlicher ausfiel, wenn das Wissen zur Modell-Phase isoliert betrachtet wurden. Demnach lernten Modellierer wider Erwarten weniger nachhaltig, obwohl das selbstständige Entwickeln von Modellen in der Literatur als fruchtbare Methode im Naturwissenschaftlichen Unterricht beschrieben und ihr Einsatz bildungspolitisch gefordert wird (Louca & Zacharia 2012; KMK 2005). Nach einer Studie von Svoboda und Passmore (2013) ermöglicht die Modellbildung das Erkennen von Wissenslücken durch Hypothesenbildung und –überprüfung, welche wiederum zur Anpassung und Optimierung eines entwickelten Modells führen können.

Die erfassten Daten über die individuelle mentale Anstrengung in den einzelnen Phasen des Unterrichtsmoduls variierten nicht wesentlich zwischen den Treatmentgruppen. Die Vermutung, dass die Modellierer eine höhere kognitive Belastung wahrnehmen oder eine Überlastung des Arbeitsgedächtnisses durch die komplexen Anforderungen der Modellbildung vorlag, musste zurückgewiesen werden (Baddeley 1992). Vielmehr schienen beide Gruppen gleichermaßen geeignete kognitive Schemata zu erstellen, um die neu erworbenen, unorganisierten Informationen zum Thema DNA zu strukturieren und zu verarbeiten. (van Merriënboer & Ayers 2005). Zusätzlich konnte beobachtet werden, dass die künstlerische Komponente der Lernmethode und die freie Materialwahl die Modellierer positiv motiviert, wodurch die mentale Anstrengung ebenfalls verringert worden sein könnte (Runco *et al.* 2017).

Die instruktionale Effizienz beider Treatments wurde auf Basis der mittelfristigen Wissenswerten und der erfassten kognitiven Belastung bezogen auf die Modell-Phase ermittelt. Dabei war eine ähnliche mentale Anstrengung der implementierten Methoden gekoppelt an unterschiedliche Wissensleistungen: Die Modellbetrachter wiesen eine geringere Vergessens-Rate auf als die Modellierer, d.h. innerhalb der Modell-Phase war die Wissensabnahme signifikant niedriger (T2-T1). Dieses Ergebnis bestätigt eine höhere instruktionale Effizienz der Modellbetrachtung im Unterrichtsmodul gegenüber dem Modellieren und deutet zunächst auf ein tieferes Verständnis des theoretischen naturwissenschaftlichen Hintergrundes für die Modellbetrachter hin (Kirschner *et al.* 2006).
Eine plausible Erklärung für die mittelfristigen Wissensunterschiede liefert die in Teilstudie B erfasste variierende Modellqualität der Modellierer. Während die Modelbetrachter anhand eines didaktisch aufbereiteten einprägsamen DNA-Modells lernten, mussten die Modellierer die zur Verfügung stehenden Informationen selbstständig in ein geeignetes Modell transferieren. Bei dieser anspruchsvollen Aufgabe gelang es nur wenigen Schülern, ein vollständiges und korrektes Modell der DNA-Struktur zu konstruieren, was in der Folge zu Fehlvorstellungen geführt haben könnte. Die Änderung der Organisationsebenen zwischen den Experimenten und der Modellphase als typische Schwierigkeit beim Verständnis genetischer Konzepte deckt sich mit der Literatur (Lewis & Wood-Robinson 2000; Langheinrich & Bogner 2015). Darüber hinaus gaben die Schüler an, sehr geringe Erfahrungen bei der Entwicklung eigener Modelle im naturwissenschaftlichen Unterricht zu haben, was eine erfolgreiche Modellierung zusätzlich erschwert haben könnte.

3.5.4 Teilstudie D

Der Fokus der Teilstudie D lag auf der Förderung des Modellverständnisses durch die modellbasierten Lernansätze und untersuchte drei Teilaspekte (alternative Modelle, Modelle als exakte Nachbildungen, veränderlicher Charakter wissenschaftlicher Modelle).

Die Schülerantworten auf die Frage nach alternativen Modelle zu einem biologischen Original gaben Einblick über das Modellverständnis zu diesem Teilaspekt: In beiden Treatmentgruppen begründete die Mehrheit der Schüler die Vielfalt an DNA-Modellen mit der Individualität der DNA-Struktur (Beispielantwort für MM2: „Jeder Mensch ist anders, also sind auch die Basen in jedem Menschen anders angeordnet“). Solche Schülerantworten waren direkt verknüpft mit spezifischen Inhalten des Unterrichtmoduls und nahmen daher eine Sonderstellung zur Erklärung alternativer Modelle ein (Grünkorn *et al.* 2014; Krell *et al.* 2012).

An zweiter Stelle gaben die Schüler ein variierendes Modelldesign (MM3) als Erklärung an, z.B. die Wahl des für den Modellbau verwendeten Materials oder die Entscheidung, ob die DNA in 2D oder 3D präsentiert wurde. In der Literatur deuten solche Argumentationen auf ein

niedriges Verständnisniveau hin, da sie sich ausschließlich auf Material- und Designeigenschaften von Modellobjekten beziehen und Modelle als Lehrmittel betrachten (Upmeier zu Belzen & Krüger 2010).

Am dritthäufigsten nannten die Schüler den Fokus des Modells als Grund für unterschiedliche Darstellungsformen (Beispielantwort für MM4: „Um verschiedene Eigenschaften zu erklären, gibt es z.B. Modelle, bei denen man nur die Basenpaarungen sehen kann und andere, bei denen die rechtshändige Doppelhelixstruktur dargestellt ist, etc.“). Solche Begründung entsprechen einem mittleren Verständnislevel (Grünkorn *et al.* 2014).

An vierter Stelle argumentierten die Schüler auf dem höchsten „Level“ und rechtfertigten die Existenz alternativer Modelle mit unterschiedlichen Vorstellungen vom Original, die zu verschiedenen Darstellungen eines Phänomens führten (Grünkorn *et al.* 2014). Einige gaben auch an, dass all diese Modelle gleichzeitig gültig sein können. Nur eine geringe Anzahl an Schülern zeigte ebenfalls ein vertieftes Verständnis, wenn neue Forschungsergebnisse (MM5) als Begründung angegeben wurden. Die statistischen Analysen ergaben keine signifikanten Unterschiede zwischen der Häufigkeitsverteilung der Kategorien in Abhängigkeit von der Treatmentgruppe.

Für die quantitative Auswertung wurde zunächst die Eignung des SUMS Fragebogens überprüft (*Students' understanding of models;* Treagust *et al.* 2002) und über Faktorenanalysen bestätigt. Die Kaiser-Meyer-Olkin-Tests bestätigten die Stichprobeneignung (KMO= 0,67), die deutlich über der akzeptablen Grenze von 0,5 lag. Der Bartlett-Test fiel hochsignifikant aus, wodurch eine ausreichend hohe Korrelation zwischen den Items gegeben war, um eine Hauptkomponentenanalyse durchzuführen (Field 2013). Die explorative Faktorenanalyse lieferte eine Zwei-Faktoren-Lösung, die die Faktorenstruktur der Originalarbeit bestätigte.

Für die Subskala ‚Modelle als exakte Nachbildungen' (ER) wurde der höchste Wert im Vortest beobachtet, im Nachtest sank der Wert signifikant und nahm im Behaltenstest wieder zu. Die empirischen Daten bestätigen die gängige Wahrnehmung von Modellen als einfache Kopien im Vortest (Grosslight *et al.* 1991). Dieses Verständnis gilt als naiv, da es Modelle in erster Linie durch Genauigkeit und übereinstimmende Details mit einer daraus resultierenden hohen Ähnlichkeit zum Original beschreibt (Grünkorn *et al.* 2014). Eine mögliche Begründung liegt darin, dass Modelle hauptsächlich als Anschauungsobjekte im Unterricht Verwendung finden, z.B. ein anatomisches Herzmodell, und weniger als naturwissenschaftliche Arbeitsmethode eingesetzt werden (Oh & Oh 2011).

Ein gegenläufiger Trend zeigt sich in der Subskala ‚Veränderlicher Charakter wissenschaftlicher Modelle' (CNM). Der niedrigste erfasste Stand wurde im Vortest gemessen,

gefolgt von einem signifikanten Anstieg im Nachtest und einem Absinken im Behaltenstest. Die beobachteten Vortestlevels deuten bereits auf eine Zustimmung mit dem sich ändernden Charakter von Modellen aufgrund neuer Erkenntnisse oder fortschrittlicher Technologien hin und bestätigen die Originaldaten in der Literatur (Treagust *et al.* 2002). Darüber hinaus kann das Modellverständnis der Schüler weiter gesteigert werden. Das Ergebnis lässt vermuten, dass den Schülern der veränderliche Charakter von Modellen noch deutlicher bewusstwurde, während sie selbst den naturwissenschaftlichen Weg der Erkenntnisgewinnung mit Hilfe von Modellen am Beispiel der DNA-Struktur im Unterricht nachvollzogen.

Die Zwischengruppenanalysen für beide Subskalen des SUMS zeigten keine Unterschiede zwischen den Modellierern und Modellbetrachtern zu allen Testzeitpunkten. Bisher wurden selten Effekte modellbasierter Lernmethoden auf das Modellverständnis untersucht, und kaum Entwicklungen über mehrere Testzeitpunkte beschrieben (Dori & Barak 2001; Gobert & Pallant 2004). Die Ergebnisse von Teilstudie D sind im Einklang mit diesen früheren Studien und zeigen, dass die Arbeit mit Modellen im Unterricht neben der Vertiefung von fachlichem Wissen auch dazu beitragen kann die Bedeutung und den Einsatz von Modellen in der Wissenschaft zu verstehen.

3.6 Schlussfolgerung und Ausblick

Für den Vergleich der Effektivität zweier modellbasierter Lernansätze in Kombination mit experimentellen Hands-on Erfahrungen im Lernort Labor bildete die Konzeption eines schülerzentrierten Unterrichtsmoduls den zentralen Ausgangspunkt für weiterführende Untersuchungen. Die Kopplung von Modellarbeit mit Experimenten zum Thema DNA-Struktur erwies sich als äußerst effektiv hinsichtlich des Wissenserwerbs und des Modellverständnisses sowohl für diejenigen Schüler, die kreativ und selbstständig ein DNA-Modell entwickelten als auch für solche die stattdessen ein handelsübliches DNA-Schulmodell betrachteten und untersuchten. Dabei sind die modellbasierten Lernaktivitäten sowie ausgewählte Versuche des Moduls keinesfalls an den isolierten Einsatz im Schülerlabor gebunden, sondern könnten mit angemessenem Aufwand auch in den Biologieunterricht in der Schule integriert werden.

Genauere Analysen über die instruktionale Effizienz beider Lernsettings offenbarten jedoch, dass die ‚Modellbetrachter' verglichen mit den ‚Modellierern' bei ähnlicher kognitiver Belastung einen geringeren mittelfristigen Wissensverlust aufwiesen. In der Folge bestätigte dieses Ergebnis die höhere Effizienz des untersuchenden Modellbetrachtens gegenüber dem kreativen Modellieren. Entwicklung, Überprüfung und Anpassung von Modellen zählen zu den elementaren Bausteinen der naturwissenschaftlichen Grundbildung (scientific literacy) und sollen aus bildungspolitischer Perspektive im Rahmen eines innovativen

naturwissenschaftlichen Unterrichts gefördert werden. Demnach sollten zukünftige Arbeiten geeignete Maßnahmen evaluieren, die zu einer Steigerung der instruktionalen Effizienz solcher Unterrichtsansätze beitragen können. Durch die Studie konnte aufgezeigt werden, dass während der komplexen und anspruchsvollen Modellierung auch fehlerhafte und/oder unvollständige Modelle konstruiert wurden, die wiederum zu Fehlvorstellungen über die DNA-Struktur führen könnten. Die Erforschung zielführender Maßnahmen für eine fruchtbare Modellevaluation stellt damit einen geeigneten Ansatzpunkt dar, die Modellbildung langfristig als erfolgreiche Lernmethode im Biologieunterricht zu etablieren. Hierbei sollte auch die Rolle der Lehrkraft als beeinflussende Variable berücksichtigt werden. Vor dem Hintergrund geringer Erfahrungen mit der Entwicklung eigener Modelle im Unterricht, sollten zukünftige Ansätze verstärkt über den theoretischen Prozess der Modellbildung informieren, damit Schüler dieses Metawissen auf konkrete biologische Sachverhalte oder beobachtete Phänomene erfolgreich übertragen und anwenden können.

Die Studie belegte weiterhin positive Auswirkungen auf mehrere Teilaspekte zur Annäherung an ein naturwissenschaftlich anerkanntes Modellverständnis. Argumentationen zu alternativen Modellen in der Wissenschaft lieferten zunächst einen typischen Querschnitt für die befragte Altersgruppe und zeigten, dass eine Mehrheit Modellunterschiede mit variierenden Eigenschaften des Originals (DNA) oder hinsichtlich des Designs begründeten. Dies entspricht eher einer Wahrnehmung von Modellen als Anschauungsobjekten und weniger als subjektiv konstruierte Repräsentation eines Originals mit bestimmtem Fokus. Eine Förderung des Modellverständnisses durch die Kombination von Experimenten mit Modellaktivitäten ließ sich schließlich eindeutig hinsichtlich einer verringerten Wahrnehmung von Modellen als exakte Nachbildungen feststellen. Zusätzlich konnte die Überzeugung der Schüler vom veränderlichen Charakter von Modellen weiter gesteigert werden.

Mit der Evaluation des kreativen, selbstständigen Modellierens konnten sowohl Geschlechtereffekte identifiziert, als auch interessante Einblicke über Zusammenhänge zwischen Wissen, Kreativität und Modellqualität offengelegt werden. Obwohl Auswirkungen der individuellen Kreativität auf die Modellqualität nicht bestätigt werden konnten, so profitierten besonders Schülerinnen von der implementierten Modellierung: Sie bauten nicht nur wesentlich exaktere Modelle, sondern ihre höhere Modellqualität korrelierte auch positiv mit dem Wissenserwerb und ermöglichte den Ausgleich von Vorwissensdefiziten gegenüber den Schülern. Darüber hinaus wurden positive Beziehungen zwischen dem Wissenszuwachs und kreativen ‚Flow'-Erfahrungen für Mädchen gefunden. Der implementierte Unterricht stellte damit ein gelungenes Beispiel für die in den letzten Jahren geforderten STEAM-Ansätze dar (STE**A**M: Science, Technology, Engineering, **A**rts, Math). Diese wollen bestehenden Geschlechterunterschieden in den Naturwissenschaften entgegenwirken, indem die

Begeisterung von Mädchen durch die Integration künstlerisch-kreativer Elemente bereits während der naturwissenschaftlichen Ausbildung in der Schule gesteigert werden soll. Gerade die Modellbildung zeigt hierbei Potential, da es sich um eine fächerübergreifende naturwissenschaftliche Arbeitsweise handelt, die auch im Physik- und besonders im Chemieunterricht eine bedeutsame Rolle einnimmt. Dies bestätigte auch die erfolgreiche Implementierung der Studie im Kontext des molekularen Aufbaus der DNA.

In Zukunft bietet die Evaluation von Lernansätzen zur Modellbildung im naturwissenschaftlichen Unterricht weiterhin ein spannendes Forschungsfeld. Den Aufbau von Modellkompetenz konsequent zu fördern sowie dem technischen Fortschritt zu folgen sind aktuelle Herausforderungen. Verbunden mit dem Aufkommen innovativer digitaler Methodenwerkzeuge, wird es schon bald problemlos möglich sein mit geringem Material- und Vorbereitungsaufwand Modelle schnell und komfortabel auf Smartphones, interaktiven Whiteboards oder Laptops im Klassenzimmer zu entwickeln. Dabei sollte nicht vergessen werden, dass neben den in dieser Studie aufgezeigten Ansatzpunkten zusätzliche Fähigkeiten von Schülern und Lehrkräften nötig sind, um die Modellbildung als elementare naturwissenschaftliche Methode zielführend in einen innovativen Unterricht zu integrieren.

4 LITERATURVERZEICHNIS DER ZUSAMMENFASSUNG

Abrams, L. R., McBride, C. M., Hooker, G. W., Cappella, J. N., Koehly, L. M. (2015). The many facets of genetic literacy: assessing the scalability of multiple measures for broad use in survey research. *PloS one 10*(10), e0141532. DOI: 10.1371/journal.pone.0141532.

Asbury, K. (2015). Can genetics research benefit educational interventions for all? *The Hastings Center report 45*(5), 39-42. DOI: 10.1002/hast.497.

Asbury, K., Plomin, R. (2013). *G is for Genes*. Hoboken: John Wiley & Sons.

Baddeley, A. (1992). Working memory. *Science 255*(5044), 556–559.

Barab, S., Hay, K. E., Barnett, M., Keating, T. (2000). Virtual solar system project: Building understanding through model building. *Journal of Research in Science Teaching 37*(7), 719–756. DOI: 10.1002/1098-2736(200009)37:7<719::AID-TEA6>3.0.CO;2-V.

Ben-Nun, M. S., Yarden, A. (2009). Learning molecular genetics in teacher-led outreach laboratories. *Journal of Biological Education 44*(1), 19–25. DOI: 10.1080/00219266. 2009.9656187.

Besançon, M., Lubart, T. (2008). Differences in the development of creative competencies in children schooled in diverse learning environments. *Learning and Individual Differences 18*(4), 381–389. DOI: 10.1016/j.lindif.2007.11.009.

Boerwinkel, D. J., Yarden, A., Waarlo, A. J. (2017). Reaching a consensus on the definition of genetic literacy that is required from a twenty-first-century citizen. *Science & Education 26*(10), 1087–1114.

Bowling, B. V., Acra, E. E., Wang, L., Myers, M. F., Dean, G. E., Markle, G. C., Moskalik, C. L., Huether, C. A. (2008). Development and evaluation of a genetics literacy assessment instrument for undergraduates. *Genetics 178*(1), 15–22. DOI: 10.1534/genetics.107. 079533.

Braben, D. W. (2004). *Pioneering research: A risk worth taking*. Hoboken: John Wiley & Sons.

Braund, M., Reiss, M. (2006). Towards a more authentic science curriculum: the contribution of out-of-school learning. *International Journal of Science Education 28* 12), 1373–1388. DOI: 10.1080/09500690500498419.

Bryce, T. G. K.; Robertson, I. J. (1985). What can they do? A review of practical assessment in Science. *Studies in Science Education 12*(1), 1–24. DOI: 10.1080/0305726850 8559921.

Buckley, B. C. (2000). Interactive multimedia and model-based learning in biology. *International Journal of Science Education 22*(9), 895–935. DOI: 10.1080/095006900 416848.

Burkam, D. T., Lee, V. E., Smerdon, B. A. (1997). Gender and science learning early in high school: subject matter and laboratory experiences. *American Educational Research Journal 34*(2), 297–331. DOI: 10.3102/00028312034002297.

Chittleborough, G. D., Treagust, D. F. (2009). Why models are advantageous to learning science. *Educacion química 20*(1), 12–17. DOI: 10.1016/S0187-893X(18)30003-X.

Chow, B. (2010). The quest for deeper learning. *Education Week* 30 (6), 1–3.

Collins, F. S., Morgan, M., Patrinos, A. (2003). The Human Genome Project: lessons from large-scale biology. *Science 300*(5617), 286–290. DOI: 10.1126/science.1084564.

Conradty, C., Bogner, F. X. (2018). From STEM to STEAM: How to monitor creativity. *Creativity Research Journal 30*(3), 233–240. DOI: 10.1080/10400419.2018.1488195.

Crosswaite, M., Asbury, K. (2019). Teacher beliefs about the aetiology of individual differences in cognitive ability, and the relevance of behavioural genetics to education. *British Journal of Educational Psychology 89*(1), 95–110. DOI: 10.1111/bjep.12224

Csikszentmihalyi, M. (2000). *Beyond boredom and anxiety*. San Francisco: Jossey-Bass.

Dori, Y. J., Barak, M. (2001). Virtual and physical molecular modeling: Fostering model perception and spatial understanding. *Journal of Educational Technology & Society 4*(1), 61–74.

Euler, M. (2004). *The role of experiments in the teaching and learning of physics*. Amsterdam: IOS Press, 175–221.

Field, A. P. (2013). *Discovering statistics using IBM SPSS statistics*. London: SAGE.

Franke, G., Bogner, F. X. (2011). Cognitive influences of students' alternative conceptions within a hands-on gene technology module. *The Journal of Educational Research 104*(3), 158–170. DOI: 10.2307/26505677.

Gerstner, S., Bogner, F. X. (2010). Cognitive achievement and motivation in hands-on and teacher-centred science classes: Does an additional hands-on consolidation phase (concept mapping) optimise cognitive learning at work stations? *International Journal of Science Education 32*(7), 849–870. DOI: 10.1080/09500690902803604.

Giere, R. (1988). *Explaining science*. Chicago: University of Chicago Press.

Gilbert, J. K. (2004). Models and Modelling: Routes to More Authentic Science Education. *International Journal of Science and Mathematics Education 2*(2), 115–130. DOI: 10.1007/s10763-004-3186-4.

Gilbert, J. K., Boulter, C., Elmer, R. (2000). Positioning models in science education and in design and technology education. In: *Developing models in science education* (3–17). Dordrecht: Springer.

Gilbert, J. K., Boulter, C., Rutherford, M. (1998). Models in explanations, Part 1: Horses for courses? *International Journal of Science Education 20*(1), 83–97. DOI: 10.1080/ 0950069980200106.

Gobert, J. D., Pallant, A. (2004). Fostering students' epistemologies of models via authentic model-based tasks. *Journal of Science education and Technology 13*(1), 7–22. DOI: 10.1023/B:JOST.0000019635.70068.6f.

Goldschmidt, M., Scharfenberg, F.-J., Bogner, F. X. (2016). Instructional efficiency of different discussion approaches in an outreach laboratory: Teacher-guided versus student-centered. *The Journal of Educational Research 109*(1), 27–36. DOI: 10.1080/ 00220671.2014.917601.

Grant, A., Grant, G., Gallate, J. (2012). *Who killed creativity? And how do we get it back?* Milton: Jossey Bass.

Green, E. D., Watson, J. D., & Collins, F. S. (2015). Human Genome Project: Twenty-five years of big biology. *Nature News*, *526*(7571), 29-31.

Graw, J. (2015). *Genetik*. Berlin: Springer Spektrum.

Griffiths, A. K., Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching 29*(6), 611–628. DOI: 10.1002/tea.3660290609.

Grosslight, L., Unger, C., Jay, E., Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science teaching 28*(9), 799–822. DOI: 10.1002/tea.3660280907.

Grünkorn, J., Upmeier zu Belzen, A., Krüger, D. (2014). Assessing students' understandings of biological models and their use in science to evaluate a theoretical framework *International Journal of Science Education 36*(10), 1651–1684. DOI: 10.1080/ 09500693.2013.873155.

Halloun, I. A. (2007). Mediated modeling in science education. *Science & Education 16*(7-8), 653–697. DOI: 10.1007/s11191-006-9004-3.

Harrison, A. G., Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education 80*(5), 509–534. DOI: 10.1002/(SICI)1098-237X(199609)80:5<509::AID-SCE2>3.0.CO;2-F.

Henriksen, D. (2014). Full STEAM ahead: creativity in excellent STEM teaching practices. *The STEAM Journal 1*(2), 1–9. DOI: 10.5642/steam.20140102.15.

Henze, I., Van Driel, J. H. (2011). Science teachers' knowledge about learning and teaching models and modeling in public understanding of science. In: *Models and modeling: cognitive tool for scientific inquiry* (239–261). Dordrecht: Springer.

Holm-Hadulla, R. M. (2010). *Kreativität: Konzept und Lebensstil*. Göttingen: Vandenhoeck & Ruprecht.

Justi, R., Gilbert, J. K. (2003). Teachers' views on the nature of models. *International Journal of Science Education 25*(11), 1369–1386. DOI: 10.1080/0950069032000070324.

Kirschner, P. A., Sweller, J., Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist 41*(2), 75–86. DOI: 10.1207/s15326985ep4102_1.

Kline, P. (2000). *The handbook of psychological testing.* London: Routledge.

KMK (2005). *Beschlüsse der Kultusministerkonferenz - Bildungsstandards im Fach Biologie für den Mittleren Bildungsabschluss*. München: Luchterhand.

Krajcik, J., Merritt, J. (2012). Engaging students in scientific practices: what does constructing and revising models look like in the science classroom? *The Science Teacher 79*(3), 38–41.

Krell, M., Upmeier zu Belzen, A., Krüger, D. (2012). Students' understanding of the purpose of models in different biological contexts. *International Journal of Biology Education 2*(2), 1–34.

Landis, R. J., Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics 33*(1), 159-174. DOI: 10.2307/2529310.

Langheinrich, J. (2015). *eLearning-gestützter Unterricht am außerschulischen Lernort Labor. Schülervorstellungen und kognitives Lernen.* Dissertation an der Universität Bayreuth.

Langheinrich, J., Bogner, F. X. (2015). Student conceptions about the DNA structure within a hierarchical organizational level: Improvement by experiment- and computer-based outreach learning. *Biochemistry and Molecular Biology Education 43*(6), 393–402. DOI: 10.1002/bmb.20888.

Langheinrich, J., Bogner, F. X. (2016). Computer-related self-concept: The impact on cognitive achievement. *Studies in Educational Evaluation 50*, 46–52. DOI: 10.1016/j.stueduc.2016.06.003.

Lewis, J., Kattmann, U. (2004). Traits, genes, particles and information: re-visiting students' understandings of genetics. *International Journal of Science Education 26(*2), 195–206. DOI: 10.1080/0950069032000072782.

Lewis, J., Wood-Robinson, C. (2000). Genes, chromosomes, cell division and inheritance - do students see any relationship? *International Journal of Science Education 22*(2), 177–195. DOI: 10.1080/095006900289949.

Louca, L. T., Zacharia, Z. C. (2012). Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. *Educational Review 64*(4), 471–492. DOI: 10.1080/00131911.2011.628748.

Lyons, T. (2006). Different countries, same science classes: students' experiences of school science in their own words. *International Journal of Science Education 28*(6), 591–613. DOI: 10.1080/09500690500339621.

Maia, P. F., Justi, R. (2009). Learning of chemical equilibrium through modelling-based teaching. *International Journal of Science Education 31*(5), 603–630. DOI: 10.1080/ 09500690802538045.

Malacinski, G. M. (1996). Manipulating the "Invisible": learning molecular biology using inexpensive models. *The American Biology Teacher 58*(7), 428–432. DOI: 10.2307/ 4450197.

Marbach-Ad, G., Stavy, R. (2000). Students' cellular and molecular explanations of genetic phenomena. *Journal of Biological Education 34*(4), 200–205. DOI: 10.1080/00219266. 2000.9655718.

Matynia, A., Kushner, S. A., Silva, A. J. (2002). Genetic approaches to molecular and cellular cognition: a focus on LTP and learning and memory. *Annual Review of Genetics 36*(1), 687–720. DOI: 10.1146/annurev.genet.36.062802.091007.

Mayring, P. (2015). *Qualitative Inhaltsanalyse: Grundlagen und Techniken*. Weinheim: Beltz.

Meissner, B., Bogner, F. X. (2011). Enriching students' education using interactive workstations at a salt mine turned science center. *Journal of Chemical Education 88*(4), 510–515. DOI: 10.1021/ed1006103.

NGSS Lead States (2013). *Next generation science standards: for states, by states.* Washington DC: The National Academies Press.

Oh, P. S., Oh, S. J. (2011). What teachers of science need to know about models: An overview. *International Journal of Science Education 33*(8), 1109–1130. DOI: 10.1080/09500693. 2010.502191.

Osborne, J., Collins, S. (2001). Pupils' views of the role and value of the science curriculum: A focus-group study. *International Journal of Science Education 23*(5), 441–467. DOI: 10.1080/09500690010006518.

Paas, F. G. W. C., Tuovinen, J. E., Tabbers, H., van Gerven, P. W. M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist 38*(1), 63–71. DOI: 10.1207/S15326985EP3801_8.

Paas, F. G. W. C., van Merriënboer, J. J. G. (1993). The efficiency of instructional conditions: An approach to combine mental effort and performance measures. *Human Factors 35*(4), 737–743. DOI: 10.1177/001872089303500412.

Plomin, R., Walker, S. O. (2003). Genetics and educational psychology. *British Journal of Educational Psychology 73*(1), 3–14. DOI: 10.1348/000709903762869888.

Plomin, R., Kovas, Y., & Haworth, C. M. (2007). Generalist genes: Genetic links between brain, mind, and education. *Mind, Brain, and Education*, *1*(1), 11-19. DOI: 10.1111/j.1751-228X.2007.00002.x

.Plucker, J. A., Shelton, A. L. (2015). General Intelligence (g): overview of a complex construct and its implications for genetics research. *The Hastings Center report 45*(1), 21-24. DOI: 10.1002/hast.494.

Polderman, T. J. C., Benyamin, B., Leeuw, C. A. de, Sullivan, P. F., van Bochoven, A., Visscher, P. M., Posthuma, D. (2015). Meta-analysis of the heritability of human traits based on fifty years of twin studies. *Nature Genetics 47*(7), 1-11. DOI: 10.1038/ng.3285.

Randler, C., Bogner, F. X. (2006). Cognitive achievements in identification skills. *Journal of Biological Education 40*(4), 161–165. DOI: 10.1080/00219266.2006.9656038.

Rennie, L. J., Goodrum, D., Hackling, M. (2001). Science teaching and learning in australian schools: results of a national study. *Research in Science Education 31*(4), 455–498. DOI: 10.1023/A:1013171905815.

Rost, J. (2004). *Lehrbuch Testtheorie – Testkonstruktion*. Bern: Verlag Hans Huber.

Rotbain, Y., Marbach-Ad, G., Stavy, R. (2006). Effect of bead and illustrations models on high school students' achievement in molecular genetics. *Journal of Research in Science Teaching 43*(5), 500–529. DOI: 10.1002/tea.20144.

Roubertoux, P. L., Baril, N., Cau, P., Scajola, C., Ghata, A., Bartoli, C., Bourgeois, P., Di Christofaro, J., Tordjman, S., Carlier, M. (2017). Differential Brain, cognitive and motor profiles associated with partial trisomy. Modeling down syndrome in mice. *Behavior genetics 47*(3), 305-322. DOI: 10.1007/s10519-017-9845-3.

Runco, M. A., Acar, S., Cayirdag, N. (2017). A closer look at the creativity gap and why students are less creative at school than outside of school. *Thinking Skills and Creativity 24*, 242–249. DOI: 10.1016/j.tsc.2017.04.003.

Scharfenberg, F.-J., Bogner, F. X. (2011). A new two-step approach for hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene technology lab. *Research in Science Education 41*(4), 505–523. DOI: 10.1007/s11165-010-9177-2.

Scharfenberg, F.-J., Bogner, F. X. (2013). Teaching gene technology in an outreach lab: students' assigned cognitive load clusters and the clusters' relationships to learner characteristics, laboratory variables, and cognitive achievement. *Research in Science Education 43*(1), 141–161. DOI: 10.1007/s11165-011-9251-4.

Scharfenberg, F.-J., Bogner, F. X., Klautke, S. (2007). Learning in a gene technology laboratory with educational focus: Results of a teaching unit with authentic experiments. *Biochemistry and Molecular Biology Education 35*(1), 28–39. DOI: 10.1002/bmb.1.

Shin, J.-E., Jung, H.-C., Choe, S.-U., & Han, K.-S. (2002). Are boys more creative than girls? Based on the scientific creativity of gifted students. *Journal of the Korean earth science society 23*(4), 324–333.

Sins, P. H., Savelsbergh, E. R., van Joolingen, W. R., van Hout-Wolters, B. H. (2009). The Relation between Students' Epistemological Understanding of Computer Models and their Cognitive Processing on a Modelling Task. *International Journal of Science Education 31*(9), 1205–1229. DOI: 10.1080/09500690802192181.

Staatsinstitut für Schulqualität und Bildungsforschung (ISB) (2007). *Lehrplan für das Gymnasium in Bayern (G8)*. Wolnzach: Kastner.

Stull, Andrew T.; Hegarty, Mary (2016). Model manipulation and learning: Fostering representational competence with virtual and concrete models. *Journal of Educational Psychology 108*(4), 509–527. DOI: 10.1037/edu0000077.

Stull, A. T., Gainer, M. J., Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction 55*, 80–92. DOI: 10.1016/j.learninstruc. 2017.09.008.

Svoboda, J., Passmore, C. (2013). The strategies of modeling in biology education. *Science & Education 22*(1), 119–142. DOI: 10.1007/s11191-011-9425-5.

Sweller, J., Ayres, P., Kalyuga, S. (2011). *Cognitive Load Theory*. New York: Springer.

Templin, M. A., Fetters, M. K. (2002). A working model of protein synthesis using lego TM building blocks. *The American Biology Teacher 64*(9), 673–678. DOI: 10.1662/0002-7685(2002)064[0673:AWMOPS]2.0.CO;2.

Treagust, D. F., Chittleborough, G. D., Mamiala, T. L. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education 24*(4), 357–368. DOI: 10.1080/09500690110066485.

Ülger, K., & Morsünbül, Ü. (2016). The differences in creative thinking: The comparison of male and female students. *The Online Journal of Counseling and Education 5*(4), 1–12.

Upmeier zu Belzen, A. (2013). Modelle. In: *Fachdidaktik Biologie* (325–334). Freising: Aulis Verlag.

Upmeier zu Belzen, A., Krüger, D. (2010). Modellkompetenz im Biologieunterricht. *Zeitschrift für Didaktik der Naturwissenschaften 16*, 41–57.

van Driel, Verloop, N. (1999). Teachers' knowledge of models and modelling in science. In: *International Journal of Science Education 21*(11), 1141–1153. DOI: 10.1080/09500 6999290110.

van Gog, T., Paas, F. G. W. C. (2008). Instructional efficiency: Revisiting the original construct in educational research. *Educational Psychologist 43*(1), 16–26. DOI: 10.1080/0046 1520701756248.

van Merriënboer, J. J. G., Ayers, P. (2005). Research on cognitive load theory and its design implications for e-learning. *Educational Technology Research and Development 53*(3), 5–13. DOI: 10.1007/BF02504793.

Watson, J. D. (1968). *The double helix. A personal account of the discovery of the structure of DNA.* London: Penguin Books.

Watson, J. D., Crick, F. H. C. (1953). Molecular structure of nucleic acids. A structure for deoxyribose Nucleic Acid. *Nature 171*(0), 737–738. DOI: 10.1101/SQB.1953.018.01. 020.

Windschitl, M., Thompson, J., Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education 92*(5), 941–967. DOI: 10.1002/sce.20259.

5 TEILARBEITEN

5.1 Publikationsliste

(A) Mierdel, J., Bogner, F. X. (2020)
Simply inGEN(E)ious!
How creative DNA-modeling can enrich classic hands-on experimentation
Journal of Microbiology and Biology Education
https://doi.org/10.1128/jmbe.v21i1.1923

(B) Mierdel, J., Bogner, F. X. (2019)
Is creativity, hands-on modeling and cognitive learning gender-dependent?
Thinking Skills and Creativity
https://doi.org/10.1016/j.tsc.2018.11.001

(C) Mierdel, J., Bogner, F. X. (2019)
Investigations of modellers and model viewers in an out-of-school gene technology laboratory
Research in Science Education
https://doi.org/10.1007/s11165-019-09871-3

(D) Mierdel, J., Bogner, F. X. (2019)
Comparing the use of two different model approaches on students' understanding of DNA Models
Education Sciences
https://doi.org/10.3390/educsci9020115

5.2 Darstellung des Eigenanteils

Das Unterrichtsmodul in Teilstudie A wurde von mir eigenständig entwickelt und zusammengestellt. Die Ideen zu den verwendeten Arbeitsmaterialien (Experimente, Versuchsanleitungen, Informationstexte, Arbeitsaufträge) wurden teilweise aus Quellen entnommen und von mir adressatengerecht adaptiert oder selbstständig entworfen und angefertigt. Der Unterricht bildete die Basis für eine Interventionsstudie im Demonstrationslabor Bio-/Gentechnik der Universität Bayreuth.

Die Erhebung aller empirischen Daten, die Entwicklung der Fragestellungen, die statistischen Analysen sowie die Interpretation der Ergebnisse erfolgte durch mich.

Die in den Teilarbeiten B bis D verwendeten Skalen wurden der Literatur entnommen und in einigen Fällen gemäß den Fragestellungen adaptiert. Der Fragenkatalog zur Erfassung des Schülerwissens wurde ebenfalls in Teilen der Literatur entnommen, von mir mit den Inhalten und Anforderungen des Unterrichtsmoduls abgestimmt und ergänzt (Teilstudie B und C). Für die Evaluation der Modellqualität (Teilstudie B) wurde ebenfalls auf ein bestehendes Kategoriensystem aus der Literatur zurückgegriffen und dieses von mir an die Fragestellung angepasst. Das Kategoriensystem zur qualitativen Auswertung des Modellverständnisses (Teilstudie D) wurde induktiv von mir selbst erstellt.

Alle Teilarbeiten wurden von mir als Erstautorin eigenständig konzipiert, verfasst und in Zusammenarbeit mit meinem Mitautor Herrn Prof. Dr. Franz X. Bogner überarbeitet.

5.3 Teilarbeit A

Journal of Microbiology and Biology Education

Vol. 21(2), pp. 1-10, 2020

First published online Mai 2020. https://doi.org/10.1128/jmbe.v21i1.1923

Simply inGEN(E)ious! How creative DNA-modeling can enrich classic hands-on experimentation

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Simply inGEN(E)ious! How creative DNA-modeling can enrich classic hands-on experimentation

Abstract

Innovative 21st-century methods for teaching biology should provide both content knowledge and diverse scientific competencies. The Curriculum Guidelines of the American Society for Microbiology highlight the importance of developing scientific thinking skills, which include the abilities to formulate hypotheses, to communicate fundamental concepts effectively, and to analyze and interpret experimental results. Additionally, contemporary science education should enhance creativity and collaboration as key student assets in its bid to overcome negative perceptions and learning difficulties. In recent years, the expanding movement for so-called “STEAM” approaches (science, technology, engineering, arts, and math) has increased in STEM curricula. The movement seeks to integrate the arts into science classes to transfer enthusiasm, support individual self-sufficiency, and encourage creative solutions. To meet all these demands, we developed an inquiry-based approach that actively engages students in hands- and minds-on activities on the topic of “decoding the DNA structure” in an outreach laboratory. Since teaching abstract molecular phenomena is a challenge in biology classes, we combine classical experimental tasks (DNA isolation, gel electrophoresis) with creative modeling. The experiments are linked by the modeling phase: immersed in the story of the discovery of the DNA structure, our participants independently construct a DNA model from a box filled with inexpensive craft supplies (e.g., glue, straws, pipe cleaners, beads). After initial pilot testing, the implementation of our approach clearly produced short- and mid-term learning effects among the students, providing a successful example of a STEAM-based approach in a laboratory setting.

Keywords

genetics, DNA, models and modeling, creativity, outreach learning, hands-on learning, laboratory exercise

Introduction

The transmission of genetic information from DNA to gene actions within an organism, within families, and within populations of organisms over many generations is a frequent subject of classroom lessons. The broad and dynamic field of genetics can even be considered a form of information science, in which discoveries are continually advancing our understanding of many other life sciences as well (1).

The discovery of DNA structure in 1953 was an important milestone for molecular genetics, as two young researchers, James Watson and Francis Crick, won the race against other groups in successfully decoding DNA's double helix (2). Without completing their own experiments, they managed to correctly interpret the complex X-ray crystallography work pioneered by Rosalind Franklin and Maurice Wilkins (3). After discussion and mental modeling based on Watson and Crick's suspicions regarding a helical DNA structure, they built a physical DNA model. Built from simple shining metal plates to weld together the atoms, the scientists conceived a model which connected the X-ray data with the laws of stereochemistry (4). The groundbreaking work of Watson, Crick, and Wilkins was honored by the awarding of the Nobel Prize in Physiology or Medicine in 1962.

The importance of the topic for fundamental knowledge acquisition in genetics and biology in general is indisputable. However, a common problem seems to be transmitting a proper understanding of the three genetics concepts - DNA, gene, and chromosome - in the classroom (5). As visual presentation is assumed to be essential in this setting, model-based learning may provide a bridge between abstract scientific theory and real-world experience, especially when direct observation is difficult (6, 7). A key factor for successful model construction is individual creativity, incorporating a process of sensitization and development of innovative solutions (8). It is further expected that cultivating creativity in science as an auxiliary skill might help the development of individual self-efficacy and foster greater motivation in science education (9).

We designed a student-centered laboratory activity that combines creative modeling with experimental work, offering an innovative way to link abstract scientific theory and practical experiences. Our hands-on approach provides scaffolds that actively involve students and support them to independently conduct experiments, create a protocol using their observations, and build a DNA model. The recently published research used to accompany our approach confirms that students demonstrate significant short-term (directly after participation) and mid-term (6 weeks after participation) gains in knowledge compared with a test–retest group. Correlating the quality of the models built to the cognitive achievement and creativity of the tested students, we found that female students in particular tend to benefit from this new artistically inspired laboratory activity (10).

Intended audience

The laboratory activities outlined in this paper are intended for high school students (ninth graders) in biology in the context of genetics. The hands-on modeling phase itself may be extended or modified for use in higher grades in molecular biology with the addition of focused material regarding molecular interactions.

Learning time

Our inquiry-based laboratory module requires 4.5 hours consisting of five phases (maximum of 60 min each). The time required for the individual learning activities is shown in Figure 1. The DNA modeling can also be done independently within a classroom session.

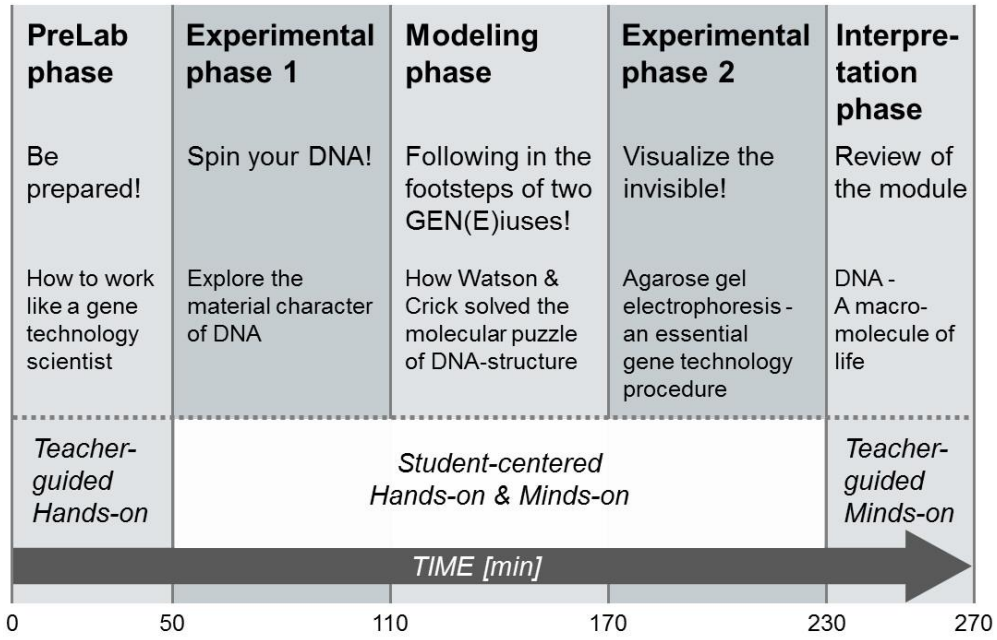

Figure 1. Schedule and learning activities of the laboratory module "Simply inGEN(E)ious! DNA as a carrier of genetic information".

Prerequisite student knowledge

The activities presented here are suitable for beginners in genetics. Nonetheless, some general skills from science classes are helpful in managing content and practical tasks. For the experiments, students should be capable of using basic laboratory materials (e.g., pipettes, beakers, test tubes). Furthermore, students should be able to make experimental observations appropriately and to derive substantiated interpretations from experimental observations. The workbook supplied (Appendix 2) provides them with templates according to the standard formatting of a scientific report. Successful DNA modeling can benefit from previous student experiences in developing scientific models, e.g.,

students have been introduced and guided by the teacher in other molecular contexts (model of a cell or a protein, etc.). Additionally, basic craft skills could be helpful for an appealing implementation of students' ideas.

Learning objectives

Upon completion of this activity, students should be able to:

1. Perform and describe selected gene technology laboratory techniques, as well as understand their purpose (e.g., micropipetting, agarose gel electrophoresis)
2. Name, describe, and explain selected aspects of DNA structure (e.g., possible base pairings, components of the DNA backbone, electrophoretic separation of DNA molecules based on phosphate [5])
3. Engage actively in class sessions by collaborating with classmates to elaborate, draw, evaluate, and/ or critique models of their creative work and identify, describe, and reorganize key elements of DNA structure during modeling (e.g., cohesion of the two DNA strands by hydrogen bonds, spatial structure of DNA as a right-handed double-helix)
4. Evaluate the importance of creativity in the scientific process using the example of the discovery of the DNA structure
5. Be familiar with the safe handling of human samples at biosafety level 2 (BSL2) using Biosafety in Microbiological and Biomedical Laboratories (BMBL) safety guidelines

The content-oriented learning objectives can be assessed with the cognitive knowledge questionnaire

(laboratory activities and learning content of the model phase; Appendix 1), and the models can be evaluated by a category system to assess the model quality with regard to key elements of DNA structure (10). In order to evaluate students' ideas on the importance of creativity in the scientific process, students can write short reflections after completing the activity. For assessment of the BMBL safety guidelines, the teacher should check orally that the students have understood them, before performing the experiments.

Procedure

Materials

The materials needed for the experiments (outlined in Appendix 2) are to be provided on the laboratory benches, and DNA modeling kits are to be distributed to the participants after the first experiment (Fig. 2). A separate gel station with two electrophoresis chambers sufficient for a maximum

of eight DNA samples is recommended (e.g., ThermoScientific Owl EasyCast B1A mini gel electrophoresis systems). Larger laboratory devices (centrifuge, water bath) can be used by several groups of students. We developed and implemented the activity with two students per group. In small classes it would be possible for students to work on their own.

Figure 2. Example of a DNA-modeling box with various inexpensive craft supplies.

Notes for instructor preparation

The preparation of this learning activity takes about 2 hours. It is advisable to set up the laboratory benches beforehand with the necessary equipment. Table 1 gives details of the materials required for the experiments. Other general equipment used by the entire class during this activity is summarized in Table 2. Table 3 shows the preparation and quantities of the required reagents and chemicals and gives information about recipes and storage conditions where necessary.

Table 1. Preparation for students' laboratory benches (each bench is prepared for 4 students, or 2 pairs).

Quantity	(Shared) Equipment and Source
2	Signs with group number
1	Discard/waste jar (lettered)
3	Boxes with rubber gloves (size S, M, L)
1	Stack of paper towels
1	Plastic tub for devices to be rinsed after laboratory activities
4	Waterproof pens
4	Pens
2	(Digital) chronometers (e.g., Fisher brand)
2	Student workbooks (Appendix 2)
2	DNA-modeling boxes (see Fig. 2)
2	One-way drinking cups (foodsafe)

1	Water bottle (foodsafe) with distilled water
2	Small beakers with color solution (e.g., water with blue food coloring or ink) and empty white Eppendorf tube
4	Plastic Pasteur pipettes (3 ml; sterile sealed)
2	Pipette pumps (e.g., Karter Scientific Labware Manufacturing)
2	Snap-cap vials (20 ml; clean and dry) (e.g., Resch Glas)
2	Tweezers (clean and dry)
2	Black placemats (e.g., laminated color paper)
1	Centrifuge
1	Linear pipettor stand with 6 micropipettes (2 x by 1000 µl, 2 x by 200 µl, 2 x 20 µl) (e.g., Eppendorf)
2	Racks with pipette tips in two sizes (sterilized; e.g., blue and yellow)
1	Rack filled with Eppendorf tubes (all sterilized; filled with adequate reagents: 2 white, 2 green, 2 blue, 2 red; and 6 closed, empty Eppendorf tubes marked with "1, 2, 3" for each group) (see Table 3 for filling)
1	Styrofoam box with ice cubes (ice bath) for storing the isopropyl alcohol snap-cap vial (P) and 2 Eppendorf tubes with isopropyl alcohol (yellow)

Table 2. General preparation in the laboratory for one class in the required order.

Quantity	Shared Equipment for One Class (up to 30 Students)
2	Standard water baths filled with distilled water (50°C)
15	Chilled, graduated pipettes (volume min. 10 ml; stored in the freezer until students need them)
1	Magnetic board (for the instruction poster "Gel electrophoresis" with removable magnet applications
2	Standard heating plates
1	Scales
2	Heat-resistant gloves
1	Roll of aluminum foil
2	Erlenmeyer flasks to prepare the agarose gel
2	Electrophoresis chambers with gel combs
1	Power supply for electrophoresis with 4 suitable power cables
1	Erlenmeyer flask with TBE electrophoresis buffer solution (1 L, to flood both electrophoresis chambers)

Table 3. Preparation and quantities of reagents and chemicals for the experiments.

Reagents and Chemicals (with recipes and storage conditions if necessary)	Unit Quantity (per student pair)	Total Quantity Per Class (for 15 student pairs)
Water with blue food coloring or ink	3 ml	45 ml
Lysis buffer (Recipe: • 27 ml H_2O • 3 ml dish soap or detergent • 0.9 g NaCl Mix ingredients by stirring and store at room temperature.	2 ml	30 ml
Standard mild detergent (e.g., Woolite Gentle Cycle Liquid Laundry Detergent) (purchased)	Five drops with the Pasteur pipette	10 ml
Isopropyl alcohol (2-propanol; Bio Reagent for molecular biology, > 99.5%); for better experimental results store in the fridge and for DNA sample processing (store in yellow Eppendorf tubes on ice)	5 ml 100 µl	75 ml 1500 µl
Certified™ Molecular Biology Agarose	350 g	700 g (two groups prepare this for the entire class)
Electrophoresis buffer (TBE: Tris-Borate-EDTA buffer; BioReagent, suitable for electrophoresis; 1% concentrate) (e.g., Sigma-Aldrich) and for DNA-Sample processing (store in blue Eppendorf tubes)	50 ml (for agarose suspension) + 450 ml (for flooding the electrophoresis chambers) 150 µl	1 L (for two agarose gel preparations) 3000 µl
SYBR® Green I (Nucleic acid gel stain; 10 000 x in DMSO; store in freezer and let thaw just before boiling agarose solution; wear rubber gloves) (Sigma-Aldrich)	5 µl	10 µl (for two agarose gel preparations)
5x Nucleic acid sample loading buffer for DNA-sample processing (store in red Eppendorf tubes)	5 µl	75 µl
DNA size standard (Recipe: • 2 µL EZ Load™ 1 kB Molecular Ruler (80 mg/ml) • 2 µL 5x Nucleic acid sample loading buffer • 6 µL H_2O (PCR Reagent) Mix solution by pipetting up and down and then centrifuge the solution shortly (14.5 rpm)	10 µl	40 µl (in the two outer wells per each agarose plate)

Student instructions and sample models

A workbook (Appendix 2) allows students to work independently throughout the hands-on activities, with information, instructions for the experiment, and upcoming challenges. In order to foster comprehension of the individual steps and the roles of the applied chemicals, participants should answer the relevant questions in the workbook during the experimentation. Based on the students' initial hypotheses that DNA seems invisible to the naked eye after a short introduction by the teacher about a real crime case, they isolate DNA threads from oral mucosal membrane cells in the first classic experiment, a process leading to the rejection of their earlier assumption. The second experiment demonstrates the molecular character of the DNA structure during gel electrophoresis.

The creative modeling phase is the key activity of our module. It connects the two experiments and provides the theoretical basis for further understanding of the experimental findings. According to the students' level of understanding, they follow the footsteps of Watson and Crick in solving the molecular puzzle of DNA structure. In preparation, our participants read an abridged version of the original letter Francis Crick wrote to his 12-year-old son in 1953 (Appendix 3). After reading, students are to answer comprehension questions in the workbook. In the process of formulating their answers, they internalize essential background information as they mentally begin their model building. DNA modeling kits containing a variety of craft materials (e.g., glue, scissors, straws, pipe cleaners, beads, cardboard, and markers) to help them construct a physical model. To foster problem-solving as well as communication skills, students work collaboratively. To consider the scope and limitations of their models, students have to compare their models' elements with the previously answered comprehension questions by making a labeled sketch. Finally, they compare their work with an unlabeled commercially available school model of the DNA structure and evaluate similarities and differences (Appendix 4). Impressions of the modeling phase are shown in Figure 3.

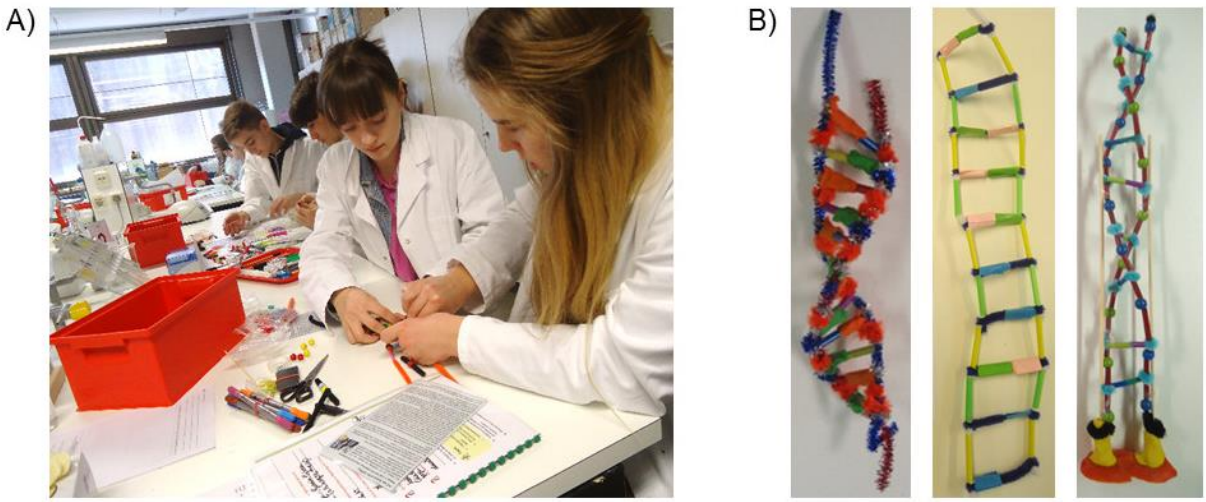

Figure 3. Impressions of the modeling phase: A) Students working on their models. B) Examples of constructed DNA models.

Faculty instructions

In this activity, short teacher-guided instructions connect the student-centered experimental subunits with the hands-on DNA modeling. The teacher supervises from the background, provides guidance during the hands-on components, and answers students' questions on request.

The first experimental phase can be introduced with the report of a hypothetical crime. In this context the teacher emphasizes the organization levels of genetic material (cell, chromosome, DNA, gene) and explains important experimental steps for the isolation of DNA from oral mucosal cells. After the teacher has given a brief historical summary of pioneering discoveries around DNA (e.g., *Proving That DNA Is the Substance That Contains the Genetic Information*, by Oswald T. Avery, in 1944), the participants read a text on the history of DNA research, following which they begin working on their models. After the students complete their model work, the teacher presents a poster with step-by-step information on the workings of gel electrophoresis. Different sections on the poster give short summaries on important theoretical background information, as well as practical instructions to successfully conduct the second experiment (Appendix 5). Leading questions are discussed with the students to emphasize the most relevant steps. During the interpretation phase, the teacher presents the experimental results of the gel electrophoresis to the class using a slide or poster as the findings, and possible sources of error are analyzed and discussed (e.g., *Describe and compare the experimental results for the different DNA samples; Specify possible sources of error that led to deviations in the experimental results*). The results can then be compared with the conclusions drawn from the first experiment, as well as with the finished models. Finally, the teacher gives a conclusive summary on DNA, presented as a macromolecule of life encoding the genetic information of all species.

Suggestions for determining student learning

Formative assessment during the lab day includes teacher-guided in-class discussions, a review of the completed workbooks (Appendix 2; for suggested solutions see Appendix 4), and monitoring by the teacher during the lab work. For the self-evaluation of the DNA models, a comparison of students' models with an adequate commercial school model is recommended (see Appendix 4, p. 9). The pupils can recognize important features of the DNA structure on the picture and quickly check them on their own models (e.g., cohesion of the two DNA strands by hydrogen bonds, possible base pairings). For a more precise and detailed evaluation of cognitive achievement during laboratory and modeling, we provide a questionnaire to test the knowledge of the participants (Appendix 1), as well as a category system the teacher can use to assess the model quality once the learning activity is completed (10). The category system for evaluating the DNA models includes five analysis sectors (e.g., Bases, Primary structure) and grades the resulting models regarding the concrete representations and structural characteristics using sum scores (e.g., analysis sector BA1: 1 point for "symbolized bases" or 2 points for "symbolized and qualified bases"; max. 19 points).

Safety issues

The activity does involve human saliva that should be handled at BSL2 according to the BMBL guidelines given by the CDC (Centers for Disease Control and Prevention) (11). The lab day starts with mandatory safety instruction in which students are initially familiarized with the laboratory rules prescribed by the ASM Biosafety Guidelines (12; e.g., wearing safety goggles and gloves is mandatory, food and drinks are not allowed) as well as crucial behaviors in case of an emergency (e.g., the way to the nearest fire escape and the use of the eye wash units). Prior to entering the laboratory, students get lab coats which they are to wear during the experiments. Gloves are placed on the middle of the tables and are to be used during the experiments in order to avoid direct contact with human saliva and contamination of the DNA samples. The saliva samples are bleached with 10% bleach for 24 hours before discarding. Additionally, personal protection when handling SYBR Green as a possible mutagen requires gloves and safety goggles for the teacher.

To prevent learning difficulties and injuries caused by lack of experience with lab work, we orient the students with an introductory pre-laboratory phase (13). In this teacher-centered phase, students are initially familiarized with the laboratory equipment and essential scientific techniques (micropipetting, decanting, and centrifugation) are presented. Students have time to ask questions about the safety instructions, and the laboratory supervisor or assistants check whether students follow them during the lab activities. As micropipetting is one of the most relevant working techniques in gene technology labs, it is a major part of the pre-lab orientation.

Discussion

Field testing

As requested by the Genetics Education Outreach Network (14), many outreach programs have been developed to offer authentic learning experiences and compensate for the limitations of time and resources within classroom settings. Our activity is in line with these programs and was conceived and implemented as field trips for students to the university with the intent of providing hands-on experience with conducting lab experiments. The contents of the lesson were modulated to follow the guidelines set by the Bavarian high school syllabus (15). In our pilot lessons, all interventions were implemented by the same instructor and the same tutor, guiding participants through lab safety, the pre-laboratory phase, all main phases, the lab investigation, and concluding with analysis and assessment. Students always worked in pairs. In gaining experience from such pilot lessons, we were able to optimize the module's elements.

In spring 2017, six classes across five different high schools (Gymnasium) in the German state of Bavaria participated in the pilot lessons. Due to space and material resource limitations in the lab, our classes have ranged in size from 20 to a maximum of 34 students. Data were collected from 114 ninth graders (40.87% female; age 14.45 ± 0.69 years [novices]). To control for the effect of repeated

measurement, a test–retest sample was also taken from a comparator group of high school students in (n = 39; 100.00% female; age 14.69 ± 0.57 years) who completed the knowledge questionnaire without having participated in the module or receiving any instruction on the topic during data collection.

Throughout the lab day, students were actively engaged in the prescribed activities: they trained with hands-on work in the lab, organized and wrote protocols for their experimental investigations, discussed their findings with peers, and thoughtfully answered the given questions. During modeling, we observed that the artistic aspect of working with craft materials positively attracted learners' attention and enhanced motivation. One reason might be that students had no restrictions in presenting information and could act more creatively than in traditional model-supported approaches (16). At the same, time they managed to visualize and connect the theoretical dimensions of the experiment (17), which helped them understand the links between the different taxonomic levels in gene theory.

Evidence of student learning

From an observer perspective, we can report positive feedback from the students; in particular, the practical work in the laboratory, the handling of materials, and the creative modeling tasks were enthusiastically perceived, as evidenced by active participation in class discussions about the experiments and DNA models. To assess the lesson as planned, we used in our recently published study (10) a quasi-experimental design to measure cognitive achievement (Fig. 4), in which we additionally observed the level of individual creativity in post-test evaluations, as well as heeding the quality of the students' models after lab day. Appendix 1 contains the applied multiple-choice knowledge questionnaire.

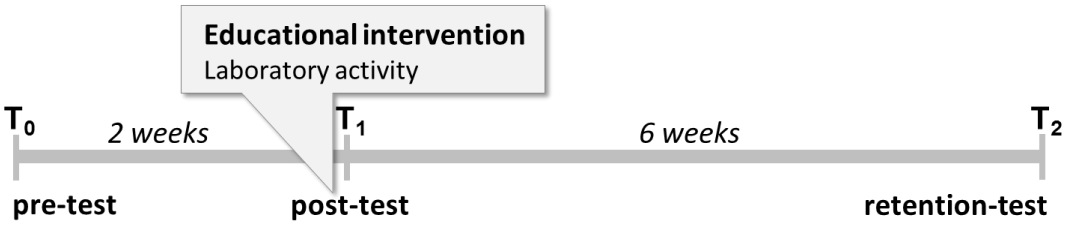

Figure 4. Quasi-experimental design of the study with regard to cognitive achievement.

Selected results of the complete module as well as results on the content of the model phase are presented in Table 4 and show that the modelers achieved significant improvement in their short- and mid-term knowledge of the subject. As modeling and creativity are both seen as key factors for science education, we examined relations between model quality scores, individual knowledge, and creativity. While both genders showed similar levels of creativity (Table 5), there was no general correlation between creativity and the quality of the models. Nonetheless, it is to be noted that relative to the male students, the female students produced better-structured models in general, and correlations between

creativity and model quality are revealed with their cognitive achievement (Spearman's correlation coefficient rs < 0.338 [p < 0.05] > 0.469 [p < 0.01]). For male students, neither creativity nor model quality correlated with their cognitive performance (10). We therefore recommend that the use of model work in biology lessons be increased in order to improve the clarity of content and maintain motivation among the students. Female students, in particular, seem to benefit from our STEAM-inspired activity, which offers a new, creative, and artistic approach in the classroom.

Table 4. Selected results of the assessed cognitive achievement.[a]

Parameter	*Knowledge (Sum Score)*			*Inner-Group Comparison*	
	Pre-Test (T_0)[b]	Post-Test (T_1)[c]	Retention-Test (T_2)[d]	Chi-square (2)	*p*
Mdn $_{test–retest}$ (*n*=39) Complete module (max. 30 points	5.00	4.64	4.38	-	ns[e]
Mdn $_{modelers}$ (*n*=114) Complete module (max. 30 points)	10.30	20.20	16.80	180.013	<0.001
Modeling phase (max. 18 points)	5.72	12.43	10.09	177.837	<0.001

[a] The multiple-choice test (Appendix 1) consisted of 30 items of varying difficulty: 18 covering the contents of the modeling phase and 12 the laboratory activities. Every item offered four response options, only one of which was correct (max. 30 points).
[b]Pre-test (T_0): 2 weeks before.
[c]Post-test (T_1): immediately after.
[d]Retention-test (T_2): 6 weeks after participation.
[e]ns = not significant

Table 5. Selected results of the activity's assessment regarding model quality and creativity (10).

Assessment	*Median Score (n)*		*Between-Group Comparison*		
	Women (47)	Men (67)	*U*	*z*	*p*
Model quality [max. 19 points]	15.58	13.50	1094.00	-2.79	0.005
Creativity subscale "act"	2.32	2.39	1486.50	-.51	[a] ns
Creativity subscale "flow"	2.33	2.21	1450.50	- .72	[a] ns

[a] ns = not significant

Possible modifications

Depending on the amount of time available, we suggest an additional pre-modeling phase to foster the development of modeling skills. Taking the approach introduced in the *Model of Modeling* by Justi and Gilbert (18), such an introductory lesson is aimed at allowing teachers to orient their students in essential lab skills, including data interpretation, consolidation of ideas, and the development of mental modeling. To add a competitive dimension to the lessons, teachers may ask the students to present their DNA models in a small exhibition and/or give out awards for the most accurate models in a classroom competition.

Further modifications for upper-level biology and microbiology courses could integrate additional layers of complexity, extending the lesson to incorporate the molecular and atomic structures of DNA. An example of such a lesson could involve students exploring, comparing, and evaluating their models vis-à-vis an interactive three-dimension molecule viewer (19).

Conclusion

Our gene technology module combines creative modeling with hands-on experimentation to be conducted in a cooperative learning environment. The targeted educational goals, which follow the Next Generation Science Standards (20), would be easy to realize within regular science classes. As our intervention is inquiry-based, students develop and use models to explain their own experimental results and to solve tasks during the lessons. In the course of the lesson, they come into contact with core ideas such as the inheritance of traits. Finally, we also attempted in the course of our lessons to implement the guidelines laid out in the NGSS *Structure and Function*. During modeling and experimentation, the students investigated the structure of DNA from different perspectives and accumulated their findings to extrapolate its functions.

We conclude that the processes of lab experiments benefit from the addition of modeling assignments, and the two complement each other in providing students with paths of learning and comprehension within the complex field of genetics. After participation, the benefits to students' short- and mid-term retained knowledge were evident. The support provided by DNA modeling in the comprehension of fundamental scientific ideas was particularly notable in the case of female students (10).

Supplemental materials

Appendix 1: Evaluation instrument (multiple-choice questionnaire)

Appendix 2: Student workbook

Appendix 3: Info text DNA structure: "Following in the Footsteps of Watson and Crick"

Appendix 4: Suggested solutions for student workbook (teacher version) and DNA model evaluation

Appendix 5: Instruction poster, "Gel electrophoresis" with applications

Acknowledgements

This study was supported by the CREATIONS project funded by the European Union's HORIZON 2020-SEAC- 2014-1 Program (Grant 665917) and by the "Qualitätsoffensive Lehrerbildung" Program funded by the German Federal Ministry of Education and Research (BMBF; Grant: 01JA160). This publication was also funded by the German Research Foundation (DFG) and the University of Bayreuth in the funding program "Open Access Publishing." The authors declare that they have no conflicts of interest. This article reflects only the authors' views; the European Union, the BMBF, and the DFG are not liable for any use that might be made of information contained herein. Special thanks to the teachers and students involved in this study for their cooperation.

References

1. Griffiths, A. J. F., Wessler, S. R., Carroll, S. B., Doebley, J. 2015. *Introduction to genetic analysis* (11th Ed.). New York, Basingstoke, England: Macmillan education.
2. Watson, J. D., Crick, F. H. C. 1953. Molecular structure of nucleic acids: A Structure for Deoxyribose Nucleic Acid. *Nature*, (171), 737–738.
3. Judson, H. F. 1996. *The eighth day of creation: Makers of the revolution in biology* (25th Anniversary Ed.). Plainview, New York: Cold Spring Harbor Laboratory Press.
4. Watson, J.D. 1968. *The double helix.* London: Penguin Books.
5. Langheinrich, J., Bogner, F. X. 2015. Student conceptions about the DNA-structure within a hierarchical organizational level: Improvement by experiment- and computer-based outreach learning. *Biochem Mol Biol Educ, 43*(6), 393–402.
6. Buckley, B. C. 2000. Interactive multimedia and model-based learning in biology. *Int J Sci Educ, 22*(9), 895–935.
7. Rotbain, Y., Marbach-Ad, G., Stavy, R. 2006. Effect of bead and illustrations models on high school students' achievement in molecular genetics. *J Res Sci Teach, 43*(5), 500–529.
8. Chow, B. 2010. The quest for deeper learning. *Education Week,* 6, 1–3.
9. Runco, M. A., Acar, S., Cayirdag, N. 2017. A closer look at the creativity gap and why students are less creative at school than outside of school. *Think Skills Creat, 24*, 242–249.
10. Mierdel, J., Bogner, F. X. 2018a. Is creativity, hands-on modeling and cognitive learning gender-dependent? *31*, 91-102.
11. Centers for Disease Control and Prevention. 2009. Biosafety in microbiological and biomedical laboratories (BMBL). https://www.cdc.gov/labs/pdf/CDC-BiosafetyMicrobiological-BiomedicalLaboratories-2009-P.PDF. Accessed 2 July 2019.
12. American Society for Microbiology. 2012. Guidelines for biosafety in teaching laboratories. https://www.asm.org/ASM/ media/Education/ASM-Biosafety-Guidelines.pdf. Accessed 2 July 2019.
13. Scharfenberg, F.-J., Bogner, F. X. 2011. A new two-step approach for hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene technology lab. *Res Sci Ed, 41*(4), 505–523.
14. American Society of Human Genetics. 2011. *Genetics education outreach network (GEON)*. http://www.ashg.org/education/k12_geon.shtml. Access 07 January 2019.
15. ISB. 2007. *Bavarian Syllabus Gymnasium G8*. Wolnzach, Germany: Kastner.
16. Oh, P. S., Oh, S. J. 2011. What teachers of science need to know about models: An overview. *Int J Sci Educ, 33*(8), 1109–1130.
17. Mierdel, J., Bogner, F. X. 2018b. Investigations of modellers and model viewers in an out-of-school gene technology laboratory – under review.

18. Justi, R. S., Gilbert, J. K. 2002. Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *Int J Sci Educ*, *24*(4), 369–387.
19. Schmitz, R.-P. 2015. *Chemie Interaktiv*. http://www.chemie-interaktiv.net/jsmol_viewer_3a.htm. Access 07 January 2019.
20. NGSS Lead States. 2013. *Next Generation Science Standards: For States, By States.* Washington, DC: The National Academies Press.

Supplemental materials

Simply inGEN(E)ious! How creative DNA-modeling can enrich classic hands-on experimentation

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Appendix 1: Evaluation instrument (multiple-choice questionnaire)

Cognitive knowledge questionnaire (adapted and extended from Langheinrich & Bogner, 2016). Questions were split up into subcategories evaluating the modeling phase (M) or the laboratory activities (L).

Note. Correct answers are written in *italics.*

L1	**In an electric field positive charged particles migrate …**
☐	back and forth between both poles.
☐	to the positive pole.
☐	*to the negative pole.*
☐	not at all.

M2	**Which of the following components is <u>not</u> included in the DNA?**
☐	adenine
☐	*ribose*
☐	guanine
☐	deoxyribose

L3	**Which option is wrong? The migration rate of electrically charged molecules depends on …**
☐	the applied voltage.
☐	*the density of the sample.*
☐	the density of the agarose gel.
☐	the size of the molecules.

M4	**In 1962, James Watson and Francis Crick received the Nobel Prize for Medicine for the Discovery of …**
☐	DNA is located in the nucleus.
☐	components that form the DNA.
☐	gel electrophoresis.
☐	*the double helix structure of the DNA.*

M5	**Which option is wrong? The DNA of human is…**
☐	carrier of genetic information.
☐	a long chain molecule.
☐	*built of amino acids.*
☐	a super molecule.

L6	**With the aid of gel electrophoresis, you get information about …**
☐	*the molecular mass.*
☐	the number of bindings of a molecule.
☐	the components of a molecule.
☐	the atoms of a molecule.

M7	**Which base pairing is correct?**
☐	*Guanine pairs with cytosine.*
☐	Thymine pairs with cytosine.
☐	Adenine pairs with guanine.
☐	Cytosine pairs with adenine.

L8	**To add 20 µl to your sample, you use …**
☐	a Pasteur pipette.
☐	a graduated pipette.
☐	*a micropipette.*
☐	a measuring cylinder.

L9	**With the help of a centrifuge …**
☐	you can mix a sample.
☐	the molecules are set into motion.
☐	single molecules can be isolated.
☐	*solid substances can be separated from liquids.*

M10	**If you speak of 'the DNA backbone', you mean …**
☐	the annular structure of the DNA.
☐	the fatty acids bound to protect the DNA.
☐	the DNA-base pairings.
☐	*the alternating phosphate-sugar-chain as part of the DNA.*

M11	**The DNA bases are located …**
☐	*at the interior of the DNA molecule and are linked with sugar.*
☐	at the exterior of the DNA molecule and are linked with sugar.
☐	at the exterior of the DNA molecule and are linked with phosphate.
☐	at the interior of the DNA molecule and are linked with phosphate.

M12	**Matching DNA strands are …**
☐	shifted arranged.
☐	identical.
☐	independent of each other.
☐	*antiparallel.*

L13	**The electrophoretic separation of DNA-molecules is based on the DNA-component …**
☐	thymine
☐	*phosphate*
☐	sugar
☐	cytosine

L14	**Which option is wrong? In cold alcohol the DNA is …**
☐	insoluble.
☐	a filamentous structure.
☐	a white solid.
☐	*soluble.*

M15	**The molecular structure of DNA can best be compared with …**
☐	a cardboard tube.
☐	*a twisted rope ladder.*
☐	railway tracks.
☐	a twine.

L16	**A DNA size standard helps to …**
☐	*estimate the length of DNA fragments*
☐	extend DNA sequences.
☐	repair DNA fragments.
☐	stain DNA strands.

M17	**The abbreviation 'DNA' stands for …**
☐	Deoxynucleic acid.
☐	Oxyribonucleic acid.
☐	*Deoxyribonucleic acid.*
☐	Dideoxyribonucleic acid.

M18	**How many different repeating DNA-components exist?**
☐	2
☐	4
☐	*6*
☐	8

M19	**Give the opposite bases to the base sequence: AATGGG** *(Capital letters = initial letter of the base, e.g. 'A' for adenine)*
☐	TTGCCC
☐	*TTACCC*
☐	TTGAAA
☐	GGACCC

M20	**The cohesion of the two DNA-strands is based on the formation of …**
☐	atomic bonds.
☐	*hydrogen bonds.*
☐	disulfide bridges.
☐	ionic interactions.

L21	**The total length of human DNA per cell is about …**
☐	200 meters.
☐	*2 meters.*
☐	20 meters.
☐	2 centimeters.

M22	**The genetic information is encoded in the DNA by …**
☐	*the sequence of the single bases.*
☐	the formation of different chromosomes.
☐	the fusion of egg and sperm cells during fertilization.
☐	the turn of the DNA strand.

M23	**A section of DNA that provides the basic information for building a particular characteristic is called …**
☐	plasmid.
☐	genome.
☐	chromosome.
☐	*gene.*

L24	**The DNA is the carrier of genetic information …**
☐	*in all organisms.*
☐	in apes.
☐	in all organisms except bacteria.
☐	in vertebrates.

L25	**In which cell organelle is the DNA located?**
☐	in the ribosome
☐	*in the nucleus*
☐	in the cytoplasm
☐	in the vacuole

M26	**The analysis of a DNA-section revealed a proportion of guanine with 30 %. Following, the proportion of adenine is …**
☐	is not determinable.
☐	also 30%.
☐	70%.
☐	*20%*.

M27	**The proportion of sugar to phosphate in the DNA-molecule is …**
☐	2:1
☐	3:1
☐	*1:1*
☐	1:2

M28	**The DNA consist of the following chemical elements:**
☐	hydrogen, sulfur, phosphorus, carbon and nitrogen
☐	hydrogen, oxygen, phosphorus, sulfur and nitrogen
☐	*hydrogen, oxygen, phosphorus, carbon and nitrogen*
☐	hydrogen, oxygen, sulfur, carbon and nitrogen

M29	**The spatial structure of DNA …**
☐	is a left-handed double-helix.
☐	*is a right-handed double-helix.*
☐	has no direction of rotation.
☐	is an alternating right- and left-handed double-helix.

L30	**Which option is wrong? Visualizing DNA-molecules in gel electrophoresis is made possible by …**
☐	*the blue-colored loading buffer*.
☐	a molecular dye, that binds on the DNA.
☐	a dye, that glows under UV light.
☐	the addition of dye into the agarose gel.

Appendix 2: Student workbook

A STEAM outreach lab module

SIMPLY INGEN(E)IOUS!

DNA AS A CARRIER OF GENETIC INFORMATION

Workbook

A practical training course for 9th graders

Group No.:

GLOSSARY

of essential working tools

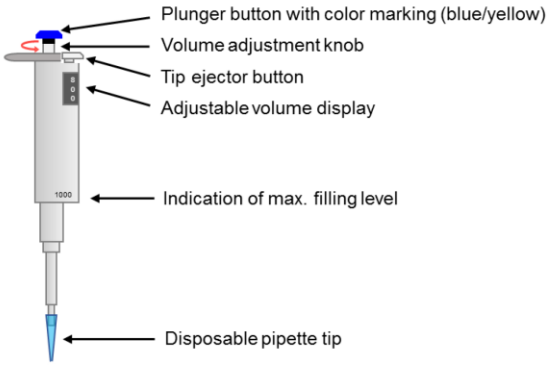
beaker	
centrifuge	
Eppendorf tubes	
Erlenmeyer flask	
graduated pipette	
micropipette	
Pasteur pipette	
pipette tips	 stored in 
pipette pump	
snap-cap vial	

WORKING WITH MICROPIPETTES

Using **micropipettes** is one of the most important working techniques in gene technology labs. You need to understand the handling of such instruments for several experimentation steps we will do today. Named after a manufacturer, micropipettes are also called 'Eppendorf pipettes'.

With these special laboratory instruments, it is possible to pipette very low liquid volumes of 2 µl (≈0,0000676 floz) to 1000 µl (≈0,0338 floz), depending on the selected micropipette and the previously adjusted volume.

Elements of a micropipette:

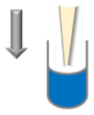
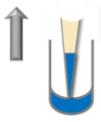


Please note:

Micropipettes are very expensive, sensitive instruments and must be handled carefully!

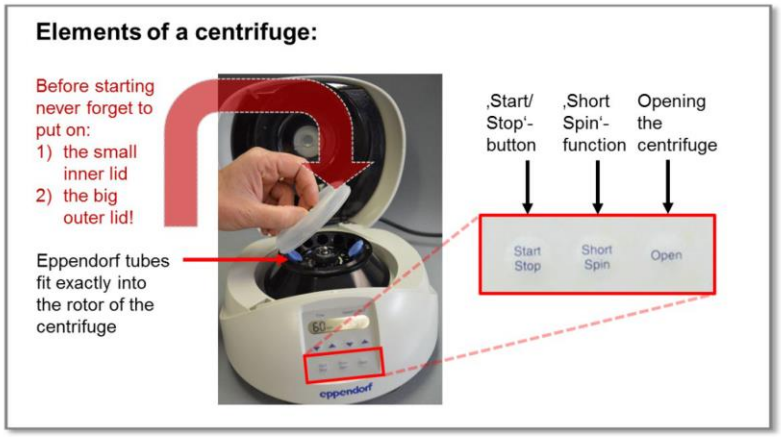
- ☞ **Micropipettes may only be used with a pipette tip attached!**
- ☞ **Always keep the tip of the pipettes downwards!**
- ☞ **Never use the same pipette tip for different substances!**
- ☞ **Discard used pipette tips into appropriate waste jar!**

How to handle a micropipette:

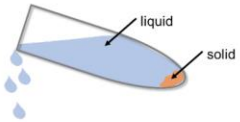
1		Turn the **volume adjustment knob** to select the desired amount of liquid. The volume is read in µl (said **'microliter'**) from top to bottom. **1000 µl ≈ 0.0338 floz** *e.g., 81.2 µl are indicated in the picture on the left (≈ 0.0027 floz)* Now put on a suitable **pipette tip**.
2		Press the plunger button down to the **first pressure point** and hold, then immerse the tip 0.2 inch in the liquid.
3		Slowly release the plunger button. The medium is sucked in.
4		To eject the medium from the pipette tip, press the plunger button down to the first pressure point again, then down to the **second pressure point** so that the tip is completely empty. Always place droplets on the vessel wall.

CENTRIFUGATION

Centrifugation is a separating-method using inertia. Thereby, a mixture of substances is accelerated in a uniform circular motion. Due to their inertia, higher density components migrate outwards and displace low density substances that get into the center.

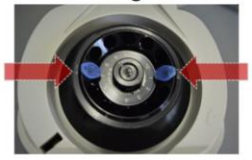


The separation process of a mixture of liquid and solid components (such as a suspension) is called **Decantation**. The liquid, from which the precipitate or sediment has settled out, *e.g.* after centrifugation, is poured off, leaving the other, solid component of the mixture behind:



Please note:

Always put two Eppendorf tubes containing an equivalent volume opposite to each other in the centrifuge, as otherwise the centrifuge will be imbalanced!



- **'Start'-button:** When this button is pressed, the centrifuge starts and runs to the previously set duration and rotational speed ('rounds per minute' = rpm).
- **'Short-Spin'-function:** When holding the 'Short-Spin'-button, the centrifuge starts and runs until the button is released. This function is used to move liquid droplets from the Eppendorf tube's edge down to the bottom of the tube.
- **'Stop'-button:** If you accidentally start the centrifuge without balancing, press the 'Stop'-button immediately.

PRACTICING WORKING TECHNIQUES

In this practical exercise, we familiarize ourselves with the handling of micropipettes and the centrifuge.

Task:

After getting into pairs, take an Eppendorf tube and alternately pipette the following amounts of color solution from the beaker into this tube.

2 µl
4 µl
10 µl
14 µl
20 µl
50 µl
150 µl
250 µl

How it works:

1) Choose the micropipette most suitable for the required volume!
2) Adjust the exact volume quantity and put on a pipette tip!
3) Press and hold the plunger button down to the first pressure point and immerse the pipette tip into the color solution!
4) Slowly release the plunger button; the color solution is sucked in.
5) To transfer the liquid completely into the Eppendorf tube, push the plunger button down to the second pressure point. Place small amounts of liquid directly on the vessel wall.
6) Throw away the used pipette tip into the waste container on the table!

Alternately repeat the steps until all of the above listed quantities of liquid are collected in the Eppendorf tube (2 µl to 250 µl)!

7) Mix solutions by pipetting up and down:
   Test this technique now by repeatedly and slowly pushing the plunger button down to the first pressure point and releasing it again!
8) Place your Eppendorf tube into the centrifuge. Make sure that another vessel is exactly opposite to it. First place the inner lid on the centrifuge and then close the device. When using the 'Short-Spin'-function, the liquid droplets will be collected in the bottom of the tube; hold the 'Short-Spin'-button for 5 seconds!
9) Finally, pipette the entire liquid from the Eppendorf tube back into the beaker in one step (Math problem: Add the volumes!)

DNA-ISOLATION
FROM ORAL MUCOSAL CELLS

Materials:

- drinking cup
- distilled water
- 2 Pasteur pipettes (sterilized)
- snap-cap vial
- chronometer
- micropipettes
- graduated pipette (iced; 0.338 floz)
- pipette pump
- water bath (122°F)
- black placemat
- waterproof pens

Chemicals:

- lysis buffer (white)
- mild detergent (green)
- chilled Isopropyl alcohol (P)

Experimental procedure:

1) Briefly rinse your mouth twice with **distilled water** from the drinking cup.

2) Then chew for 2 minutes (do not swallow!) so that **saliva** containing **ablated oral mucosal cells** forms.

3) Fill the **Pasteur pipette** with distilled water from the drinking cup up to the mark in front of the suction head. Release the water into your mouth and **intensively swill it around for 40 seconds** (as if rinsing with water after brushing your teeth).

4) Afterwards, the 'rinse water' should be spat into the **snap-cap vial**. Make sure you **label** your vial with your group number to avoid confusion.

5) Use a micropipette to add **2000 µl lysis buffer (white)** to the contents of the vial. Then put on the snap-cap and carefully (!) tilt it back and forth **five times** to mix it with the saliva.

Explain the role of the lysis buffer:

_____

_____

6) Use a second Pasteur pipette to add **5 drops of mild detergent (green)** to the solution in the snap-cap. Close the cap and carefully tilt it back and forth **once again**.

Explain the role of the mild detergent:

_____

_____

7) Place the snap-cap vial in a 122°F **water bath for 10 minutes** and then return it to your workplace.

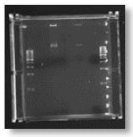
Explain the role of the warm water bath:

8) Take an **iced graduated pipette and pipetting pump with 0.17 floz of chilled alcohol (P)**. The alcohol must be carefully and slowly run down the inside wall of the snap-cap vial to build a second phase over the saliva sample. This is known as over-coating with alcohol.

Explain why you over-coat with alcohol:

9) Close the snap-cap vial and leave it on the **black placemat** for **5 minutes** without touching it.

Observation:



AGAROSE GEL ELECTROPHORESIS

A METHOD TO VISUALIZE DNA-MOLECULES

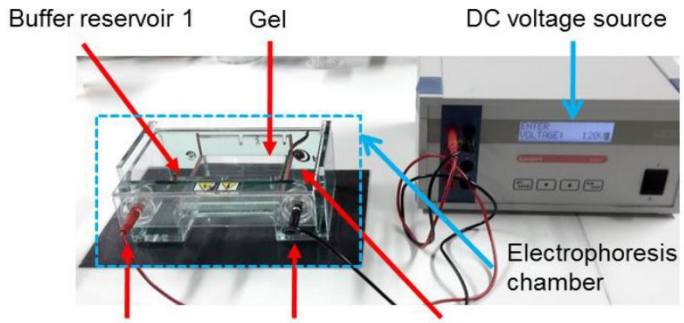
Agarose:

A carbohydrate from the cell wall of red algae. After boiling in water and cooling down, it forms a solid **gel** ('carrier material').

Electrophoresis:

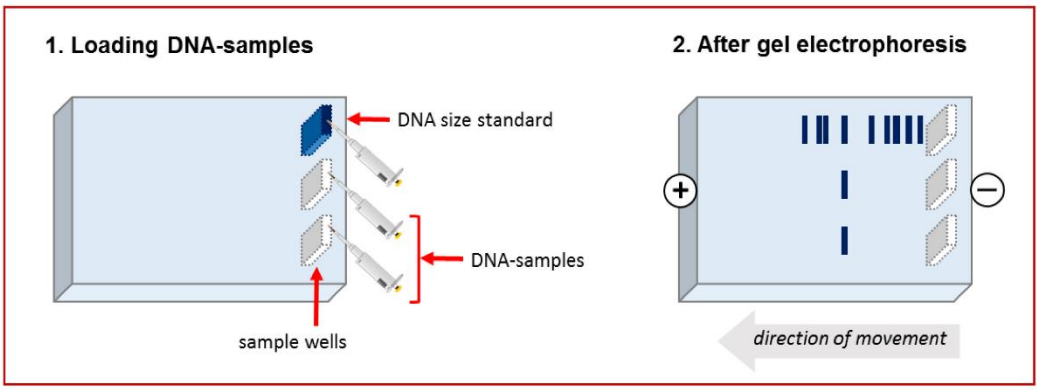
The migration of electrically charged particles through a substance which serves as a carrier material in an electric field.

Elements of the apparatus:



Please note:

- The method distinguishes only between **shorter and longer DNA molecules**.
- For exact length determination, a so-called **'DNA size standard'** is necessary for comparison!
- The **migration rate of electrically charged molecules** depends on:
  - the applied voltage
  - the density of the gel
  - the size / length of the DNA molecules



DNA GEL ELECTROPHORESIS

Materials:

Agarose-Gel (Preparation)

- heating plate
- scales
- Erlenmeyer flask
- spatula
- aluminum foil
- heat-resistant gloves
- rubber gloves
- chronometer

Gel electrophoresis

- electrophoresis chamber
- Eppendorf tubes
- micropipettes
- tweezers
- centrifuge
- ice bath
- waterproof pens

Chemicals:

- agarose
- molecular dye 'SYBR-Green'
- electrophoresis buffer (TBE; blue)
- chilled Isopropyl alcohol (yellow)
- loading buffer (red)

Gel station: Preparing an agarose gel

1) Weigh out **0.012 oz agarose** into an Erlenmeyer flask, suspend it with **1.7 floz electrophoresis buffer (TBE)** and seal the Erlenmeyer flask with a piece of aluminum foil.

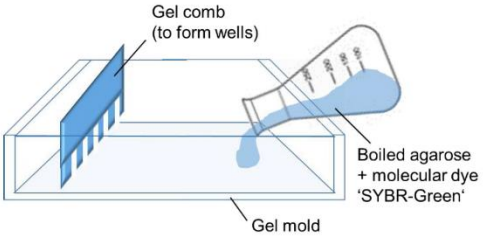
2) The agarose suspension is **boiled** on the heating plate and then stored in a drying oven (140°F) until use.
   Caution very hot! **When transporting the hot Erlenmeyer flask, always wear a heat-resistant glove!**

3) To avoid contamination, wear **rubber gloves** when working with the gel!
   Your laboratory supervisor should add **5 µl of the molecular dye 'SYBR-Green'** to the boiled agarose solution. Distribute the dye by gently swirling the Erlenmeyer flask.

Explain the role of the molecular dye 'SYBR-Green':

4) Pour the agarose solution into the **gel mold** of the electrophoresis chamber and insert the **gel comb**.
   The agarose solution **solidifies** as it cools down (ca. 30-40 min).

5) For proper electrophoresis the mold with the prepared gel needs to be **turned** so that the gel comb is in line with the (-)-electrode. Now carefully (!) **remove the gel comb**.



6) Finally, the right buffer reservoir is filled with an **electrophoresis buffer** until the gel is flooded. Then fill the left buffer reservoir up to the 'max filling' line.

DNA-sample processing and gel electrophoresis

1) Use the tweezers to transfer some of your **DNA** from the snap-cap vial into the **Eppendorf tube (1)**. It is easier when the snap-cap vial is held slightly inclined.

2) The transferred DNA is dissolved with **100 µl electrophoresis buffer (blue)**.
Pipette up and down for at least **1 minute** to mix it. Please keep the pipette tip in the liquid to avoid bubbles!

3) Transfer **20 µl of the DNA-solution** into another **Eppendorf tube (2)**.
The following instructions concern **the sample processing**.

   - First add **100 µl of chilled alcohol (yellow; stored on ice)** and pipette up and down again for **1 minute**. Then, the sample should be **centrifuged for 1 minute** (14.5 rpm).
   - After centrifugation, a **solid sediment (pellet)** can be seen at the bottom of the Eppendorf tube. Before doing anything else, the **alcohol** must be **completely (!) decanted** onto a piece of paper.
   - Leave the Eppendorf tube **open** for **2 minutes** so that the remaining alcohol evaporates.
   - Add **50 µl electrophoresis buffer (blue)** into the Eppendorf tube with the pellet and pipette up and down again for **1 minute**.

Explain the purpose of the sample processing:

_____

_____

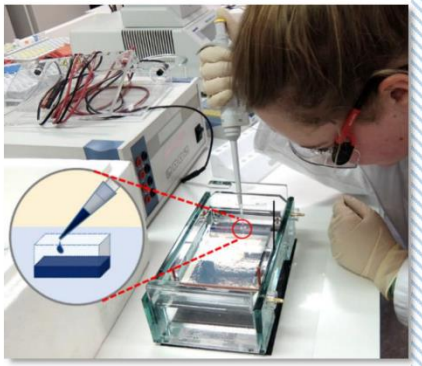
4) After transferring **20 µl of the processed sample** into another **Eppendorf tube (3)**, add **5 µl of loading buffer (red)**. Slightly mix the solutions by snapping on the closed Eppendorf tube, then centrifuge for **5 seconds ('Short Spin'-function)** to collect liquid droplets from the tube's edge. Now your DNA-sample is ready for electrophoresis! Store it **on ice** until application.

Explain the role of the loading buffer:

_____

_____

5) At the gel station carefully (!) inject **20 µl of the chilled DNA-sample** into an empty well on the agarose gel (*Note your well number!*).



6) Additionally, the laboratory supervisor should inject a **'DNA size standard'** into a different well for length determination. The supervisor should **start** the gel electrophoresis with a voltage of **120 V**.

7) The electrophoresis should be **terminated** as soon as the first dye of the loading buffer reaches the leading edge of the gel (ca. 2 hours). The laboratory supervisor should remove the gel from the apparatus. Finally, the gel is **observed under UV** and the findings are **analyzed** in plenary.

DNA-MODELING

After it had been proven by experiments that DNA carries the genetic information, important questions about the structure of the DNA and the encryption of the genetic code were raised. At the beginning of the 1950s there was a race between several groups of researchers who wanted to answer these questions.

Tasks:

1) Read the **information text** about DNA-structure which you find in the modeling box!
2) **Underline** the chemical **components** that compose the **DNA**!
3) Answer the **following questions about DNA structure** with the help of the text!

(1) How many strands does the DNA consist of?

(2) Please tick as appropriate! The DNA-strands are …

- ☐ independent of each other.
- ☐ antiparallel.
- ☐ shifted arranged.
- ☐ identical.

(3) Explain the cohesion of the DNA-strands!

(4) The DNA backbone: Name the associated components and describe their set up!

(5) Which DNA backbone's compound are the bases linked to?

(6) Name the bases and indicate possible base pairings!

(7) Give the opposite bases to the base sequence 'GATCTA'!

(8) Check! The bases are located …

- ☐ at the interior of the DNA-molecule.
- ☐ at the exterior of the DNA-molecule.

(9) The DNA forms a right-handed double-helix. Explain what this means!

(10) Describe how genetic information is encoded in the DNA!

4) Slip into the role of the scientists Watson & Crick and **build a DNA-model** with the help of the answered questions! Work in pairs.
You will find a selection of material in the box (glue, straws, scissors, pipe cleaners, colored beads and cardboards etc.).

Some clues:

- First consider which materials could represent the single components of the DNA (several options are possible)!
- Decide upon appropriate material and start modeling. Build just a short sequence of the giant molecule!
- Try to visualize as many characteristics of the DNA-structure as possible in your model! Do not hesitate to change and test your DNA-model's properties; this is part of the modeling process!

5) Finally, draw a **simplified sketch** of your model and label the components!
You will be given an extra sheet of paper for this purpose.

Appendix 3: Info text DNA structure: 'Following in the footsteps of Watson and Crick'

Following in the footsteps of two GEN(E)iuses:

How Watson and Crick solved the molecular puzzle of DNA structure

Source: http://cshlarchives.blogspot.de/2013/03/dna-letters-1951-1953.html

In 1953 two until then little-known scientists won the race to encode the structure of DNA: James Watson and Francis Crick (see picture). Although they did not perform their own experiments, they understood how to link and correctly interpret the findings of other researchers.

This is what Francis Crick wrote to his twelve year old son on March 19th 1953:

'My Dear Michael,

Jim Watson and I have probably made a most important discovery. We have built a model for the structure of dex-oxi-ribose-nucleic-acid (read it carefully) called D.N.A. for short. …'

After numerous discussions and exchanges of ideas, the two researchers caused a sensation: They succeeded in translating the available DNA data into a spatial model which they had formed from the simplest materials, such as wire, cardboard and staples.

In the letter to his son, Francis Crick describes the structure of their *'very beautiful'* DNA-model in detail. According to this, the simplest way to imagine the DNA is like a twisted rope ladder. The alternating spars consist of firmly linked phosphate groups and a sugar called deoxyribose. These phosphate-sugar-chains are also called the DNA backbone, because they are at the exterior of the DNA-molecule. At the interior of the giant molecule are the four different bases adenine (A), thymine (T), guanine (G) und cytosine (C). The bases form pairwise the ladder rungs of the DNA, whereby the individual bases are firmly attached to the sugar components of the lateral spars. The complete DNA-molecule is composed of two single DNA strands, each consisting of one of the two sugar-phosphate-chains and each with one base attached to the sugar components. Both single strands are linked to each other via hydrogen bonds between the complementary base pairs. It is crucial that there are only two possible base pairings. Adenine always pairs with thymine and guanine always pairs with cytosine.

The special nature of the DNA structure is that the base sequence of one single strand (*e.g.* TTCAG) automatically specifies the base sequence of the complementary single strand (→ AAGTC), because there are only two possible base pairings. Furthermore, the resulting base sequence is a code: Certain sections form different genes which carry the basic information for the expression of different hereditary characteristics.

In summary, the DNA is an aliphatic giant molecule consisting of two opposing DNA single strands. If you look at the vertical single strands from above, you see that they are helically wound around each other in a clockwise direction. This is also called a right-handed double helix structure.

In 1962, the scientists Watson & Crick awarded the Nobel Prize for Medicine for their discovery of the double-helix structure of DNA.

Appendix 4: Suggested solutions for student workbook (teacher version) and DNA-model evaluation

A STEAM outreach lab module

SIMPLY INGEN(E)IOUS!

DNA AS A CARRIER OF GENETIC INFORMATION

Suggested solutions

for experimental tasks and modeling

A practical training course for 9th graders

DNA-ISOLATION
FROM ORAL MUCOSAL CELLS

Materials:

- drinking cup
- distilled water
- 2 Pasteur pipettes (sterilized)
- snap-cap vial
- chronometer
- micropipettes
- graduated pipette (iced; 0.338 floz)
- pipette pump
- water bath (122°F)
- black placemat
- waterproof pens

Chemicals:

- lysis buffer (white)
- mild detergent (green)
- chilled Isopropyl alcohol (P)

Experimental procedure:

10) Briefly rinse your mouth twice with **distilled water** from the drinking cup.

11) Then chew for 2 minutes (do not swallow!) so that **saliva** containing **ablated oral mucosal cells** forms.

12) Fill the **Pasteur pipette** with distilled water from the drinking cup up to the mark in front of the suction head. Release the water into your mouth and **intensively swill it around for 40 seconds** (as if rinsing with water after brushing your teeth).

13) Afterwards, the 'rinse water' should be spat into the **snap-cap vial**. Make sure you **label** your vial with your group number to avoid confusion.

14) Use a micropipette to add **2000 µl lysis buffer (white)** to the contents of the vial. Then put on the snap-cap and carefully (!) tilt it back and forth **five times** to mix it with the saliva.

Explain the role of the lysis buffer:

The lysis buffer (dishwashing detergent-salt solution) causes the dissolution of nuclear and cell membranes (more precise: The phospholipid bilayer is destroyed by the detergent component; the saline component increases solubility of DNA in the fluid).

15) Use a second Pasteur pipette to add **5 drops of mild detergent (green)** to the solution in the snap-cap. Close the cap and carefully tilt it back and forth **once again**.

Explain the role of the mild detergent:

Enzymes in the mild detergent degrade proteins, fats and carbohydrates.

16) Place the snap-cap vial in a 122°F **water bath for 10 minutes** and then return it to your workplace.

Explain the role of the warm water bath:

The heat improves the effect of the detergents and the enzymes.

17) Take an **iced graduated pipette and pipetting pump with 0.17 floz of chilled alcohol (P)**. The alcohol must be carefully and slowly run down the inside wall of the snap-cap vial to build a second phase over the saliva sample. This is known as over-coating with alcohol

Explain why you over-coat with alcohol:

The DNA is insoluble in alcohol (more precise: At the interface alcohol molecules affect DNA molecules' hydration shell. In consequence, DNA becomes macroscopically visible through interaction between single DNA molecules).

18) Close the snap-cap vial and leave it on the **black placemat** for **5 minutes** without touching it.

Observation:

At the phase boundary between the upper alcohol layer and the lower saliva layer whitish threads and/or lumps become visible.

DNA GEL ELECTROPHORESIS

Materials:

Agarose-Gel (Preparation)

- heating plate
- scales
- Erlenmeyer flask
- spatula
- aluminum foil
- heat-resistant glove
- rubber gloves
- chronometer

Gel electrophoresis

- electrophoresis chamber
- Eppendorf tubes
- micropipettes
- tweezers
- centrifuge
- ice bath
- waterproof pens

Chemicals:

- agarose
- molecular dye 'SYBR-Green'
- electrophoresis buffer (TBE; blue)
- chilled Isopropyl alcohol (yellow)
- loading buffer (red)

Gel station: Preparing an agarose gel

7) Weigh out **0.012 oz agarose** into an Erlenmeyer flask, suspend it with **1.7 floz electrophoresis buffer (TBE)** and seal the Erlenmeyer flask with a piece of aluminum foil.

8) The agarose suspension is **boiled** on the heating plate and then stored in a drying oven (140°F) until use.

Caution very hot! **When transporting the hot Erlenmeyer flask, always wear a heat-resistant glove!**

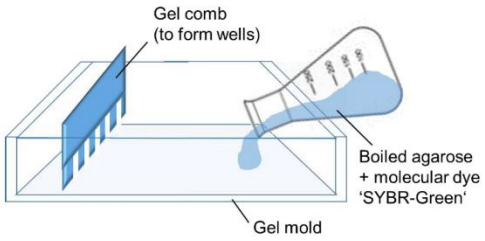
9) To avoid contamination, wear **rubber gloves** when working with the gel!
Your laboratory supervisor should add **5 µl of the molecular dye 'SYBR-Green'** to the boiled agarose solution. Distribute the dye by gently swirling the Erlenmeyer flask.

Explain the role of the molecular dye 'SYBR-Green':

The dye (detection reagent) binds specifically to double-stranded DNA-molecules. These dye-DNA particles become visible by emitting green light (at 521 nm) under UV light.

10) Pour the agarose solution into the **gel mold** of the electrophoresis chamber and insert the **gel comb**.
The agarose solution **solidifies** as it cools down (ca. 30-40 min).

11) For proper electrophoresis the mold with the prepared gel needs to be **turned** so that the gel comb is in line with the (-)-electrode. Now carefully (!) **remove the gel comb**.



12) Finally, the right buffer reservoir should be filled with an **electrophoresis buffer** until the gel is flooded. Then fill the left buffer reservoir up to the 'max filling' line.

DNA-sample processing and gel electrophoresis

8) Use the tweezers to transfer some of your **DNA** from the snap-cap vial into the **Eppendorf tube (1)**. It is easier when the snap-cap vial is held slightly inclined.

9) The transferred DNA is dissolved with **100 µl electrophoresis buffer (blue)**.
Pipette up and down for at least **1 minute** to mix it. Please keep the pipette tip in the liquid to avoid bubbles!

10) Transfer **20 µl of the DNA-solution** into another **Eppendorf tube (2)**.
The following instructions concern **the sample processing**.

- First add **100 µl of chilled alcohol (yellow; stored on ice)** and pipette up and down again for **1 minute**. Then, the sample should be **centrifuged for 1 minute** (14.5 rpm).
- After centrifugation, a **solid sediment (pellet)** can be seen at the bottom of the Eppendorf tube. Before doing anything else, the **alcohol** must be **completely (!) decanted** onto a piece of paper.
- Leave the Eppendorf tube **open** for **2 minutes** so that the remaining alcohol evaporates.
- Add **50 µl electrophoresis buffer (blue)** into the Eppendorf tube with the pellet and pipette up and down again for **1 minute**.

Explain the purpose of the sample processing:

During sample processing interfering substances are removed so that the DNA-sample is prepared for further investigation. Such reactions are also referred to as reprecipitation.

11) After transferring **20 µl of the processed sample** into another **Eppendorf tube (3)**, add **5 µl of loading buffer (red)**. Slightly mix the solutions by snapping on the closed Eppendorf tube, then centrifuge for **5 seconds ('Short Spin'-function)** to collect liquid droplets from the tube's edge. Now your DNA-sample is ready for electrophoresis! Store it **on ice** until application.

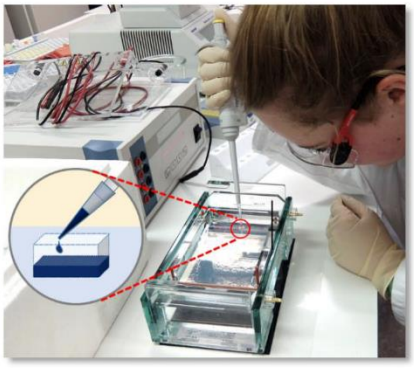
Explain the role of the loading buffer:

The loading buffer contains glycerol and sucrose which cause the DNA-sample to sink into the gel wells due to their relatively high density. The included blue dye allows to control the movement of the DNA.

12) At the gel station carefully (!) inject **20 µl of the chilled DNA-sample** into an empty well on the agarose gel (*Note your well number!*).

13) Additionally, the laboratory supervisor should inject a **'DNA size standard'** into a different well for length determination. The supervisor should **start** the gel electrophoresis with a voltage of **120 V**.

14) The electrophoresis should be **terminated** as soon as the first dye of the loading buffer reaches the leading edge of the gel (ca. 2 hours). The laboratory supervisor should remove the gel from the apparatus. Finally, the gel is **observed under UV** and the findings are **analyzed** in plenary.



DNA-MODELING

After it had been proven by experiments that the DNA carries the genetic information, important questions about the structure of the DNA and the encryption of the genetic code were raised. At the beginning of the 1950s there was a race between several groups of researchers who wanted to answer these questions.

Tasks:

6) Read the **information text** about DNA-structure which you find in the modeling box!
7) **Underline** the chemical **components** that compose the **DNA**!
8) Answer the **following questions about DNA structure** with the help of the text!

(11) How many strands does the DNA consist of?

The DNA consists of two single strands.

(12) Please tick as appropriate! The DNA-strands are …

- ☐ independent of each other.
- ☒ antiparallel.
- ☐ shifted arranged.
- ☐ identical.

(13) Explain the cohesion of the DNA-strands!

The DNA single strands are linked to each other via hydrogen bonds between the individual base pairs.

(14) The DNA backbone: Name the associated components and describe their set up!

It consists of phosphate groups and a sugar called deoxyribose. These components are arranged alternately resulting in a phosphate-sugar-chain.

(15) Which DNA backbone's compound are the bases linked to?

The single bases are firmly attached to the sugar components of the DNA backbone.

Following in the footsteps of two GEN(E)iuses

(16) Name the bases and indicate possible base pairings!

The bases are adenine (A), thymine (T), guanine (G) and cytosine (C). Only two possible base pairings exist: (A) pairs with (T) and (G) pairs with (C) (complementary base pairing).

(17) Give the opposite bases to the base sequence 'GATCTA'!

The base sequence of the complementary DNA strand is CTAGAT.

(18) Check! The DNA bases are located …

- [x] at the interior of the DNA-molecule.
- [ ] at the exterior of the DNA-molecule.

(19) The DNA forms a right-handed double-helix. Explain what this means!

If you look at the vertical single strands from above, you see that they are helically wound around each other in a clockwise direction.

(20) Describe how genetic information is encoded in the DNA!

The base sequence is a code: Certain sections form different genes which carry the basic information for the expression of different hereditary characteristics.

9) Slip into the role of the scientists Watson & Crick and **build a DNA-model** with the help of the answered questions! Work in pairs.
You will find a selection of material in the box (glue, straws, scissors, pipe cleaners, colored beads and cardboards etc.).

Some clues:

- First consider which materials could represent the single components of the DNA (several options are possible)!
- Decide upon appropriate material and start modeling. Build just a short sequence of the giant molecule!
- Try to visualize as many characteristics of the DNA-structure as possible in your model! Do not hesitate to change and test your DNA-model's properties, this is part of the modeling process!

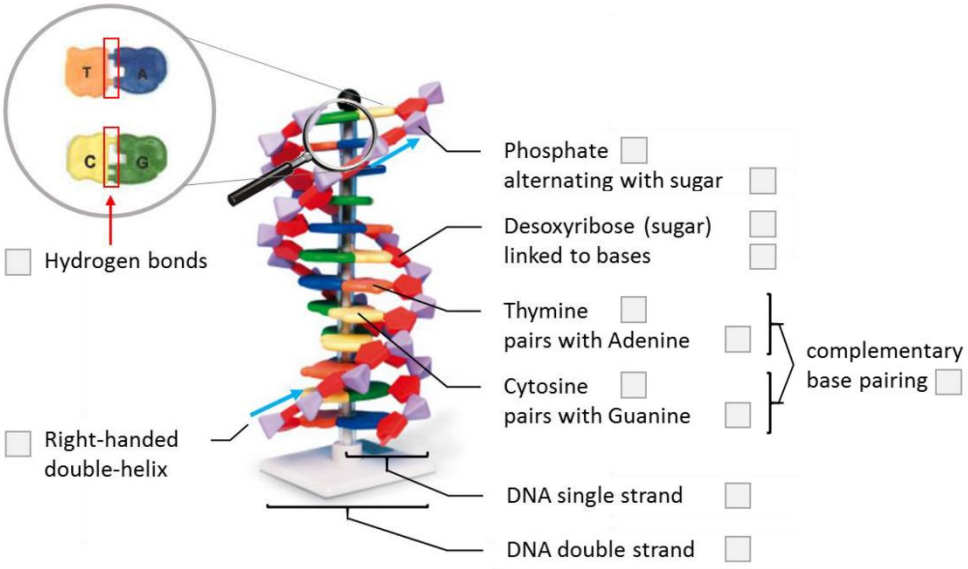
10) Finally, draw a **simplified sketch** of your model and label the components!
You will be given an extra sheet of paper for this purpose.

DNA-MODEL EVALUATION

Tasks:

1) **Look** closely at your DNA model and **compare** it with the distributed school model (similarities / differences)!

2) **Check** the image below to identify which DNA components are represented in both your elaborated model and the school model!



Additional task for young researchers:

3) Search for a picture of Watson & Crick's original DNA-model on the internet and compare it to yours!

Appendix 5: Instruction poster 'Gel electrophoresis' with removable magnet applications

Simply inGEN(E)ious! Visualize the invisible with

AGAROSE GEL ELECTROPHORESIS

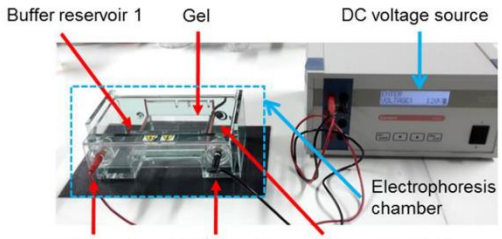
Agarose:

A carbohydrate from the cell wall of red algae. After boiling in water and cooling down, it forms a solid **gel** ('carrier material').

Electrophoresis:

The migration of electrically charged particles through a substance which serves as a carrier material in an electric field.

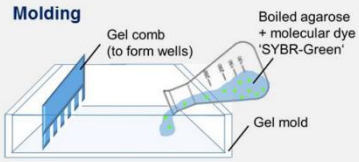
Elements of the apparatus:

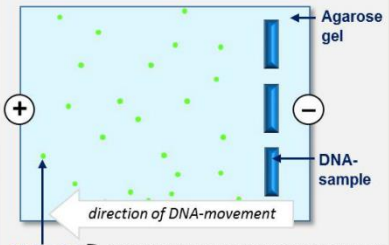


Preparing an agarose gel:

What makes DNA visible in gel electrophoresis?

Addition of the molecular dye 'SYBR-Green'



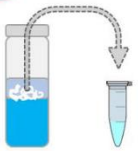


The DNA consists of 5 different chemical elements:

1,0	12,0	14,0	16,0	31,0
1 H 2,2	6 C 2,5	7 N 2,2	8 O 3,5	15 P 2,1

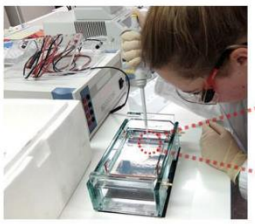
Before starting the gel electrophoresis:

Why is the DNA-sample not applied directly?

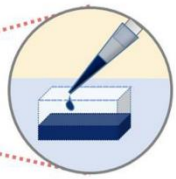


Processing the DNA-sample:
Interfering substances are removed so that the DNA-sample is prepared for further investigation

Addition of the loading buffer:
Weights the sample + dye controls the movement



Application of the samples:

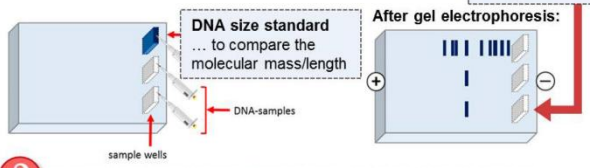


A giant molecule carries our genetic information

The DNA has a relatively large molecular weight, since it is a chain molecule of up to one hundred thousand repetitive single components.

Which component(s) cause(s) the DNA-movement in the electric field?

Only **six different components** form the DNA-molecule:



On what does the migration rate of the DNA depend?

- … on the applied voltage.
- … on the density of the gel.
- … on the size/length of the DNA molecules.

Simply inGEN(E)ious! Visualize the invisible with

AGAROSE GEL ELECTROPHORESIS

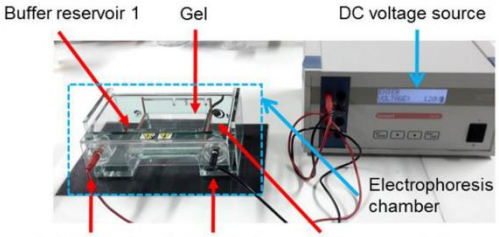
Agarose:

A carbohydrate from the cell wall of red algae. After boiling in water and cooling down, it forms a solid **gel** ('carrier material').

Electrophoresis:

The migration of electrically charged particles through a substance which serves as a carrier material in an electric field.

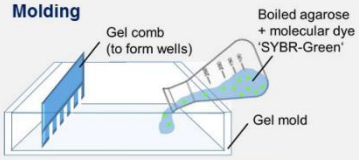
Elements of the apparatus:

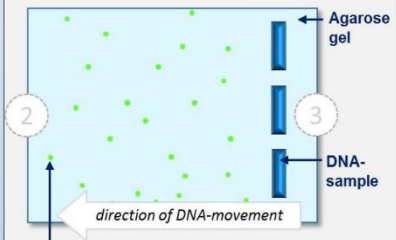


Preparing an agarose gel:

What makes DNA visible in gel electrophoresis?

1



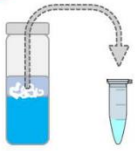


The DNA consists of 5 different chemical elements:

10

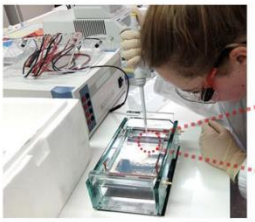
Before starting the gel electrophoresis:

Why is the DNA-sample not applied directly?

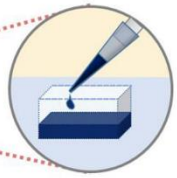


5

6



Application of the samples:



A giant molecule carries our genetic information

The DNA has a relatively large molecular weight, since it is a chain molecule of up to one hundred thousand repetitive single components.

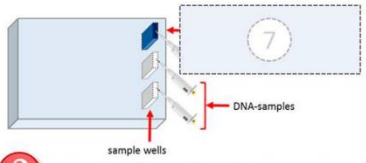
Which component causes the DNA-movement in the electric field?

Only **six different components** form the DNA:

A T G C = the four bases of the DNA

= sugar

P = phosphate



After gel electrophoresis:

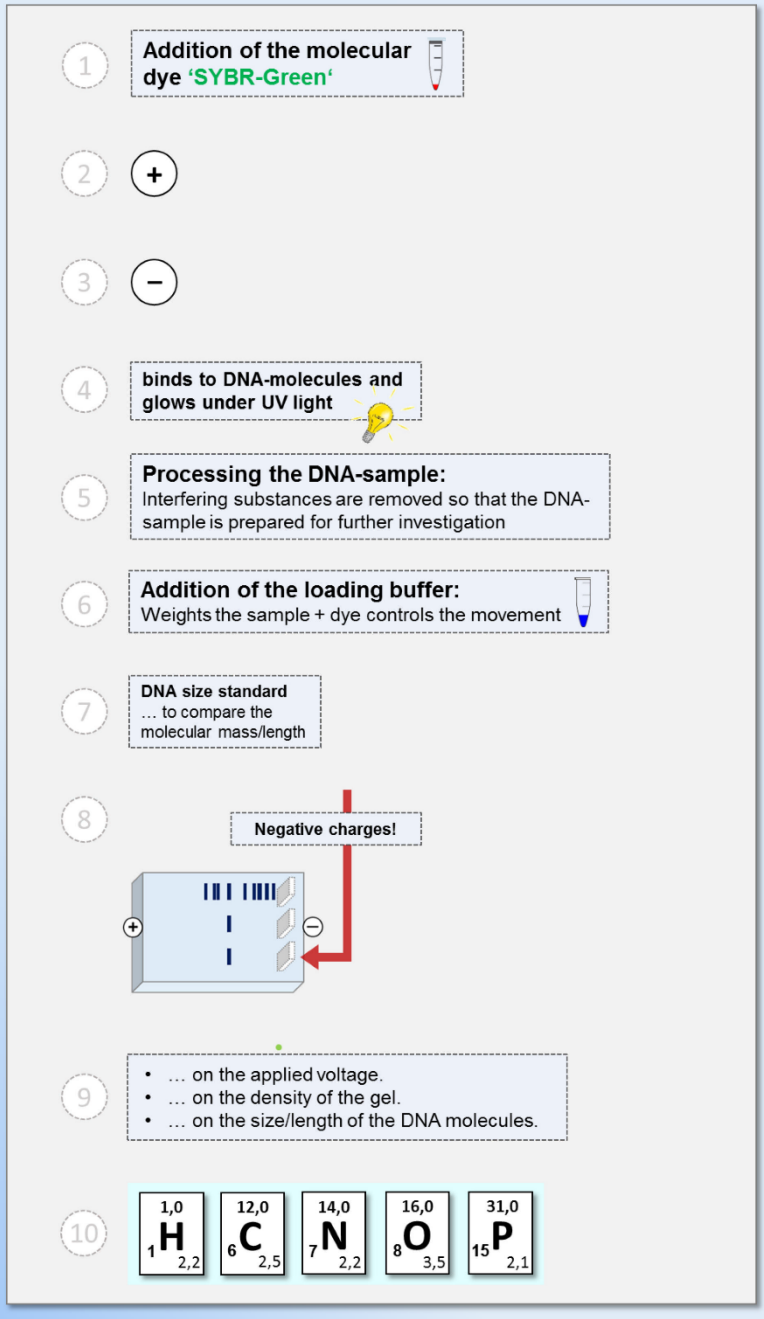
8

On what does the migration rate of the DNA depend?

9

Magnet applications:

Can be cut out, laminated and used with magnetic tape on a metallic board onto the poster version with blank spaces.
(Recommended print sizes for the posters: DIN A0 → 33.1 x 46.8 inches)



5.4 Teilarbeit B

Thinking Skills and Creativity

Vol. 31, pp. 91-102, 2019

First published online November 2018. https://doi.org/10.1016/j.tsc.2018.11.001

Is creativity, hands-on modeling and cognitive learning gender-dependent?

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Is creativity, hands-on modeling and cognitive learning gender-dependent?

Abstract

Modeling plays a key role in science research and education is considered to increase comprehensibility of abstract concepts and processes. Especially hands-on experiences in authentic learning environments offer students the opportunity to feel like real researchers and support the development of problem-based thinking skills. In our study, we applied an inquiry-based, out-of-school laboratory module that uses classic experimental challenges as well as innovative model-supported teaching to promote cognitive achievement. Our hands-on module was designed for 9th graders and combined experimentation and creative model work to visualize molecular and otherwise invisible contents of DNA structure. After mental modeling, participants (*N*=114; 40.87% female) produced a physical DNA-model using handcrafting materials. Our major aims were to evaluate the model qualities and to monitor potential relationships between successful model elaboration, individual creativity and knowledge levels. Therefore, we correlated students' creativity levels with model quality scores as well as with cognitive achievement. While no relations were found for creativity and model elaboration further results were gender-dependent. Girls produced significantly higher model quality scores and significant positive correlations were revealed between short-term and mid-term knowledge levels. Correlations also were observed between girls' cognitive achievement and the creativity subscale 'flow'. In contrast, neither creativity nor model quality were decisive for boys cognitive achievement. Their average simpler modeling results did not correlate with the short-term and mid-term knowledge levels, although they achieved similar scores on both. Model elaboration seemingly provides more support for girls and offers a suitable approach for emphasizing creativity in science education. In attempting to attract girls to scientific ideas, creative modeling may further support hands-on experimentation.

Keywords

Cognitive knowledge, Modeling, Creativity, Outreach learning, Science education

1. Introduction

Out-of-school settings have a long history in science education and offer authentic and student-centered learning environments (Bryce & Robertson, 1985; Gerstner & Bogner, 2010; Randler & Bogner, 2006). Outreach labs may provide learners with a sense of authenticity and the feeling of being a real scientist: appropriate experiments based on realistic problems connect autonomous hands-on experiences with newly acquired theoretical knowledge and affect cognitive achievement scores (Franke & Bogner, 2011; Langheinrich & Bogner, 2016). Earlier studies with molecular contents have demonstrated that hands-on experiments can lead to an increase of both knowledge and conceptual understanding (Langheinrich & Bogner, 2015; Scharfenberg, Bogner, & Klautke, 2007). For secondary school students, Ben-Nun and Yarden (2009) demonstrated that outreach learning in the context of DNA-structure caused a significant improvement in the quality of mental models as did their procedural understanding regarding DNA-manipulations. Approaches to outreach learning are often inquiry-based; learners propose ideas, explain observations, and verify hypotheses (Schmid & Bogner, 2015). Such learning scenarios tend to emphasize critical, independent and problem-based thinking; related challenges are often connected with students' everyday experience (Sotiriou, Bybee, & Bogner, 2017). Inquiry methods generally include tasks like detecting problems, planning investigations, researching for information, assessing alternatives, evaluating experiments, constructing models and discussing with peers (Linn, Davis, & Bell, 2004). Inquiry-based learning may provide differing emphases on students´ autonomy and the role of the teacher, allowing a spectrum from extremely tight, teacher-centered versions to open inquiry alternatives with few predefined structures but high student involvement (Blanchard, Southerland, Osborne, Sampson, Annetta, & Granger, 2010). Although both extremes have been observed and criticized in detail, we prefer a situation in which students become more independent in reasoning and exploring, reach a deeper understanding of the learning content and transfer learned information to other contexts (Schmid & Bogner, 2015). A more structured version of inquiry may allow learners for example to focus on interpretation of results and on linking experiment with theory (*e.g.*, Hmelo-Silver, Duncan, & Chinn, 2006; Kirschner, Sweller, & Clark, 2006).

Additionally, visual representations in classrooms are important, especially when otherwise invisible classroom issues such as complex molecular contents need further explanation (Ferk, Vrtacnik, Blejec, & Alenka, 2003; Sotiriou & Bogner, 2008). In genetics, the application of models seems essential for adequate exemplification (Rotbain, Marbach-Ad, & Stavy, 2006). Langheinrich and Bogner (2016) reported a substantial knowledge acquisition in an outreach lab module when digital 3D representations were combined with classic hands-on experiments. Due to the fact, that teachers can use models for several purposes in science instruction we additionally observed the efficiency of two basically different instructional settings for model-based learning (Mierdel & Bogner, 2018). On the one hand, models are used as teaching tools to illustrate certain aspects and to transmit content knowledge. On the other hand, elaborating models when testing and representing scientific ideas provides further benefits such as offering multiple ways for learning science and understanding routes to historical discoveries (Svoboda

& Passmore, 2013; Werner, Förtsch, Boone, von Kotzebue, & Neuhaus, 2017). When comparing two different model-supported approaches, *model viewing* turned out to be significantly more instructional efficient than *model elaboration* in terms of sustainable mid-term knowledge while no differences concerning cognitive load were observed (Mierdel & Bogner, 2018). Nevertheless, modeling as a student-centered activity takes a key role in science education and is required by in national science education standards (KMK, 2005). This is why further research on modeling is necessary, so that it can be established as an up-to-date and frequently used approach to scientific learning.

1.1. Model-based teaching and creativity

Research on model application and modeling is widespread (*e.g.*, Buckley, 2000; Treagust, Chittleborough, & Mamiala, 2002; Gilbert, 2004): It is undisputable that models in classrooms may help to develop, transmit and receive scientific knowledge (Giere, 1988). A famous example is the discovery of DNA-structure by Watson and Crick (1953), where a model successfully helped to explain and simplify complex relations. Bridging theoretical messages and real-world experience is assumed to provide a basis for scientific prediction (Gilbert, Boulter, & Rutherford, 1998). As models are products of human thoughts and often developed within inspiring social environments, Van Driel and Verloop (1999) reported a key role of creativity and communication when investigating science teachers views towards modeling.

Gilbert (2004) emphasized two requirements for increasing the authenticity of science education: On the one hand, with models and modeling taking a central position, it is inevitable that they will be adopted in classrooms as well. Genetics is one of the most important topics in modern biology, yet it is very difficult to learn as well as to teach abstract concepts and invisible processes (*e.g.*, Fisher, 1992; Kindfield, 1991). Numerous studies strongly recommended the inclusion of models in order to enhance teaching routines in genetics (*e.g.*, Malacinski & Zell, 1996; Templin & Fetters, 2002). On the other hand, the core element of creativity has made science a major cultural achievement, specifically in the context of modeling (Van Driel & Verloop, 1999). Holm-Hadulla (2010) defined creativity as a combination of talent, knowledge, ability, intrinsic motivation, and personality traits, additionally impacted by environmental aspects. Additionally, a mental state called ‘flow’ is often connected with creative processes: it is characterized by complete absorption in an activity (meaning that a person is fully immersed in a feeling of energized focus, full involvement and enjoyment; Csikszentmihalyi, 2000). Neuroscientific research has shown promising ways to identify particular brain areas associated with aspects of creative thinking (*e.g.*, Aberg, Doell, & Schwartz, 2016; Thagard & Stewart, 2011). However, research on quantifying creativity is still ambiguous (*e.g.*, Amabile, 2012; Runco, 2004). Recent studies have demonstrated a valid and reliable way in order to empirically monitor this variable (Miller & Dumford, 2016). Subsequently, Conradty and Bogner (2018) adjusted the creativity scale for adolescent age groups of secondary school students.

1.2. Gender differences in science education

Although progress has been made in narrowing the 'gender gap', women continue to be underrepresented in science (Gilbert & Calvert, 2003; Scantlebury & Baker, 2007). Numerous studies of science and gender have been published from various areas such as psychology, sociology, philosophy, and various branches of education (Brotman & Moore, 2008). The results of Fortus and Vedder-Weiss (2014) showed once again the motivational gap between boys and girls in science and revealed that this gap is also evident in everyday extracurricular scientific activities, and that already for 5th graders. Focusing on high school students' views of science, Miller, Blessing, and Schwartz (2006) reported low female interest in science classes and science in general. Biology made an exception, probably because of its connection to medicine or other popular health professions rather than to science *per se*. One possible reason could lie in the identified masculine nature of science associated with certain gender role expectations and conflicts about balancing family and scientific careers (Kahle & Meece, 1994; Scantlebury & Baker, 2007). Even scientifically gifted girls regard their academic strength more in verbal areas (Olszewski-Kubilius & Turner, 2002). However, the performance scores on science achievement within standardized tests often do no longer show significant gender differences (National Science Board, 2002).

As most scientific workplaces remained strongly masculine, numerous approaches to promote girls' interest in science have been developed in the last decades (Gilbert & Calvert, 2003): An appropriate strategy seems to temporarily separate girls and boys in sciences classes. Nonetheless, the adaptation of science curricula to support girls' interests appears to be effective (Häussler & Hoffmann, 2002). Considering changing societal views toward women, the historical development of feminist perspectives on science education also has been observed in several studies (*e.g.*, Brickhouse, 2001; Howes, 2002). However, factors such as the presence of strong female role models in young women's lives have not been decisive in supporting science interests at university level (Gilbert & Calvert, 2003). With regard to science laboratory experience and outreach labs, the learning environment, hands-on activities as well as collaborative learning methods seemed to be gender-related (Goldschmidt & Bogner, 2016): Female students tend to prefer learning methods in which they could act as cooperative teams with students helping each other (Miller, Blessing, & Schwartz, 2006), while male students seem to benefit more from teacher-centered methods (Lord, 2001; Meece, Glienke, & Burg, 2006). Additionally, authentic learning situations and an everyday-life context of the learning activities are regarded as important factors for girls to develop an interest in science (Linn, Davis, & Bell, 2004). In line with this, Burkam, Lee, and Smerdon, (1997) described student-centered, hands-on lab activities as successfully supporting girls, in emphasizing the importance of learners' active involvement - as realized in outreach labs - in order to promote gender equality.

Nonetheless, model-supported teaching approaches in outreach labs have still been subject to little research, especially regarding gender or individual creative thinking abilities. As modeling and creativity are both seen as key factors for science learning (Van Driel & Verloop, 1999), observing

impacts on elaborating models is an issue of research. When within an outreach genetic module hands-on modeling is combined with experimentation, creativity may successfully influence modeling and learning. Additionally, our approach could give a working example to promote gender-equality in science education as it includes several collaborative hands-on activities embedded in an authentic learning environment. Our study sought to answer four questions:

(1) Whether and how does a modeling-based approach influence students' cognitive achievement in a hands-on module?
(2) To what extent is creativity related to cognitive achievement when models are constructed in a hands-on module?
(3) How is model quality related to individual creativity levels and cognitive achievement?
(4) Whether and in which way does gender matter?

2. Methods

2.1. Instructional design

Our intervention was implemented at an outreach university lab, designed for hands-on teaching. Completion of the inquiry-based module '*Simply inGEN(E)ious! The DNA as carrier for genetic information*' required 270 min and included five phases: one pre-lab phase, two experimental phases, one model phase and one interpretation phase. A detailed schedule of learning activities is presented in Table 1. Always before starting the hands-on activities the subsequent tasks were introduced in theoretical minds-on activities presented by the teacher (Scharfenberg & Bogner, 2011). A workbook led through the module with information, experiment instructions and upcoming challenges during experimentation and modeling.

To prevent learning difficulties caused by a lack of basic experimental skills, a teacher-centered pre-laboratory phase was included (Scharfenberg & Bogner, 2011). Hypothesizing about the identification of a hypothetical murderer, the first experimental phase of isolating individual DNA from oral mucosal cells was introduced (Langheinrich & Bogner, 2015). To discover the molecular DNA-structure, the second experiment required completing a gel electrophoresis. The experimental sections were linked together by the model phase: After mental modeling students produced a physical DNA-model with no further instructions except an information text with selected leading questions. Additionally, an ad-hoc modeling box containing various handcrafting materials (*e.g.*, glue, straws, scissors, pipe cleaners, colored beads and cardboards) was supplied for the independent model elaboration. During the final interpretation of the experimental results, the findings of the model phase were discussed. All learning contents followed the current syllabus (ISB, 2007). The entire intervention was implemented by the same teacher. Students always worked in pairs. To optimize the module elements, the teaching-unit had been pilot-tested.

Table 1 Schedule and learning activities of the gene technology module '*Simply inGEN(E)ious! DNA as a carrier of genetic information*' with hands-on modeling.

Timeline [min]	*Phase of teaching unit*	*Content*	*Learning activity*
50	PreLab phase	Be prepared! How to work like a gene technology scientist	Practicing essential techniques of a scientist in a gene technology lab, *e.g.*, micro pipetting, decantation and centrifugation.
60	Experimental phase 1	Spin your DNA! The material character of DNA	Based on the report of a real crime, students initially hypothesize what evidence is needed to convict a murderer flawlessly. In the practical task students isolate individual DNA from oral mucosal cells. Students recognize that the molecular DNA-structure is invisible for the naked eye.
60	Experimental phase 2.1	Visualize the invisible (Part 1): Agarose gel electrophoresis - an essential gene technology procedure	To gain more information about the DNA-structure the teacher introduces the agarose gel electrophoresis. Students prepare their previously isolated DNA for the electrophoresis and the teacher then starts the electrophoresis device.
60	Modeling phase	On the footsteps of two GEN(E)iuses: How Watson & Crick solved the molecular puzzle of DNA-structure	Reading a text about Watson & Cricks' breakthrough in decoding the DNA, the students acquire essential knowledge about DNA-structure and answer comprehension questions in their workbooks. Originating from their answers they construct independently a model of the molecular DNA-structure.
25	Experimental phase 2.2	Visualize the invisible (Part 2): Results of the agarose gel electrophoresis	Students describe the results of the agarose gel electrophoresis and think about appropriate explanations.
15	Interpretation phase	DNA - A macromolecule of life: Review of the module	Group discussion of the experimental results by connecting them to students' DNA-models.

2.2. Participants

114 ninth graders at the highest stratification secondary school level ('Gymnasium') participated in our study (40.87% female; age $M \pm SD = 14.45 \pm 0.69$). Data were collected from six classes of five different secondary schools in Bavaria. A test-retest sample also from highest stratification secondary school level ($n = 39$; 100.00% female; age $M \pm SD = 14.69 \pm 0.57$) completed the knowledge questionnaire neither

participating in the module nor receiving any instruction on the topic during data collection. As genetics is a new topic in the grade 9 curriculum (ISB, 2007), participants were regarded as novices.

2.3. Instruments

Our study applied a pre-test (T0), post-test (T1) and retention-test (T2); the first two weeks before the teaching-unit, the second immediately after and the last six weeks after participation. The multiple-choice knowledge-test (KN0, KN1, KN2) consisted of 30 items with varying difficulty levels (*see* Table 2), covering the contents of the gene technology module in order to evaluate cognitive achievement. Every item offered four response options, only one of which was correct. At each testing schedule, the order of questions and answers were changed randomly. Students were never aware of any testing schedules.

Table 2 Item examples with varying difficulty levels of the cognitive knowledge questionnaire (partly adapted from Langheinrich, & Bogner, 2016). Questions were split up into subcategories evaluating the model subunit or the laboratory activities. Correct answers are written in *italics*.

Evaluated subunit	*Level of difficulty*	*Item example*
laboratory activity	1 (reproduction)	The electrophoretic separation of DNA-molecules is based on the DNA-component … a) thymine b) *phosphate* c) sugar d) cytosine
	1 (reproduction)	With the help of a centrifuge … a) you can mix a sample. b) the molecules are set into motion. c) single molecules can be isolated. d) *solid substances can be separated from liquids.*
model phase	2 (reorganization)	Give the opposite bases to the base sequence: AATGGG *(Capital letters = initial letter of the base, e.g. 'A' for adenine)* a) TTGCCC b) *TTACCC* c) TTGAAA d) GGACCC
	3 (transfer)	The analysis of a DNA-section revealed a proportion of guanine with 30%. Following, the proportion of adenine is … a) *20%.* b) 70%. c) also 30%. d) is not determinable.

The analysis was conducted using sum scores: correct answers were scored ‘1’, incorrect answers ‘0’. Internal consistency testing yielded reasonable Cronbachs’ *alpha* values above 0.7 (number of items = 30; *alpha* $_{KN0}$ = 0.736, *alpha* $_{KN1}$ = 0.869, *alpha* $_{KN2}$ = 0.864). Item difficulty ranged between 10% and 90%. The mean-item-difficulty, defined as the percentage of students answering an item correctly (Döring & Bortz, 2016) showed an average of 49.1% for all items during all test intervals. To control for any effects of repeated measure designs, a test-retest sample followed the same procedure of completing the tests without participation in the module. Additionally, we assessed creativity in the pre-test (T0) using the modified scale of Conradty and Bogner (2018) with its 4-digit Likert-scale response pattern ranging from ‘1’ (*never*) to ‘4’ (*very often*). The Cronbach’s *alpha* was 0.736. Two subscales were applied: ‘act’ covered conscious and trainable cognitive processes and ‘flow’ monitored elements of flow experiences, a mental state of creativity (*e.g.* Table 3).

Table 3 Item examples for monitoring creativity (Conradty & Bogner, 2018) using an adjusted version of the ‘Cognitive Processes Associated with Creativity’ scale (Miller & Dumford, 2016).

Subscale	*Item example*
Act	I combined dissimilar concepts to create a novel idea.
	I incorporated a previously used solution in a new way.
	I made a connection between a current problem or task and a related situation.
Flow	I was fully immersed in my work on a problem or task.
	I lost track of time when working intensely.
	I felt that work was automatic and effortless during an enjoyable task.

For evaluating the DNA-models, we followed the category system of Langheinrich & Bogner (2015) by analyzing the models and corresponding drawings produced, and taking five different categories (*e.g.*, analysis sector ‘Bases’) into consideration. We adapted the existing category system with regard to the expected performance of 9th graders and the content of the module (Table 4). We simultaneously graded the resulting models, drawings and inscriptions regarding the concrete representations and structural characteristics using sum scores (*e.g.*, analysis sector BA1: ‘1′ point for ‘symbolized bases’ or ‘2’ points for ‘symbolized and qualified bases’; max. 19 points for the complete model evaluation). To guarantee reliability we randomly selected 15% of students’ DNA-models for intra- and inter-rater categorization. The dataset was categorized for a second time by the first author after three months (intra-rater) and by a nonpartisan person (inter-rater). We computed Cohen’s Kappa coefficient (Cohen, 1968) and obtained reliability scores for the intra-rater reliability of *kappa* = 0.815 and for the inter-rater reliability of *kappa* = 0.693. These scores can be rated as almost perfect or rather substantial (Landis & Koch, 1977) justifying a high degree of objectivity for the applied category system. Participants were unaware of any testing cycles and received no further instructions on the topic

during data collection except from our teaching module. All questionnaires were paper-and-pencil-tests completed under controlled conditions.

Table 4 The category system for evaluating modelled and drawn elements (adapted from Langheinrich & Bogner, 2015)

Analysis sector		*Evaluation scale*	*Description*
Bases	**BA1**	0	No bases symbolized
		1	Bases symbolized
		2	Bases symbolized and qualified
		3	Base pairs symbolized
		4	Base pairs symbolized and qualified
	BA2	0	Hydrogen bonds not symbolized
		1	Hydrogen bonds symbolized
		2	*Hydrogen bonds correctly symbolized*
	BA3	0	Bases are not linked with the backbone
		1	Bases are linked with the backbone
		2	Bases are correctly linked with the backbone
Deoxyribose	**DE**	0	Deoxyribose not symbolized
		1	Deoxyribose symbolized
		2	*Deoxyribose symbolized and named*
Phosphate	**PH**	0	Phosphate not symbolized
		1	Phosphate symbolized
		2	*Phosphate symbolized and named*
Primary structure	**PR1**	0	*No primary structure identifiable*
		1	Single strand identifiable
		2	Double strand composed of two single strands identifiable
	PR2	0	No linkage between deoxyribose and phosphate
		1	Linkage between deoxyribose and phosphate
		2	Deoxyribose and phosphate symbolized alternating as a polymer
Secondary structure	**SE**	0	No secondary structure identifiable
		1	False secondary structure identifiable
		2	*Double helix identifiable*
		3	*Right-handed double helix identifiable*

Note. Adapted or supplemented categories are written in *italics*. The subcategory OR (organizational level) was not applied in the context of the module.

2.4. Statistical analysis

All statistical tests were conducted using IBM SPSS Statistics 23.0. Our analyses were based on non-parametric methods due to a non-normal distribution examined by Kolmogorov-Smirnov-test [Lilliefors modification]; $p < .01$), the assessment of Skewness and Kurtosis as well as investigating Q-Q-Plots. Changes in knowledge within the three test schedules were analyzed by using Friedman's ANOVA and Wilcoxon's *post-hoc* analyses. Second, Mann-Whitney-*U*-tests (MWU) were used for comparisons between the gender subgroups. In case of significant results, we additionally calculated effect sizes *r* according to Field (2013) and assumed scores of 0.1, 0.3, and 0.5 as small, medium and large effect sizes (Cohen, 1992). Furthermore, we used Spearman's Rho for correlation analyses between cognitive achievement, creativity and model quality.

3. Results

As expected, a simple test-retest sample did not produce any testing effects (Mdn $_{KN0}$ = 5.00, Mdn $_{KN1}$ = 4.64, Mdn $_{KN2}$ = 4.38): the completion of the knowledge questionnaire did not affect learning processes. In contrast, knowledge scores for the main sample varied significantly between measurement schedules (Mdn $_{KN0}$ = 10.04, Mdn $_{KN1}$ = 20.73, Mdn $_{KN2}$ = 17.24; Chi-squared (2) = 177.278, $p < .001$). Table 5 presents the inner-group comparison of knowledge levels within the gender subsamples.

Table 5 Inner-group comparison of knowledge levels. Knowledge scores within the gender subsamples differed significantly between measurement times(T0: pre- , T1: post- , T2: retention-test).

	z	*p*	*r*
[a] *Boys*			
T1-T0	-7.12	<.001***	-.62
T2-T0	-6.15	<.001***	-.53
T2-T1	-5.87	<.001***	-.51
[b] *Girls*			
T1-T0	-5.97	<.001***	-.62
T2-T0	-5.96	<.001***	-.61
T2-T1	-4.78	<.001***	-.49

Note: [a]$n = 67$; [b]$n = 47$.

Gender produced a difference in prior knowledge, before participation in our teaching-unit (Mdn $_{boys}$ = 10.89; Mdn $_{girls}$ = 9.00), $U = 1208.00$, $z = -2.23$, $p = .026$, $r = -0.21$ (Fig. 1). However, no differences in short-term knowledge levels between the gender subsamples appeared (Mdn $_{boys}$ = 20.31;

Mdn $_{girls}$ = 21.13), U = 1323.50, z = −1.57, *n.s.* Furthermore, the mid-term knowledge levels did not vary significantly in the content knowledge of the module (Mdn $_{boys}$ = 16.71; Mdn $_{girls}$ = 17.70), U = 1374.00, z = −1.28, *n.s.* Between-group comparisons have shown that the knowledge increase (KN1-KN0) varied significantly between boys and girls (U = 1052.00, z = −3.12, p = .002, r = −0.29) but no gender-dependent significant differences for the knowledge decrease rate (KN2-KN1) were revealed (U = 1590.50, z = −0.04, *n.s.*). Since the students were free to decide with which classmates they would like to work together, we also examined the gender distribution in the student pairs: only 10.4% worked in a mixed gender group, whereas 54.8% were male pairs and 34.8% female pairs. When focusing students prior knowledge differences coupling in the pairs we revealed no significant results (Mdn $_{DifKN0\ males}$ = 2.59, Mdn $_{DifKN0\ females}$ = 2.73, Mdn $_{DifKN0\ mixed}$ = 3.29; Chi-squared (2) = 1.022, *n.s.*).

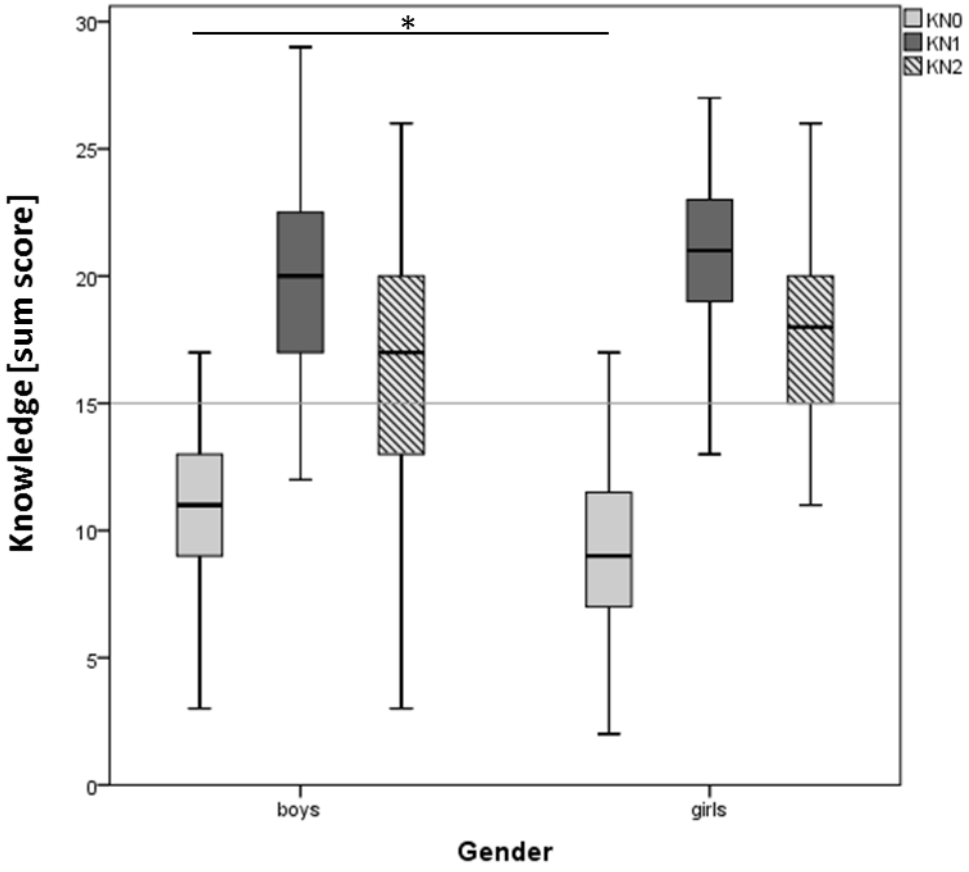

Fig. 1 Cognitive achievement for the gender subsamples (knowledge sumscore of all items; max. ∑30): Girls showed a significantly (p = .026; r = −.21) lower knowledge sumscore in pre-test (KN0).

Additionally, the creativity measure did not indicate any gender differences for the subscale ‘act’ (Mdn $_{boys}$ = 2.39; Mdn $_{girls}$ = 2.32), U = 1486.50, z = -0.51, *n.s.* as well as for the subscale ‘flow’ (Mdn $_{boys}$ = 2.21; Mdn $_{girls}$ = 2.33), U = 1450.50, z = -0.72, *n.s.*

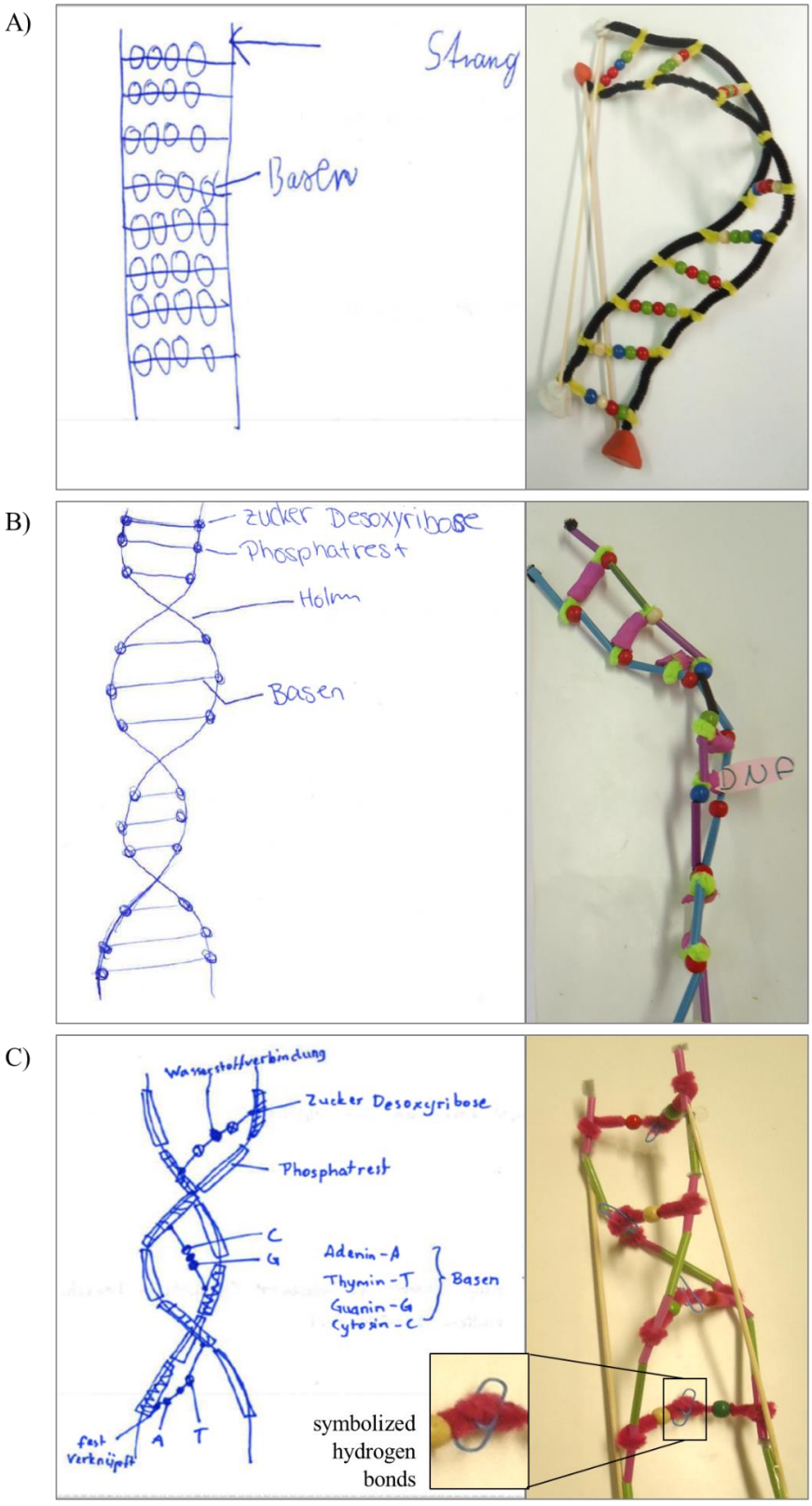

Fig. 2 Key examples model evaluation: Results of the hands-on modeling phase with corresponding drawings. A) low rated DNA-model (5 points) B) medium rated DNA-model (12 points) C) high rated DNA model (19 points).

Note. Strang = strand; Basen = bases; Holm = holm; Wasserstoffverbindung = hydrogen bonds; Zucker = sugar; fest verknüpft = firmly linked

The hands-on modeling phase revealed a variety of model qualities, ranging from little evidence to plenty of DNA characteristics (Mdn $_{model\ quality}$ = 13.78). Key examples for different model qualities and corresponding drawings are presented in Fig. 2. There were significant gender differences: Fig. 3 shows that the girls achieved significantly higher scores for their constructed models than the boys (Mdn $_{boys}$ = 13.50; Mdn $_{girls}$ = 15.58), U = 1094.00, z = −2.79, p = 0.005, r = -0.26. When comparing the model quality of the mixed pairs with the female pairs we found no significant differences (Mdn $_{mixed}$ = 15.00; Mdn $_{females}$ = 15.80), U = 219.50, z = −0.45, *n.s.*

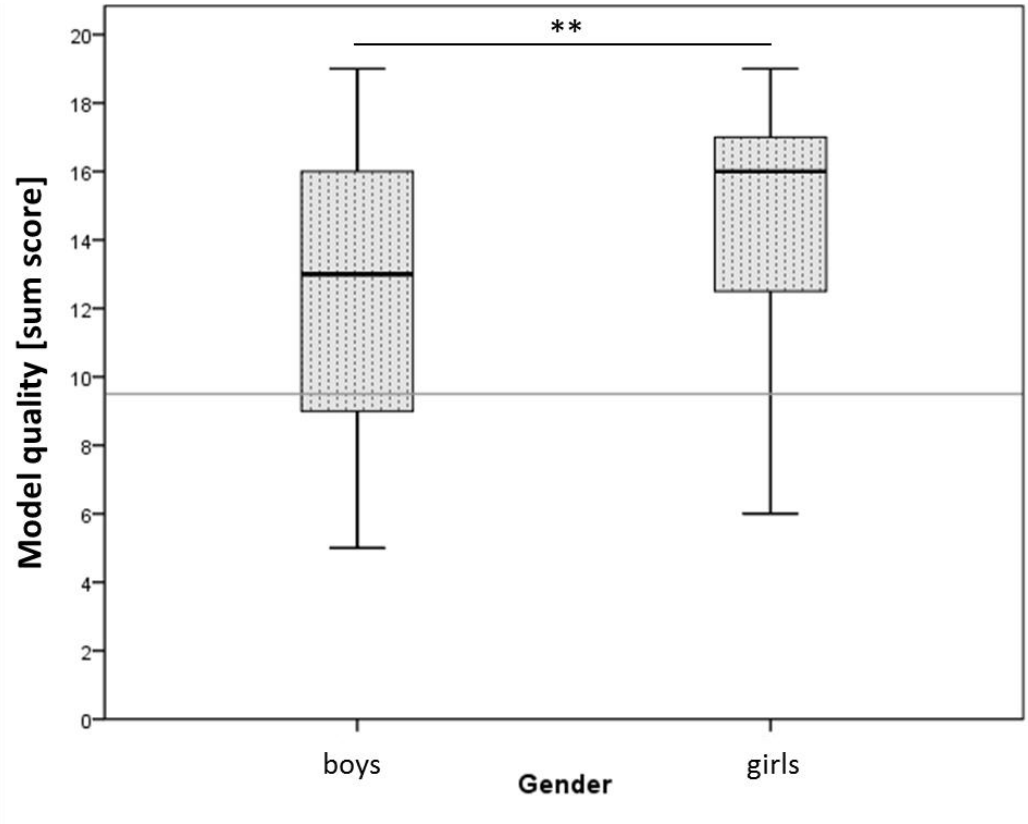

Fig. 3 Gender differences in the model quality sum scores of the hands-on modeling phase (max. ∑ 19): Girls´ modelled and drawn results of the modeling phase are significantly higher (p = .005; r = −.26). *Note*. n_{boys} = 67; n_{girls} = 47.

We correlated knowledge sum scores at all test times with the creativity subscales ‘act’ (conscious and trainable cognitive processes) and ‘flow’ (describing typical elements of flow experiences). Gender produced different patterns: There was no relationship between cognitive achievement and creativity for the boys across all test times or for the girls at the pre-test (KN0). Significant positive correlations were revealed between girls’ short-term (KN1) and mid-term knowledge levels (KN2) with the creativity subscale ‘flow’. In contrast, no relations with the creativity subscale ‘act’ were observed.

Correlations between cognitive achievement and students’ model quality did not exist for the boys’ knowledge scores at any test time. Girls’ prior-knowledge (KN0) is not related to model quality.

In contrast, the girls' model quality correlates clearly positively with their short-term (KN1) and mid-term knowledge levels (KN2).

Considering possible connections between students' creativity and the model quality, no correlations with either gender subsample were observed. Table 6 summarizes the relations between model constructor girls' short- and mid-term knowledge levels with the creativity subscale 'flow' and with the model quality.

Table 6 Correlations for the model constructor girls between the model quality (model sumscore) and the creativity subscale 'flow' to cognitive achievement (complete module).

	girls' cognitive achievement		
	KN0	*KN1*	*KN2*
Model quality	*n.s.*	.408**	.385**
Creativity subscale 'flow'	*n.s.*	.338**	.469**

Notes. n (*girls*) = 47; Spearman´s correlation coefficient r_s; *KN1*: knowledge post-test; *KN2*: knowledge retention-test; *KN0*: no correlations at knowledge pre-test ($r_s \leq .232$; $p \geq .117$).

4. Discussion

Combining hands-on experimentation with creative model-construction is beneficial for boys and girls in producing short- and a mid-term knowledge increases. Although girls started from significantly lower prior knowledge levels, they closed the knowledge gap during our module. Higher model quality scores and 'flow' experiences might probably help girls to benefit the most. In summary, even short-term interventions combining hands-on model work with experimentation promote cognitive achievement: this is in agreement with research in the field of outreach learning (*e.g.*, Meissner & Bogner, 2011; Sellmann & Bogner, 2013) and for learning in gene technology out-of-school labs (Goldschmidt, Scharfenberg, & Bogner, 2016; Langheinrich & Bogner, 2016; Mierdel & Bogner, 2018). When comparing the effectiveness of illustrations versus three-dimensional models in the context of genetics, Rotbain, Marbach-Ad, & Stavy (2006) also reported such knowledge gains for model application. Hence, our out-of-school module may bridge modeling with experimental work and offer a promising method for linking abstract scientific theory with practical experiences (Gilbert, Boulter, & Rutherford, 1998). Furthermore, as modeling and creativity are both seen as key factors for science learning (Van Driel & Verloop, 1999), a closer investigation of individual creativity levels and model quality is of potential interest in supporting learning.

National education standards (KMK, 2005) have a number of requirements referring to the nature of models and emphasize modeling as a typical scientific procedure. However, model elaboration still is a neglected methodical aspect of scientific model application in science classrooms (Grünkorn, Upmeier zu Belzen, & Krüger, 2014; Oh & Oh, 2011). Svoboda and Passmore (2013) named benefits

of modeling like concretizing abstract ideas, simplifying and clarifying complex phenomena, making predictions about future events, and facilitating the communication of ideas. Thus, model elaboration is regarded a powerful inquiry-based learning strategy: it is thought to strengthen important modeling abilities like shaping various models of a selected phenomenon. Students worked with no instructions except an information text, and were expected to independently find a solution for the given challenge. As successful modeling seems to demand a complex suite of strategies, we observed, with respect to the schedule of the model phase, that some participants struggled to complete an acceptable DNA-model within the time limits set. Although the time aspect of modeling in biology class has scarcely been investigated, we conclude that model construction is a time-intensive activity, which may explain its rare application in biology classroom routines.

Individual creativity might be essential for successful model elaboration, including a process of sensitization for problems or knowledge gaps, searching for solutions and even contributing to a 'deeper learning' (Chow, 2010). As repeatedly shown in science history, creativity occupies a unique place for innovation and may contribute to the quality of education (Braben, 2004; Lunn & Noble, 2008). In the context of genetics, Watson and Crick (1953) provided a paradigm in benefitting from individual creativity when discovering by modeling the code of DNA-structure. Such discovery processes are reported as most enjoyable experiences linking creativity and science as closely related fields (Csikszentmihalyi, 2015). The potential impact of creativity within educational approaches is under-researched although art education is an established school subject (Zimmerman, 2009). However, creativity is not exclusively connected to arts; and creative mental abilities are required for all spheres of life and maybe especially for science (Conradty & Bogner, 2018). As traditional science education (STEM=Science, Technology, Engineering, Maths) is often associated with negative perceptions and learning difficulties (Schumm & Bogner, 2016; Epstein & Fischer, 2017), increased efforts have been taken to modify STEM to STE**A**M, thus integrating arts and encouraging creative solutions (Henriksen, 2014). STE**A**M (STEM & **A**rts) might help to transfer enthusiasm from artistic work to science to support individual self-efficacy and thus, to close the 'creativity gap' (Runco, Acar, & Cayirdag, 2017). Observation of our participants led us to strongly agree with these assumptions; the artistic aspect of working with handcraft materials positively attracts learners' attention and supports motivation during model construction. One reason could be that students can act more creatively and without restrictions in presenting information than in traditional model-supported approaches, in which the medial perception (model viewing) is typically favored (Mierdel & Bogner, 2018; Oh & Oh, 2011; Treagust, Chittleborough, & Mamiala, 2002).

Following Miller and Dumford's (2016) request for further research into creative thinking in science classrooms, we investigated the impact of creativity in a STEAM gene technology module finding equal creativity levels for both genders. Surprisingly, we also obtained no correlations between individual creativity levels and model quality, although more creative students are expected to achieve a higher model quality score. Therefore, other variables apparently contribute to creativity, such as

novice learners' difficulty in handling complex information. Genetics as an abstract topic may generate a large working memory load which, of course, hinders the learning processes (Kirschner, Sweller, & Clark, 2006): *Model constructors* had to deal especially with transmitting the text's information correctly into an adequate model of DNA-structure, thus blocking their individual creativity especially when perfectionism or strict target orientation was demanded (Grant, Grant, & Gallate, 2012). However a closer look reveals the relation between 'flow' experiences and cognitive achievement for girls: the subscale 'flow' influences girls' short- and mid-term knowledge and is also linked with high intrinsic motivation scores. High 'flow' level signals a fully immersed status in a feeling of energized focus and enjoyment (Csikszentmihalyi, 2000). Even though boys reached similar knowledge and creativity levels, no effects regarding a correlation of these variables were observed; other factors such as hands-on experimentation and the scientific workspace concept may contribute. Discussions of different gender creativity scores in the literature are ambiguous: some studies regard women as more creative (*e.g.*, Ülger & Morsünbül, 2016), others men (*e.g.*, Shin, Jung, Choe, & Han, 2002), and yet others deny any differences (Besançon & Lubart, 2008).

4.1. Methodological aspects

According to our results we can reject an effect of repeated measures, confirming that students did not learn just from completing the knowledge questionnaire. However, the test-retest sample performed at a first look much worse at measurement moment KN0, although both test groups worked on the same knowledge test. At a statistical rate probability of 25%, students cross on average 7.5 correct answers for 30 items with four answer options each. As data of the test-retest sample was collected at a girls' school, prior knowledge levels need to be compared with the girls' prior knowledge of the main sample ($Mdn_{girls\ test\text{-}retest} = 5.00$ vs. $Mdn_{girls\ main\ sample} = 9.00$). It can be stated that the test-retest sample is just below the guessing probability while the girls' main sample is just above. Those differences could be explained with motivational reasons: While the main sample was aware that the pre-test was a requirement for visiting a laboratory at the university, the test-retest sample had no incentive to make any particular effort for the test. Especially with regard to still further decreasing knowledge scores of the test-retest sample at KN1 and KN2, an explanation based on low motivation seems reasonable.

4.2. Impact of model quality and educational implications

The influence of model quality on girls' cognitive achievement is apparent, as successful modeling goes hand in hand with a short- and a mid-term knowledge increase. This connection emphasizes the importance of model elaboration for learning genetics, although this relationship appears to exist for girls only. Higher model quality demonstrates that girls are more attracted to our creative and artistic hands-on approach, providing a working example of a successful STEAM approach to promote gender equality (Burkam, Lee, & Smerdon, 1997). Although we must reject the impact of

modeling on boys' cognitive achievement, a combination of hands-on experimentation with modeling might be appropriate for both genders. Nonetheless, adaptions for current model constructing approaches need further discussion.

To overcome potential influences we monitored individual modeling experiences by self-assessment, revealing low levels of modeling skills (investigated in detail Mierdel & Bogner, 2018). A lack of modeling experience could explain lower rated DNA-models and lower individual knowledge scores. Justi and Gilbert (2002) pointed to the need for teachers' competence in modeling: As many teachers possess only a suboptimal understanding of 'models and modeling', modeling application for science classes may need extra emphasis in pre- and in-service teacher education.

Additionally, as some DNA-models remained incomplete, a few *model constructors* may have had misconceptions about the DNA-structure. Langheinrich and Bogner (2015) demonstrated as a typical problem the correct understanding of the three genetics concepts: DNA, gene and chromosome. Changing the hierarchical organizational level of DNA-structure between the experimentation and the modeling phase may have prevented the achievement of a correct and complete result. When discussing adaptions for our model constructing approach (Mierdel & Bogner, 2018) we gave two recommendations regarding the 'Model of Modeling' (Justi & Gilbert, 2002): First, a pre-modeling phase to explain and train necessary modeling skills. Second, a post model evaluation, *e.g.* within a group discussion, to identify and correct misconceptions about DNA-structure.

Nevertheless, our study may have two limitations: First, as students were from the highest stratification secondary school level ('Gymnasium'), we cannot generalize the results for other school levels or other grades. As genetics is a complex and abstract field, we decided on the highest school level because genetics is already part of the curriculum in 9th grade. Additionally, in other school levels the topic receives less attention and is taught in higher classes so that comparability would be difficult. A second restriction might be the sample size when comparing girls (n = 47) and boys (n = 68 boys). However, the implemented activities (experimentation and modeling) in a laboratory situation were complex in preparation as well as in evaluation. For these reasons, we examined only five classes and think that more research could give a closer look on relations between modeling and gender.

5. Conclusion

Strategies aiming towards a more authentic science education, thus integrating modeling as a typically scientific procedure, are required to provide further benefits such as offering multiple ways for learning science (Gilbert, 2004). Integrating arts in science might offer a chance to overcome negative perceptions of traditional science views, by transferring enthusiasm from arts to science (Runco, Acar, & Cayirdag, 2017). As creativity plays a key role for both, connecting arts and creative mental abilities may introduce an innovative approach for science education (Conradty & Bogner, 2018). Our findings

clearly demonstrate the potential of creative hands-on modeling in addition to classic experimental challenges in an inquiry-based outreach module.

We conclude that both genders had similar requirements while model constructing; both showed similar individual creativity levels as well as no influence of creativity on their model quality. However, a closer investigation paints a more precise picture: Although girls started with significant lower prior knowledge levels, they closed their knowledge gap during participation. Additionally, significant relations between model quality and 'flow' experiences were observed only between girls' short- and midterm knowledge levels. In summary, the model constructing approach seems to better support girls, while the boys compensated for their simpler modeling outcomes possibly with acquired knowledge from the experimental parts of the module. Our module presents a suitable STEAM teaching method to introduce new impulses into science classes. Although modeling as a student-centered and authentic scientific teaching method has been praised in theory for years and its application requested by national education standards, it remains an outsider in educational practice. This must be changed.

Acknowledgements

This study was supported by the 'CREATIONS' project funded by the European Union's HORIZON 2020-SEAC-2014-1 Program (Grant: 665917) and by the 'Qualitätsoffensive Lehrerbildung' Program funded by the German Federal Ministry of Education and Research (BMBF; Grant: 01JA160). This article reflects only the author's views and the European Union as well as BMBF are not liable for any use that might be made of information contained herein. Special thanks go to teachers and students involved in this study for their cooperation. We also thank Michael Wiseman for discussing earlier stages of our paper.

References

Aberg, K. C., Doell, K. C., & Schwartz, S. (2016). The 'Creative right brain' revisited: Individual creativity and associative priming in the right hemisphere relate to hemispheric asymmetries in reward brain function. *Cerebral Cortex*. https://doi.org/10.1093/cercor/bhw288.

Amabile, T. M. (2012). *Social psychology of creativity*. New York, U.S: Springer.

Ben-Nun, M. S., & Yarden, A. (2009). Learning molecular genetics in teacher-led outreach laboratories. *Journal of Biological Education*, 44(1), 19–25. https://doi.org/ 10.1080/00219266.2009.9656187.

Besançon, M., & Lubart, T. (2008). Differences in the development of creative competencies in children schooled in diverse learning environments. *Learning and Individual Differences*, 18(4), 381–389. https://doi.org/10.1016/j.lindif.2007.11.009.

Blanchard, M. R., Southerland, S. A., Osborne, J. W., Sampson, V. D., Annetta, L. A., & Granger, E. M. (2010). Is inquiry possible in light of accountability? A quantitative comparison of the relative effectiveness of guided inquiry and verification laboratory instruction. *Science Education*, 94(4), 577–616. https://doi.org/10.1002/sce.20390.

Braben, D. (2004). Pioneering research: A risk worth taking. Hoboken, New Jersey, U.S: John Wiley & Sons.

Brickhouse, N. W. (2001). Embodying science: A feminist perspective on learning. *Journal of Research in Science Teaching*, 38(3), 282–295.

Brotman, J. S., & Moore, F. M. (2008). Girls and science: A review of four themes in the science education literature. *Journal of Research in Science Teaching*, 45(9), 971–1002. https://doi.org/10.1002/tea.20241.

Bryce, T., & Robertson, I. (1985). What can they do? A review of practical assessment in science. *Studies in Science Education*, 12, 1–24.

Buckley, B. C. (2000). Interactive multimedia and model-based learning in biology. *International Journal of Science Education*, 22(9), 895–935. https://doi.org/10.1080/095006900416848.

Burkam, D. T., Lee, V. E., & Smerdon, B. A. (1997). Gender and science learning early in high school: Subject matter and laboratory experiences. *American Educational Research Journal*, 34(2), 297–331.

Chow, B. (2010). The quest for deeper learning. *Education Week*, 30(6), 1–3.

Cohen, J. (1968). Weighted Kappa: Nominal scale agreement with provision for scaled disagreement or partial credit. *Psychological Bulletin*, 70(4), 213–220.

Cohen, J. (1992). A power primer. *Psychological Bulletin*, 112(1), 155–159.

Conradty, C., & Bogner, F. X. (2018). From STEM to STEAM: How to monitor creativity. *Creativity Research Journal*, 30(3), 233-240. https://doi.org/10.1080/10400419.2018.1488195.

Csikszentmihalyi, M. (2000). *Beyond boredom and anxiety* (25th ed.). San Fransisco, U.S: Jossey-Bass Publishers.

Csikszentmihalyi, M. (2015). *The systems model of creativity. The collected works of Mihaly Csikszentmihalyi*. Dordrecht: Springer.

Döring, N., & Bortz, J. (2016). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften [Research methods and evaluation in social and human sciences]* (5th ed). Berlin Heidelberg, Germany: Springer-Verlag.

Epstein, N., & Fischer, M. R. (2017). Academic career intentions in the life sciences. Can research self-efficacy beliefs explain low numbers of aspiring physician and female scientists? *PloS One*, 12(9), e0184543. https://doi.org/10.1371/journal.pone.0184543.

Ferk, V., Vrtacnik, M., Blejec, A., & Alenka, G. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education*, 25(10), 1227–1245. https://doi.org/10.1080/0950069022000038231.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics* (4th ed.). London, UK: SAGE.

Fisher, K. M. (1992). *Improving high school genetics instruction. Teaching genetics: Recommendations and research proceedings of a national conference*. 199224–28.

Fortus, D., & Vedder-Weiss, D. (2014). Measuring students' continuing motivation for science learning. *Journal of Research in Science Teaching*, 51(4), 497–522. https://doi.org/10.1002/tea.21136.

Franke, G., & Bogner, F. X. (2011). Cognitive influences of students' alternative conceptions within a hands-on gene technology module. *The Journal of Educational Research*, 104, 158–170.

Gerstner, S., & Bogner, F. X. (2010). Cognitive achievement and motivation in hands-on and teacher-centred science classes: Does an additional hands-on consolidation phase (concept mapping) optimise cognitive learning at work stations? *International Journal of Science Education*, 32(7), 849–870. https://doi.org/10.1080/09500690902803604.

Giere, R. (1988). *Explaining science*. Chicago, U.S: University of Chicago Press.

Gilbert, J. K., Boulter, C., & Rutherford, M. (1998). Models in explanations, Part 1: Horses for courses? *International Journal of Science Education*, 20(1), 83–97. https://doi.org/10.1080/0950069980200106.

Gilbert, J., & Calvert, S. (2003). Challenging accepted wisdom: Looking at the gender and science education question through a different lens. *International Journal of Science Education*, 25(7), 861–878. https://doi.org/10.1080/09500690305030.

Gilbert, J. K. (2004). Models and modeling: Routes to more authentic science education. *International Journal of Science and Mathematics Education*, 2, 115–130.

Goldschmidt, M., Scharfenberg, F.-J., & Bogner, F. X. (2016). Instructional efficiency of different discussion approaches in an outreach laboratory: Teacher-guided versus student-centered. *The Journal of Educational Research*, 109(1), 27–36. https://doi.org/10.1080/00220671.2014.917601.

Goldschmidt, M., & Bogner, F. X. (2016). Learning about genetic engineering in an outreach laboratory: Influence of motivation and gender on students' cognitive achievement. *International Journal of Science Education Part B: Communication and Public Engagement*, 6(2), 166–187. https://doi.org/10.1080/21548455.2015.1031293.

Grant, A., Grant, G., & Gallate, J. (2012). *Who killed creativity? And how do we get it back?* Milton, Australia: Jossey Bass.

Grünkorn, J., Upmeier zu Belzen, A., & Krüger, D. (2014). Assessing students' understandings of biological models and their use in science to evaluate a theoretical framework. *International Journal of Science Education*, 36(10), 1651–1684. https://doi.org/10.1080/09500693.2013.873155.

Häussler, P., & Hoffmann, L. (2002). An intervention study to enhance girls' interest, self-concept, and achievement in physics classes. *Journal of. Research in Science Teaching*, 39(9), 870–888. https://doi.org/10.1002/tea.10048.

Henriksen, D. (2014). Full STEAM ahead. Creativity in excellent STEM teaching practices. *The STEAM Journal*, 1(2), 1–9. https://doi.org/10.5642/steam.20140102.15.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2006). Scaffolding and achievement in problem-based and inquiry learning: A response to kirschner, sweller, and clark. *Educational Psychologist*, 42(2), 99–107.

Holm-Hadulla, R. M. (2010). *Kreativität: Konzept und Lebensstil [Creativity: Concept and lifestyle]* (3rd ed). Göttingen, Germany: Vandenhoeck & Ruprecht.

Howes, E. V. (2002). *Connecting girls and science: Constructivism, feminism, and science education reform*. New York, U.S: Teachers College Press.

ISB (2007). *Bavarian syllabus gymnasium G8*. Wolnzach, Germany: Kastner.

Justi, R. S., & Gilbert, J. K. (2002). Modeling, teachers' views on the nature of modeling, and implications for the education of modellers. *International Journal of Science Education*, 24(4), 369–387. https://doi.org/10.1080/09500690110110142.

Kahle, J. B., & Meece, J. (1994). Research on gender issues in the classroom. In D. L. Gable (Ed.). *Handbook of research on science teaching and learning* (pp. 542–557). New York, U.S: Macmillan.

Kindfield, A. C. (1991). Confusing chromosome number and structure: A common student error. *Journal of Biological Education*, 25(3), 193–200 1991.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery,problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, 41(2), 75–86. https://doi.org/10.1207/s15326985ep4102_1.

KMK (2005). *Beschlüsse der Kultusministerkonferenz - Bildungsstandards im Fach Biologie für den Mittleren Bildungsabschluss [Resolution of the standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany - Standards of biology education for secondary school]*. Munich, Germany: Luchterhand.

Landis, R. J., & Koch, G. G. (1977). The Measurement of observer agreement for categorical data. *Biometrics*, 33, 159–174.

Langheinrich, J., & Bogner, F. X. (2015). Student conceptions about the DNA structure within a hierarchical organizational level: Improvement by experiment- and computer-based outreach learning. *Biochemistry and Molecular Biology Education*, 43(6), 393–402. https://doi.org/10.1002/bmb.20888.

Langheinrich, J., & Bogner, F. X. (2016). Computer-related self-concept: The impact on cognitive achievement. *Studies in Educational Evaluation*, 50, 46–52.

Linn, M. C., Davis, E. A., & Bell, P. (Eds.). (2004). *Internet environments for science education*. London, UK: Routledge (Lawrence Erlbaum Associates).

Lunn, M., & Noble, A. (2008). Re-visioning science 'love and passion in the acientific imagination': Art and science. *International Journal of Science Education*, 30(6), 793–805. https://doi.org/10.1080/09500690701264750.

Lord, T. R. (2001). 101 reasons for using cooperative learning in biology teaching. *The American Biology Teacher*, 63(1), 30–38. https://doi.org/10.1662/0002-7685(2001)063[0030:RFUCLI]2.0.CO;2.

Malacinski, G. M., & Zell, P. W. (1996). Manipulating the 'invisible': Learning molecular biology using inexpensive models. *The American Biology Teacher*, 58(7), 428–432 1996.

Meissner, B., & Bogner, F. X. (2011). Enriching students' education using interactive workstations at a salt mine turned science center. *Journal of Chemical Education*, 88(4), 510–515. https://doi.org/10.1021/ed1006103.

Meece, J. L., Glienke, B. B., & Burg, S. (2006). Gender and motivation. *Journal of School Psychology*, 44(5), 351–373. https://doi.org/10.1016/j.jsp.2006.04.004.

Miller, A. L., & Dumford, A. D. (2016). Creative cognitive processes in higher education. *The Journal of Creative Behavior*, 50(4), 282–293. https://doi.org/10.1002/jocb.77.

Miller, P. H., Blessing, J., & Schwartz, S. (2006). Gender differences in high-school students' views about science. *International Journal of Science Education*, 28(4), 363–381. https://doi.org/10.1080/09500690500277664.

Mierdel, J., & Bogner, F. X. (2018). Investigations of modellers and model viewers in an out-of-school gene technology laboratory (*submitted*).

National Science Board (2002). *Science and engineering indicators, Vol. 1*. Arlington, VA: National Science Foundation, Government Printing Office.

Oh, P. S., & Oh, S. J. (2011). What teachers of science need to know about models: An overview. *International Journal of Science Education*, 33(8), 1109–1130. https://doi.org/10.1080/09500693.2010.502191.

Olszewski-Kubilius, P., & Turner, D. (2002). Gender differences among elementary school-aged gifted students in achievement, perceptions of ability, and subject preference. *Journal for the Education of the Gifted*, 25(3), 233–268.

Randler, C., & Bogner, F. X. (2006). Cognitive achievements in identification skills. *Journal of Biological Education*, 40(4), 161–165. https://doi.org/10.1080/00219266.2006.9656038.

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2006). Effect of bead and illustrations models on high school students' achievement in molecular genetics. *Journal of Research in Science Teaching*, 43(5), 500–529. https://doi.org/10.1002/tea.20144.

Runco, M. A. (2004). Creativity. *Annual Review of Psychology*, 55(2004), 657–687.

Runco, M. A., Acar, S., & Cayirdag, N. (2017). A closer look at the creativity gap and why students are less creative at school than outside of school. *Thinking Skills and Creativity*, 24, 242–249. https://doi.org/10.1016/j.tsc.2017.04.003.

Scharfenberg, F.-J., Bogner, F. X., & Klautke, S. (2007). Learning in a gene technology laboratory with educational focus: Results of a teaching unit with authentic experiments. *Biochemistry and Molecular Biology Education*, 35(1), 28–39. https://doi.org/10.1002/bmb.1.

Scharfenberg, F.-J., & Bogner, F. X. (2011). A new two-step approach for hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene technology lab. *Research in Science Education*, 41(4), 505–523. https://doi.org/10.1007/s11165-010-9177-2.

Schmid, S., & Bogner, F. X. (2015). Effects of students' effort scores in a structured inquiry unit on long-term recall abilities of content knowledge. *Education Research International*. https://doi.org/10.1155/2015/826734 Article ID 826734.

Sellmann, D., & Bogner, F. X. (2013). Climate change education: Quantitatively assessing the impact of a botanical garden as an informal learning environment. *Environmental Education Research*, 19(4), 415–429.

Sotiriou, S., & Bogner, F. X. (2008). Visualizing the invisible: Augmented reality as an innovative science education scheme. *Advanced Science Letters*, 1(1), 114–122. https://doi.org/10.1166/asl.2008.012.

Sotiriou, S., Bybee, R. W., & Bogner, F. X. (2017). PATHWAYS – A case of large-scale implementation of evidence-based practice in scientific inquiry-based science education. *International Journal of Higher Education*, 6(2), 8. https://doi.org/10.5430/ijhe.v6n2p8.

Scantlebury, K., & Baker, D. (2007). Gender issues in science education research: Remembering where the difference lies. In S. Abell, & N. Lederman (Eds.). *Handbook of research on science education* (pp. 257–286).

Schumm, M., & Bogner, F. X. (2016). Measuring adolescent science motivation. *International Journal of Science Education*, 38(3), 434–449. https://doi.org/10.1080/09500693.2016.1147659.

Shin, J.-E., Jung, H.-C., Choe, S.-U., & Han, K.-S. (2002). Are boys more creative than girls? Based on the scientific creativity of gifted students. *Journal of the Korean Earth Science Society*, 23(4), 324–333.

Svoboda, J., & Passmore, C. (2013). The strategies of modeling in biology education. *Science Education*, 22(1), 119–142. https://doi.org/10.1007/s11191-011-9425-5.

Templin, M. A., & Fetters, M. K. (2002). A working model of protein synthesis using LegoTM building blocks. *The American Biology Teacher*, 64(9), 673–678 2002.

Thagard, P., & Stewart, T. C. (2011). The AHA! experience: creativity through emergent binding in neural networks. *Cognitive Science*, 35(1), 1–33. https://doi.org/10.1111/j.1551-6709.2010.01142.x.

Treagust, D. F., Chittleborough, G., & Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education*, 24(4), 357–368. https://doi.org/10.1080/09500690110066485.

Ülger, K., & Morsünbül, Ü. (2016). The differences in creative thinking: The comparison of male and female students. *The Online Journal of Counseling and education*,5(4), 1–12.

Van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modeling in science. *International Journal of Science Education*, 21(11), 1141–1153. https://doi.org/10.1080/095006999290110.

Watson, J. D., & Crick, F. H. C. (1953). Molecular structure of nucleic acids. A structure for deoxyribose nucleic acid. *Nature*, 171, 737–738.

Werner, S., Förtsch, C., Boone, W., von Kotzebue, L., & Neuhaus, B. J. (2017). Investigating how German biology teachers use three-dimensional physical models in classroom instruction: A video study. *Research in Science Education*, 1–27. https://doi.org/10.1007/s11165-017-9624-4.

Zimmerman, E. (2009). Reconceptualizing the role of creativity in art education theory and practice. S*tudies in Art Education*, 50(4), 382–399.

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Research in Science Education

pp. 1-22, 2019

First published online 9. Juli 2019. https://doi.org/10.1007/s11165-019-09871-3

Investigations of modellers and model viewers in an out-of-school gene technology laboratory

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Investigations of modellers and model viewers in an out-of-school gene technology laboratory

Abstract

Genetics is known to be one of the most challenging subjects in biology education because of its abstract concepts and processes. Therefore, hands-on experiments in authentic learning environments are supposed to increase comprehensibility and provide otherwise unavailable experiences to students. We applied a hands-on module in an out-of-school gene technology lab, combining experimentation and model work, in order to support the experimental work. In comparing the impact of two different approaches on cognitive achievement, cognitive load and instructional efficiency, we divided our sample (N=254) into two groups: While both were subjected to the experimental part of the module, the *modellers* (n=120) were required to generate a DNA model using assorted handcrafting materials, whereas the *model viewers* (n=134) worked with a commercially available school model of DNA structure. Interestingly, the *model viewers* performed significantly better regarding a mid-term knowledge increase, while individual cognitive load scores during the activity remained similar. Accordingly, the model viewing approach produced significantly higher scores for instructional efficiency, pointing to enhanced cognitive achievement through a more intense perception of the DNA models' correct contents. While at the first glance our results seem surprising, implications for teaching when models come into play and ways to avoid such discrepancies are discussed. Consequently, recommendations for classroom impacts are presented.

Keywords

Cognitive knowledge, Models and modelling, Mental effort, Outreach learning, Science education

Introduction

Student-centred learning in outreach laboratories has produced a long series of studies (Bryce and Robertson 1985; Franke and Bogner 2011). The connection of newly acquired knowledge with autonomous hands-on learning has repeatedly been investigated and compared to conventional teacher-centred science classes (Gerstner and Bogner 2010, Randler and Bogner 2006). Authentic first-hand experiences in realistic environments as implemented in outreach labs may allow learners to feel like scientists who develop experiments to solve realistic problems. Such scenarios produce interesting learning settings and also positively affect well-being scores (Meissner and Bogner 2011). Studies in the context of molecular instruction have demonstrated an increase in both knowledge and conceptual understanding (Langheinrich and Bogner 2015; Scharfenberg et al. 2007). Ben-Nun and Yarden (2009) reported a significant improvement of students' mental models of DNA and of procedural understanding of DNA manipulation.

Additionally, the importance of visual representations in education increases constantly while its application needs understanding (Ferk et al. 2003; Girwidz et al. 2006). They play a central role in the presentation of information when otherwise invisible classroom issues need further visualization (Sotiriou and Bogner 2008). The Langheinrich and Bogner (2016) reported knowledge increases in an e-learning module in which digital 3D representations were applied in addition to hands-on experiments. Buckley (2000) used a model-based approach to illustrate hidden or abstract phenomena in cases where direct observation is difficult. In genetics, visual presentation is assumed essential (Rotbain et al. 2006). German national education standards (KMK 2005) based on current education research require a central place for models and modelling in science education, especially to promote a knowledge balance in complex themes. It is also supposed to attract learners' attention and to maintain motivation (Mayer and Wittrock 1996).

The aim of our study is to observe model-supported learning strategies in combination with out-of-school laboratories. We first summarize science education research regarding models, modelling and modelling activities in learning genetics. Secondly, we introduce our approach with respect to cognitive load theory and present the objectives of our study.

The Meaning of Models, Modelling, and Modelling Activities in Science Education

Numerous studies have examined the role of models in science education (Buckley 2000; Gilbert 2004; Treagust et al. 2002). Models can be defined as constructed representations with differing theoretical perspectives, focusing different aspects of an original to explain complex or unknown entities (Grosslight et al. 1991). Starting from observations of scientific phenomena, modelling can be specified as the process of constructing concrete representations of abstract ideas by respecting underlying mechanisms (Sins et al. 2009; Windschitl et al. 2008). Therefore, models and modelling hold a special place in science classrooms because they are essential for developing and transmitting scientific

knowledge (Giere 1988; Henze and Van Driel 2011). Providing a bridge between abstract scientific theory and real-world experience, models may explain and simplify complex connections and provide the basis for scientific prediction (Gilbert et al. 1998). Krajcik and Merritt (2012) described models as external representations of mental concepts. A well-known example is the decoding of DNA's double helix. Watson and Crick arrived at the most appropriate interpretation of their complex data by building a model (Harrison and Treagust 2000). Their solution used simple shining metal plates to position the atoms to incorporate both the laws of stereochemistry and the X-ray data base (Watson 1968).

Consequently, models and modelling are important to scientific inquiry and communication and several national education standards highlight its meaning as an integral part of scientific literacy (e.g. KMK 2005; NGSS Lead States 2013). To increase the authenticity of science curricula, it is necessary to incorporate both in science lessons (Gilbert 2004). As an appropriate strategy for teaching and learning through modelling activities, several studies investigated modelling-based learning approaches (MbL) and have demonstrated their value and great potential to enhance science teaching and learning (e.g. Barab et al. 2000; Maia and Justi 2009). Louca and Zacharia (2012) described MbL as a method that helps learners to form a deeper understanding of an observed scientific phenomenon by constructing an externalized representation of the related abstract mechanism. Herein, the learning process is realized by the inquiry-based construction of models via students, which should result in a physical representation of an original, including selected characteristics and entities. However, learners often have difficulty in distinguishing scientific models, teaching models and models in general (Chittleborough and Treagust 2009). In many cases, students regard models as visual objects and do not understand their role as mediators between theory and practice (Grünkorn et al. 2014). Students' appreciation of models often is limited and even naïve, when they primarily think about models as physical copies (Grosslight et al. 1991).

When focusing specific biological contexts, Marbach-Ad and Stavy (2000) reported difficulties in explaining macroscopic genetic phenomena by using the so-called organizational micro level. Such abstract concepts and processes of genetics make it difficult to learn and to teach (Kindfield 1991). Therefore, numerous studies recommend the inclusion of models to enhance teaching (Malacinski and Zell 1996; Peebles and Leonard 1987; Templin and Fetters 2002). Rotbain et al. (2006) compared the application of two types of models: an illustration model and a bead model. Although both improved individual knowledge levels, the use of the three-dimensional bead model was shown significantly more effective. Furthermore, in the context of models and modelling in genetics, a classification of related curriculum contexts might be relevant. From our perspective, 9th graders in Germany (Bavaria, highest stratification secondary school level "Gymnasium") should be able to define several key concepts from chemistry classes, which help them to bridge newly acquired knowledge about molecular DNA structure (ISB 2004). Selected basic knowledge about molecules and atoms is comparable to the curricula in other European countries at secondary level, e.g. in France (Cokelez et al. 2008). Students should be aware that many identical molecules build a pure substance and that in turn these molecules consist of a

combination of different atoms. Introducing a simplified model of an atom with positively charged nucleus and negatively charged moveable electrons around, students achieve fundamental knowledge to understand phenomena like chemical bonding or intermolecular interactions, like hydrogen bonds. Additionally, chemistry education standards for 8th and 9th grade recommend to use and construct molecular models, to work with molecular kits or virtual models on the computer (ISB 2004). Nevertheless, several studies have identified misconceptions regarding students' understanding of atoms and molecules (Cokelez 2012). Common problems seem to be the distinction between atoms and molecules (Griffiths and Preston 1992) and the frequent belief that both are very small, but macroscopic and can be seen with a powerful microscope. Additionally, students describe atoms as generally grouped and are unaware that molecules are themselves basic chemical entities (Harrison and Treagust 1996; Taber 1998). These misconceptions could also be relevant when learning the typical structure of the DNA macromolecule, which may result in further learning difficulties.

Cognitive Load and Model-Based Teaching Strategies

From the cognitive perspective, learning can be defined as a construction and sequential modification of knowledge representations (Steiner 2006). Constructivism is often connected to learning in experimental lessons. On the basis of personal experiences, learners could confirm or disprove, adapt or develop new mental representations during experimentation (Hodson 1998). According to Tobin (1990), laboratory activities engage students in a process of constructing knowledge by doing science. Following (Franke and Bogner 2011), we refer to a moderate constructivist understanding of learning when we focus on monitoring achievement within the cognitive domain (cognitive achievement) in an out-of-school laboratory. To monitor relative efficiency of instructional settings, Paas and Van Merriënboer (1993) combined cognitive achievement data (performance), and cognitive load data (mental effort) to receive instructional efficiency. Cognitive load is defined as the mental activity of working memory required to complete a task. Due to limitations of working memory's capacities (Baddeley 1992), learners have to struggle to construct appropriate cognitive schemata while handling a large volume of newly acquired, unorganized information (Van Merriënboer and Ayers 2005). Sweller et al. (1998) postulated three components of contribution to load levels: (a) intrinsic load, which is caused by the element interactivity of the present content, being influenced by learners' expertise and the number of simultaneously processed elements, (b) extraneous load, which relates to the instructional strategy and does not contribute to or, at worst, impedes learning, and (c) germane load, which is needed for individually processing information and transferring it to long-term memory. The three cognitive load components are regarded as additive, so that reducing intrinsic or extraneous load may have the potential to strengthen the germane component, regarded as a key factor for learning (Sweller 2006).

Students' mental effort is defined by the actual amount of controlled cognitive processing assigned to learners' working memory (Paas 1992; Paas and Van Merriënboer 1993). In consequence, mental effort is conventionally used as an index of cognitive load, because it reflects the actual existing

mental workload (Paas et al. 1994; Van Gog and Paas 2008). Combining students' mental effort with information about their performance can provide insight into the cognitive costs at which learners' performance is achieved, and can determine instructional efficiency. Thereby, the instructional efficiency of an instructional approach represents the relative efficiency of different instructional conditions in consideration of mental effort and cognitive achievement data (Paas and Van Merriënboer 1993).

There is still little literature on model-based instructional designs and cognitive load theory, although there are several reasons for investigations in this research area (Cook 2006; Stull et al. 2018). The application of visual representations has revealed promising teaching strategies in order to reduce extraneous load (Mayer 2001). However, there is a risk to interfere with learning, if the use is without proper design and consideration for individual differences among learners (Linn 2003). According to Cook (2006), most novice learners face difficulties in coordinating multiple representations, since their cognitive resources are engaged in interpretation rather than linking information in a broader context. Computer-based externalizing of mental processes such as the rotation of molecular models appears to free cognitive resources in learning (Cook 2006). Hmelo-Silver et al. (2006) specified instructional designs to decrease cognitive load, e.g. by structuring a task relevant to the learning goals. After initial adaption in using problem-based routines, students tend to quickly act cooperatively in order to extract facts and generate ideas towards solution. Chemistry education showed molecules made of several atoms with certain spatial arrangements leading to overload of spatial working memory (Shah and Miyake 1996; Stull and Hegarty 2016).Stull et al. (2018) found that enacting with hand-held molecular models reduced the demand of imaging concepts and processes in mind by lowering cognitive load. Herein, models can serve to off-load cognition, especially if students can use them to improve mental rotation skills while manually performing spatial transformations compared to another group of students that passively watched an instructors' model-supported demonstration without enacting. As mentally transforming novel representations is very memory intense, models may help students to learn, organize and integrate important information with their previous knowledge (Stull and Hegarty 2016).

In this context, the present research examines the influence of model-based approaches on cognitive load. We compared two model-supported teaching approaches (*model elaboration* versus *model viewing*) in an outreach laboratory in the context of learning genetics. Our study sought to answer the following research questions:

(1) How do model-based approaches influence students' cognitive achievement when *model elaboration* or *model viewing* are applied in a hands-on gene technology module?

(2) To what extent do the two model-based approaches affect students' cognitive load?

(3) Which effect do the two implemented approaches have on instructional efficiency, i.e. the standardized difference between mental effort and performance?

Methods

Educational Intervention

Our study was completed at an outreach gene technology laboratory, designed for hands-on teaching in an out-of-school setting (see in detail Mierdel and Bogner 2019b). Students worked in pairs. The intervention was designed for 9th graders and implemented by a single teacher. Our module *Simply inGEN(E)ious! DNA as a carrier of genetic information* included six lessons (in total 270 min) consisting of five phases: one pre-lab phase, two experimental phases, one model phase and one interpretation phase (Table 1). Both experimental subunits and the model subunit consisted of theoretical, teacher-led minds-on activities followed by hands-on student activities (Scharfenberg and Bogner 2011). Since students worked in a real university lab, we decided on an inquiry-based learning scenario providing an authentic environment, in which they can propose ideas, explain observations, and verify hypotheses. A workbook leads the participants through the module with information, experiment instructions and upcoming challenges during experimentation and model work. Before performing the hands-on phases students completed the tasks in the workbook.

Table 1 Phases and descriptions of the gene technology module *Simply inGEN(E)ious! DNA as a carrier of genetic information*.

Phase of teaching-unit	*Description*	*Students' activities*
Pre-laboratory phase	Be prepared! How to work in a gene technology lab: Practicing essential techniques of a gene technology scientist	Hands-on
Experimental phase 1	Spin you DNA! The material character of DNA: Isolation of DNA from students' oral mucosal cells	Minds-on Hands-on
Model phase	On the footsteps of two GEN(E)iuses: Acquiring essential knowledge about DNA structure when working with models independently and reading about Watson & Crick solving the molecular puzzle of DNA structure	
Experimental phase 2	Visualizing the invisible: Agarose gel electrophoresis of the previously isolated DNA	
Interpretation phase	DNA – a macromolecule of life: Discussing experimental results by connecting them to DNA models (review of the module)	Minds-on

In order to prevent learning difficulties caused by a lack of basic experimental skills, we started the lab day with an introductory pre-laboratory phase (Scharfenberg and Bogner 2011). In this teacher-centred phase, participants were familiarized with the laboratory equipment and trained in essential scientific techniques (micro-pipetting, decantation and centrifugation). Presenting a newspaper article describing a real crime scene, pupils brainstormed in a group discussion about required evidences to convict a murderer flawlessly. Based on participants' hypotheses regarding the murderer's DNA tracks, the teacher emphasized the organization levels of genetic material (cell, chromosome, DNA, gene), leading to the first experimental phase, where students isolated individual DNA from oral mucosal cells (Langheinrich and Bogner 2015). In the practical task of the second experimental phase, students prepared their previously isolated DNA for the gel electrophoresis to gain more information about the molecular character of DNA structure (e.g. 'Which component is responsible for the migration of DNA in the electric field?'). The model phase linked the two experimental sections: students learned essential background information about the DNA structure while working with models following the historic approach by Watson and Crick (1953). The theoretical base of this student-centred subunit was provided by an information text with comprehension questions. This didactical reduced text described the story how Watson and Crick solved the molecular puzzle of DNA structure based on the original letter Francis Crick wrote to his 12-year-old son in March 1953 (Mierdel and Bogner 2019b). The text's content concentrates on e.g. the phosphate-sugar chains as DNA backbone, names and arrangement of the bases, possible base pairings or the right-handed double-helix structure. During the final interpretation of the experimental results, the findings of the model phase were discussed and compared with previously formulated hypotheses. Our module's contents followed the current syllabus (Bavarian Ministry of Education 2007). A pilot study was conducted to optimize the learning materials especially for the model phase.

Design of the Study and Participants

Our study followed a quasi-experimental design with pre-test (T0), post-test (T1) and retention test (T2). Students completed a knowledge pre-test (T0) 2 weeks before the teaching unit, the post-test (T1) immediately after and the retention test (T2) 6 weeks after participation.

The sample consisted of 293 Bavarian 9th graders of the highest stratification secondary school level ("Gymnasium"): 59.04% female; age $M \pm SD = 14.51 \pm 0.69$. We collected data from 14 classes in 8 different schools.

Due to the fact that teachers can use models for different purposes in science instruction, our major aim was to observe the efficiency of two basically different instructional settings for model-based learning. On the one hand, models are described as changeable tools for testing and representing scientific ideas in the best way (Werner et al. 2017). A few studies have indicated that an understanding of models could be fostered by elaborating and reflecting on models (e.g. Baek et al. 2011; Schwarz et

al. 2009). On the other hand, teachers mainly use models as teaching tools to illustrate certain aspects and to transmit content knowledge (Gilbert et al. 2000; Upmeier zu Belzen 2013).

According to the model of modelling (Justi and Gilbert 2002a, p. 371), a source prior to (mental) modelling is required. Taking into account different levels of understanding, both treatments initially read the same information text based on Crick's letter writing his son the story of solving the molecular puzzle of DNA structure and answer comprehension questions (e.g. 'Name the bases of the DNA and indicate possible base pairings!'). In the process of formulating their answers, they internalize essential background information as they mentally begin to develop a model of DNA structure. In the following model-based activities, students were randomly assigned to two subsamples and one test-retest sample: 120 students (Treatment 1: *modellers [md]*) creatively generated a DNA model with no instructions provided. They got DNA modelling kits containing a variety of handcrafting materials for the independent model elaboration (e.g. glue, scissors, straws, pipe cleaners, coloured beads and cardboards, felt-tip pens). Another 134 students (Treatment 2: *model viewers [mv]*) worked instead with a completed but unlabelled commercially available school model of the DNA structure by comparing and analysing the substructures of the model with their mental models. Finally, both treatments had to consider scope and limitations of their models. Students had to make a labelled drawing to explain the model's elements and had to compare it with the previously answered comprehension questions. A test-retest sample (n = 39) completed the knowledge questionnaire neither participating in the module nor receiving any instruction on the topic. Because genetics is a new topic in biology of the state's grade 9 curriculum (Bavarian Ministry of Education 2007), little prior knowledge is to be expected. Participating students were only included in the study after parents had given their permission and teachers were willing to participate.

Instruments

The ad hoc multiple-choice knowledge test consisted of 30 content items (item examples, see Table 2), 12 assessing project-oriented knowledge of the laboratory activities. Another 18 items examined the content knowledge of the model phase originating from the information text provided to both treatments, as we want to compare students' short- and mid-term knowledge increase due to the differing model-based approaches. Every item offered four response options, only one of which was correct. Subsequent analyses used sum scores: correct answers were scored '1', incorrect ones '0'. The maximum knowledge score was 30.

At each test time, the order of questions and answers was changed randomly. Cronbach's alpha values are shown in Table 3 (scores above 0.7 were regarded as reasonable). The content validity of the items of the knowledge test is implied by following the state school curriculum (Bavarian Ministry of Education 2007). The inter-item correlation of the knowledge items was below 0.2 for all test times (T0 = 0.08, T1 = 0.19, and T2 = 0.18), confirming that each item was related to different content knowledge of the teaching unit. For complex constructs, such as cognitive achievements, heterogeneity of test items

enhances construct validity (Rost 2004). According to the classical test theory, the mean item difficulty is the percentage of students that answered an item correctly (Döring and Bortz 2016); the average for all items during all test intervals was 49.1%. Item difficulty ranged between 10 and 90%. More item examples with assigned levels of difficulty (level 1: ‘reproduction’, level 2: ‘reorganization’, and level 3: ‘transfer’) are presented in a recently published parallel study Mierdel and Bogner 2019a). To control for learning effects of the repeated measures design, a test-retest sample completed the same knowledge questionnaire three times over an interval of 8 weeks, but without participating in our module. Students were not aware of the testing cycles.

Table 2 Item examples of the cognitive knowledge questionnaire (partly adapted from Langheinrich and Bogner 2016). Correct answers are written in italics. Questions were split up into subcategories evaluating the model subunit or the laboratory activities. The full version of the knowledge test is available as supplementary online material.

Item example	*Evaluated subunit*
The cohesion of the two DNA-strands is based on the formation of … a) Atomic bonds b) *Hydrogen bonds* c) Disulfide bridges d) Ionic interactions	Model phase
What is wrong? In cold alcohol the DNA is … a) Insoluble b) A filamentous structure c) A white solid d) *Soluble*	Laboratory activity
The proportion of sugar to phosphate in the DNA-molecule is… a) 2 : 1 b) 3 : 1 c) *1 : 1* d) 1 : 2	Model phase
With the aid of gel electrophoresis, you get information about … a) *The molecular mass* b) The number of bindings of a molecule c) The components of a molecule d) The atoms of a molecule	Laboratory activity

Table 3 Number of items and Cronbach's alpha scores of the cognitive knowledge questionnaire. Out of a total of 30 content-related items, 18 refer to the model phase. Cronbach's alpha scores are calculated for pre- (T0), post- (T1) and retention-test (T2).

Knowledge questions evaluating	*Number of items*	α_{T0}	α_{T1}	α_{T2}
a. complete module	30	.736	.869	.864
b. model phase	18	.741	.847	.840

Additionally, we assessed the theoretical construct cognitive load (CL) according to Paas and colleagues (Paas et al. 2003a, b) by measuring mental effort (ME) as an index of CL (Paas et al. 2003a; Van Gog and Paas 2008). Based on that unidimensional 9-point Likert-type self-rating scale, students indicated their ME during task performance at eight points in time during the teaching unit (see Appendix). The ME scale is frequently used in CL research (Van Gog and Paas 2008) and has formerly been demonstrated valid and sensitive (Ayres 2006).We calculated four ME scores for the four different phases of our module (pre-laboratory, experimental, model and interpretation; see Table 1), based on a scale from'1' (*very, very low mental effort*) to '9' (*very, very high mental effort*). The midpoint of the scale constitutes an anchor score linked to the average ME necessary during biology lessons to prevent potential individual differences (Franke and Bogner 2011). In order to monitor potential effects of the two instructional modes within the model phase ([*mv*] and [*md*]), we decided on a frequently used method to combine ME data with task performance indicators and to calculate instructional efficiency (IE; Sweller et al. 2011 p. 75). We follow Van Gog and Paas (2008) in the most common definition of the term 'performance' in the field, that is, an evaluation of the learning outcomes in terms of scoring correct answers. To obtain information on the relative efficiency of the two observed instructional conditions, we applied the adapted form of measuring ME during the learning process (Van Gog and Paas 2008). We calculated IE as relative efficiency (i.e. the standardized difference between ME and performance) of the two model-based approaches by combining the mid-term knowledge increase (T2-T1) of the 18 items monitoring the performance of model phase and the ME scores during the model phase. For IE calculation, only the performance and ME data from students with fully completed ME scale were used ($n = 233$). To obtain efficiency scores, the performance and the ME data are standardized to *z* scores and displayed in two orthogonal axes (Sweller et al. 2011). Instructional efficiency E is the calculated perpendicular distance to the reference line ($E = 0$) that represents the average instructional efficiency score (i.e. a balance between mental effort and performance scores). Following Paas et al. (2003a), two effects can be specified as crucial when comparing the efficiency of two different instructions: (1) Similar ME results in different performances and (2) different ME results in similar performances. In consequence, if high-performance scores are combined with low ME scores, the

instruction mode is highly efficient and indicates that the allocated working memory capacity was used for processes relevant to learning, and suggests low extraneous load (Kester et al. 2006).

Statistical Analysis

For all statistical analyses we used IBM SPSS Statistics 23.0. Distribution of the variables was not normal (Kolmogorov-Smirnov tests [Lilliefors modification]; p <.01), so we applied non-parametric tests. Changes in knowledge within the three test times were analysed using Friedman's ANOVA and Wilcoxon's *post hoc* analyses. Second, Mann-Whitney *U* tests were used for the evaluation of intergroup differences. In case of significant results, we calculated effect sizes *r* according to Field (2013) and assumed that values of 0.1, 0.3, and 0.5 correspond to small, medium, and large effect sizes (Cohen 1992). To avoid cumulative type I errors caused by multiple testing, we used the Bonferroni correction (Field 2013).

Results

Cognitive Achievement

As expected, knowledge scores of the test-retest sample for all items showed no significant differences at all three test times (Mdn_{T0} = 5.00, Mdn_{T1} = 4.64, Mdn_{T2} = 4.38). On the contrary, knowledge scores for the main sample (both treatments) differed significantly between measurement times (Mdn_{T0} = 10.38, Mdn_{T1} = 20.64, Mdn_{T2} = 18.29; chi-squared (2) = 373.733, p <.001). Table 4 shows the pair-wise comparisons of all three test times and Table 5 presents the pair-wise comparisons for the items of the model phase for the two treatment groups (*modellers* [*md*]; *model viewers* [*mv*]).

Table 4 Complete module: inner-group comparison of knowledge levels. Knowledge scores within both treatments differed significantly between measurement times (T0: pre-, T1: post-, T2: retention-test).

	z	*p*	*r*
[a]*Treatment 1 [md]*			
T1-T0	-9.50	<.001***	-.61
T2-T0	-8.81	<.001***	-.57
T2-T1	-7.66	<.001***	-.49
[b]*Treatment 2 [mv]*			
T1-T0	-10.01	<.001***	-.61
T2-T0	-9.78	<.001***	-.60
T2-T1	-5.60	<.001***	-.34

md: modellers, *mv*: model viewers; [a]n = 120; [b]n = 134.

Table 5 Model phase: inner-group comparison of knowledge levels. Knowledge scores within both treatments differed significantly between measurement times (T0: pre-, T1: post-, T2: retention-test).

	z	*p*	*r*
[a]*Treatment 1 [md]*			
T1-T0	-9.51	<.001***	-.61
T2-T0	-8.70	<.001***	-.56
T2-T1	-7.02	<.001***	-.45
[b]*Treatment 2 [mv]*			
T1-T0	-9.94	<.001***	-.61
T2-T0	-9.61	<.001***	-.59
T2-T1	-4.75	<.001***	-.29

md: modellers, *mv*: model viewers; [a]*n* = 120; [b]*n* = 134.

Between-group comparisons are shown in Fig. 1a, showing that prior knowledge did not vary significantly before participation (Mdn_{md} = 10.12; Mdn_{mv} = 10.70; max. score: 30), U = 7945.50, z = -.16, *n.s.*, r = -.01. Similarly, no significant differences in short-term knowledge increase between the treatment groups appeared (Mdn_{md} = 20.61; Mdn_{mv} = 20.67; max. score: 30), U = 7777.50, z = -.45, *n.s.*, r = -.03. On contrary, mid-term knowledge increase differed significantly in the content knowledge of the complete module (Mdn_{md} = 17.19; Mdn_{mv} = 19.07; max. score: 30), U = 6493.50, z = -2.65, p =.008*, r = -0.17. Even more significant (Fig. 1b) was the result for students' mid-term knowledge monitoring the model unit (Mdn_{md} = 10.13; Mdn_{mv} = 12.59; max. score: 18), U = 5667.50, z = -4.08, p <.001***, r = -0.26. The *model viewers'* knowledge increase was significantly higher than that of the *modellers*. Levels of statistical significance p after Bonferroni correction yielded to **$a \leq .003$ and *$a \leq .016$.

Mental Effort

Statistical analysis of the mental effort scale (ME) showed no significant differences between the treatment groups (Table 6). This result includes the ME scores for the two modelling approaches, *model elaboration* versus *model viewing*, which did not vary significantly.

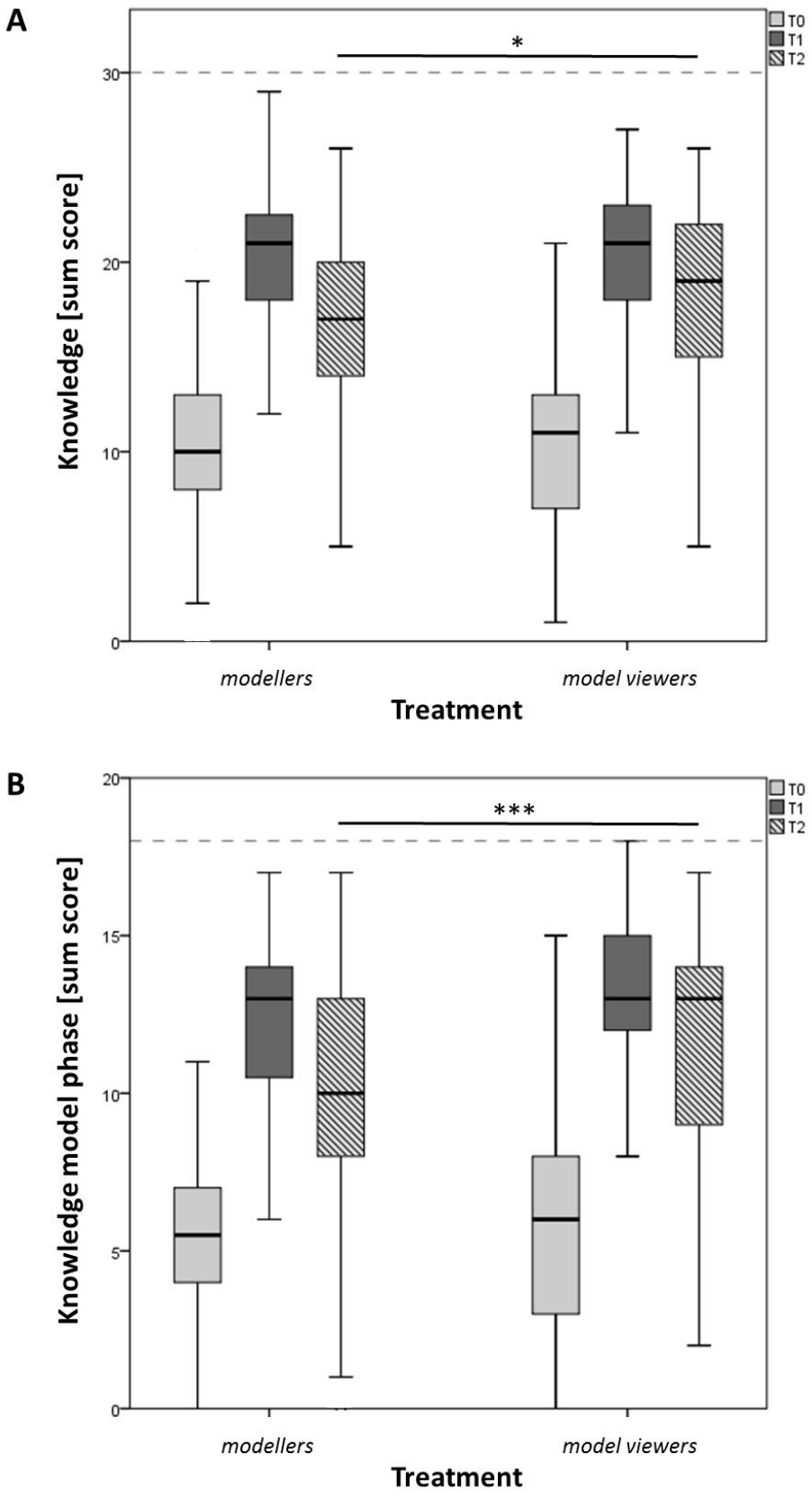


Fig. 1 Knowledge sum scores for the two treatments at the three test times (T0 = pre-test, T1 = post-test, T2 = retention-test). **A** = Knowledge sum scores of all items (∑30) evaluating the complete gene technology module; **B** = Knowledge sum scores of the items (∑18) focusing on the content knowledge of the model phase.

Table 6 Between-group comparison of ME scores for the complete module.

Phase(s) of the teaching unit	[a]Mdn$_{md}$	[b]Mdn$_{mv}$	*U*	*z*	*p*
Pre-laboratory phase	2.52	2.61	6504.50	-.48	n.s.
Experimental phases	4.36	4.49	6291.50	-.38	n.s.
Model phase	4.53	4.71	6555.00	-.72	n.s.
Interpretation phase	4.31	4.09	6290.50	-.37	n.s.

md: modellers, *mv*: model viewers; [a]*n* = 107: [b]*n* = 126.

Instructional Efficiency

Instructional efficiency differed significantly between the two treatments (Fig. 2), with significantly higher scores of the *model viewers* (p =.011). Similar effort induced different performance, for instance, a similar mental effort within the model phase induced a lowered knowledge decrease rate (T2-T1) for the *model viewing* approach and a higher knowledge decrease rate (T2-T1) for the *modelling* approach (small effect). These results suggest that a higher mid-term increase in knowledge of the model subunit (performance), coupled with a similar mental effort during the model phase, results in a significant higher instructional efficiency for the *model viewing* approach.

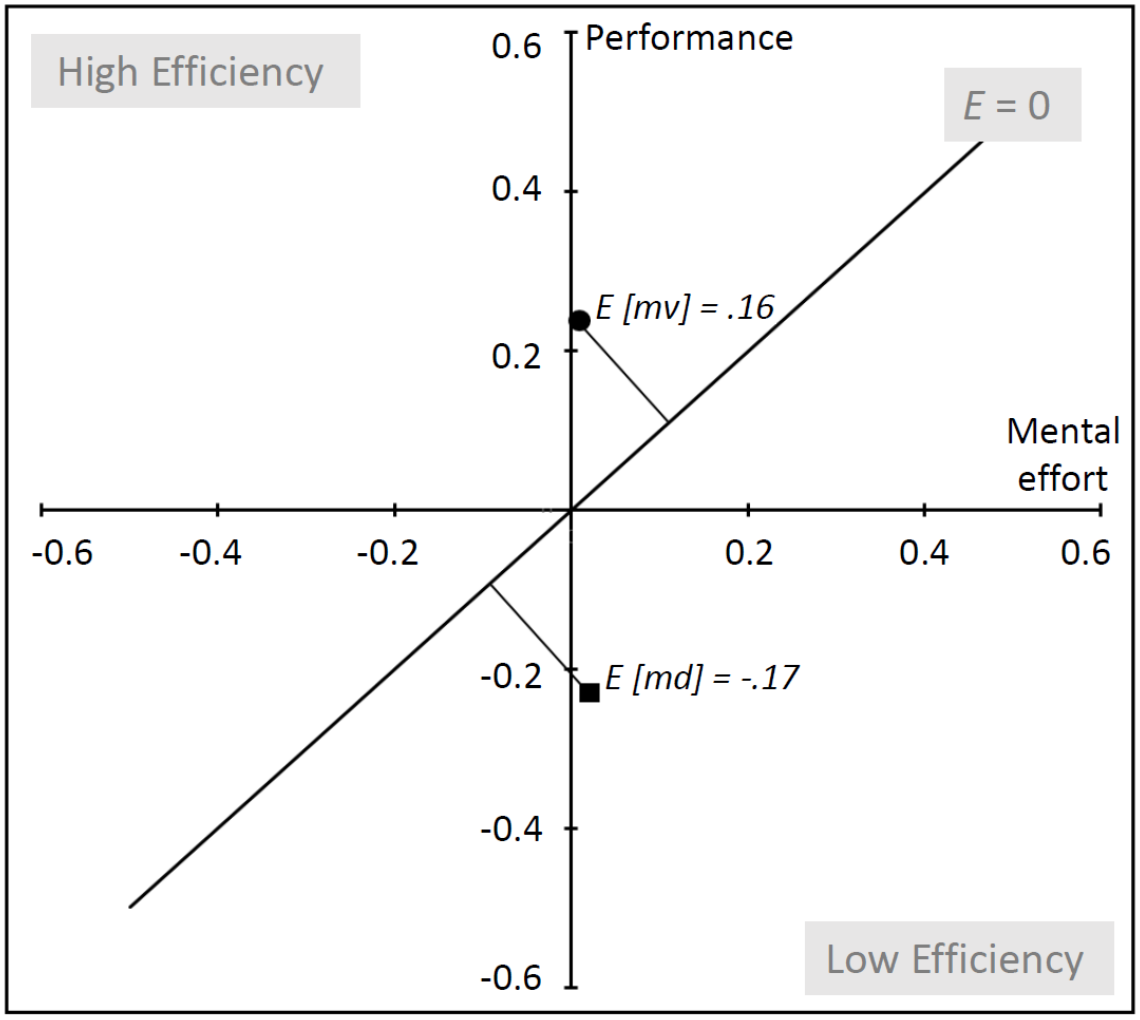


Fig. 2 Between-group comparison of instructional efficiency *E* ($E = (z_{performance} - z_{mental\ effort})/\sqrt{2}$; Paas and Van Merriënboer 1993) of the model phase. *E* [*mv*]: The mental effort within the *model viewing* approach is coupled with higher performance (in this case, a lowered knowledge decrease rate: T2-T1). *E* [*md*]: A similar mental effort within the *modelling* approach is coupled with lower performance (in this case, a higher knowledge decrease rate: T2-T1). $U = 5438.00$, $z = -2.54$, $p = .011$*, $r = -0.17$, $n = 233$.
Note. E = 0 represents the average instructional efficiency score as reference line (i.e. a balance between mental effort and performance scores).

Discussion

As expected, model-support within a hands-on teaching unit produces a short- and a mid-term knowledge increase. Surprisingly, the *model viewing* approach was shown to be more effective than the *model elaboration* approach, despite similar levels of cognitive load.

Effects on Cognitive Achievement

The observed short- and mid-term knowledge increase is in line with the literature on outreach learning (Meissner and Bogner 2011; Sellmann and Bogner 2013), and with that on learning gene

technology in out-of-school labs (Goldschmidt et al. 2015; Langheinrich and Bogner 2016). Additionally, in the context of model-based approaches in teaching genetics, Rotbain et al. (2006) reported such knowledge gains when students used an illustrated model or a three-dimensional bead model in contrast to a control group. It is encouraging that even short-term interventions combining model-supported strategies with experimental work generally promote students' cognitive achievement in the abstract field of DNA structure. Hence, linking model work with experimentation in an outreach lab is a promising teaching approach that bridges abstract scientific theory and real-world experience (Gilbert et al. 1998) and should be applied in biology classrooms as well.

The comparison of cognitive achievement levels shows a significant higher midterm knowledge increase for the *model viewers,* indicating a deeper understanding of the scientific theory due to a lowered decrease rate (Kirschner et al. 2006). Both methods describe, explain and simplify the abstract background of DNA structure, while they lead to varied ways of perception: *model viewers* acquire the scientific background in a didactically prepared representation form originating in our idea that medial perception of models is typically applied in science classrooms (Oh and Oh 2011; Treagust et al. 2002). Werner et al. (2017) reported that biology teachers use models not only for illustration but also as tools to encourage students' understanding of scientific reasoning: however, critical reflection on the effectiveness of models for scientific reasoning usually failed to appear.

On the other hand, *model elaboration* is often a neglected aspect in science education (Grünkorn et al. 2014; Oh and Oh 2011). *Modellers* are assumed to strengthen important modelling abilities like shaping various models of a phenomenon or modifying their models. Svoboda and Passmore (2013) consider the potential of a variety of scientific reasoning strategies, suggesting modelling as a powerful inquiry-based learning strategy to guide initial phases of hypothesising, identifying knowledge gaps or testing the accuracy of explanations and predictions. German national education standards (KMK 2005) require various aspects of models, additionally to the point of simple visualization, in emphasizing modelling as a typical scientific procedure. Thus, we had expected the recent *model elaboration* approach to lead to better knowledge increase than the conventional *model viewing* approach did.

Knowledge differences between our treatments may have other causes. First of all, the theoretic base to answer the multiple-knowledge test correctly was the information text with comprehension questions provided to both treatments in the same way. However, we think of differing model qualities as a result from the *modellers*. While *model viewers* were presented with an optimal DNA model accompanied by an appropriate text, *modellers* additionally needed to transfer the same text's content correctly into their specially designed models. In doing so, only some of the *modellers* achieved the quality of the commercially available school model (Fig. 3; investigated in detail Mierdel and Bogner 2019a). A larger number may have developed misconceptions about the DNA structure as their models were incomplete. Model drawings support this explanation as a difference between both treatments is apparent. As expected, the sketches of model viewers differ much less from each other and show more correct/complete representations of the DNA structure than those of the modellers (Fig. 4). According

to the Langheinrich and Bogner (2015), a typical complex problem is the correct understanding of the three genetics concepts: DNA, gene and chromosome. In consequence, changing the hierarchical organizational level of DNA structure between the experimentation and the modelling phase may have hindered a correct and complete result.

The impact of modelling experience needs to be taken into account. Low levels of modelling skills in both treatments (U = 6737.50, z = -1.35, p =.178) were observed. The lack of modelling experience could explain that the *modellers* in our study did not succeed as well as the second group did. Introducing modelling needs further support, as only few studies of modelling in classrooms have been reported (Svoboda and Passmore 2013). One reason for this may be that even teachers seem to estimate modelling primarily done by scientists (Justi and Gilbert 2002b).

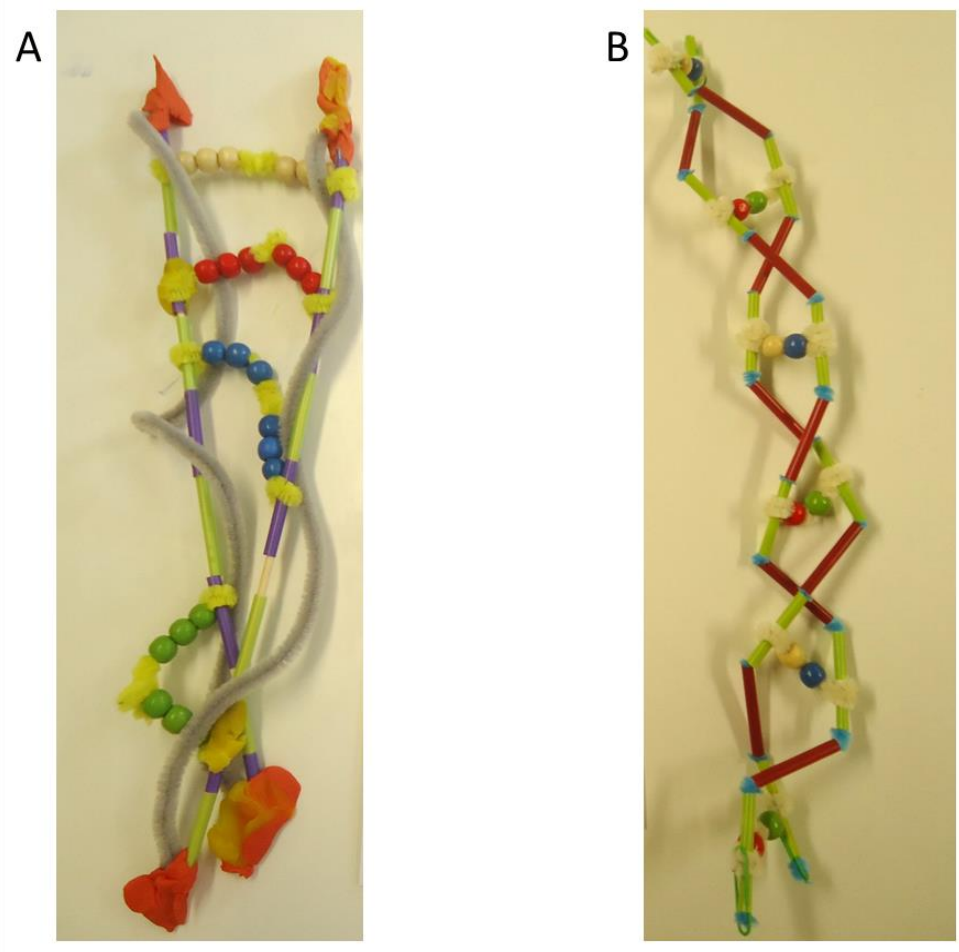


Fig. 3 Key examples model evaluation (Mierdel and Bogner 2018): modellers' results of the hands-on modelling phase, A) low rated DNA-model and B) high rated DNA model.

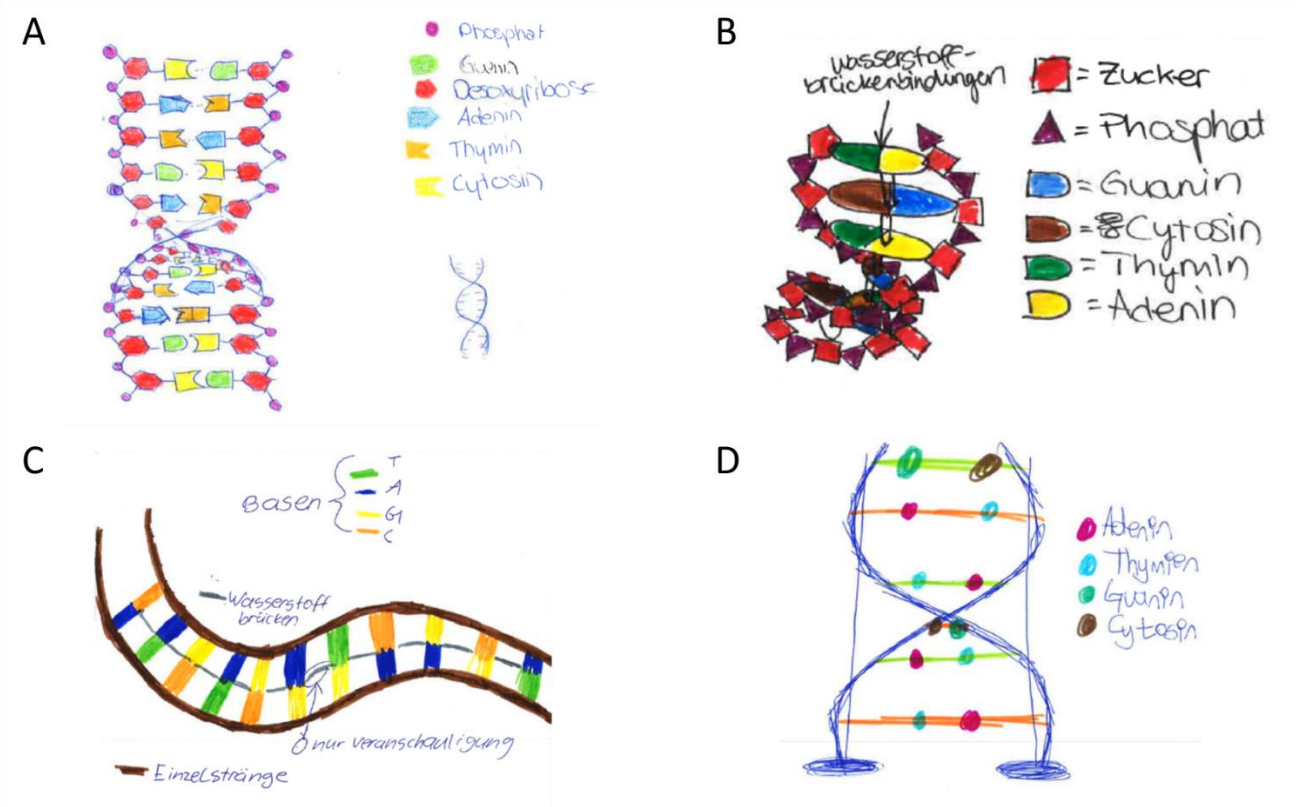


Fig. 4 Examples for students' labelled model drawings for both treatments and from four different classes. The model viewers' sketches A) and B) differ much less from each other and show more correct/complete representations of the DNA structure than those of the modellers C) and D).
Note. Basen=bases; Wasserstoffbrücken/-bindung=hydrogen bonds; Zucker=sugar; Einzelstränge= single strands; nur Veranschaulichung=only illustration.

With respect to the schedule of the model phase, we also observed that some of the *modellers* ran out of time in finishing an acceptable DNA model. Although the time aspect of modelling in biology class has hardly been investigated in educational research, successful modelling seems to incorporate a complex suite of strategies: this is time-consuming. Svoboda and Passmore (2013) listed various activities like concretizing abstract ideas, simplifying and clarifying complex phenomena, making predictions about future events and facilitating the communication of ideas. We agree that the *model viewing* approach requires noticeably less time, as the DNA model has already been completed and didactically optimized.

In the present research situation, we renounced a more detailed model evaluation for the *modellers*. Although students had to produce a descriptive and labelled drawing of their generated models and had to compare it with the previously answered text comprehension questions, no prime example was shown. An explicit correction of models' errors or/and missing aspects of the DNA structure may have prevented differing knowledge outcomes. Teacher effects can be also excluded since the interventions were managed by the same teacher.

Effects on Cognitive Load

We first consider the validity of the mental effort measurement. Often ignored is the aspect how much time students need to invest on a specific problem (Paas *et al.* 2003a). One cannot conclude whether a rating would be similar if the time spent on a task varied. This criticism can be rejected if we impose a time span in the model phases. Beckmann (2010) pointed out that the validity of self-reported mental effort ratings may depend on student's level of subject specific 'ability'. As already stated, we recorded that all participants had little to no modelling skills. Therefore, we can exclude potential influences.

Our expectation of differences within the treatments was not confirmed. We suspect higher mental effort for the *model elaboration* approach, as research indicates that minimal guidance hinders the learning process (Kirschner et al. 2006). Particularly novice learners tend to struggle with handling of highly complex information that generates an enormous load on working memory. As the *modellers* had to 'translate' the text's information into an adequate model of DNA structure, higher mental effort compared to the *model viewers* seemed probable. Our results do not confirm this assumption. Perhaps *modellers* act more creatively and without any limitations in presenting the given information. We observed that the artistic compound in working with various handcrafting materials positively attracts learners' attention during model elaboration. Compared with this, the *model viewers* had to understand what is already demonstrated in the completed DNA model, regardless of their preferred methods of representation forms. Both model-supported strategies result in similar levels of extraneous mental load. Independently of the initial perception, we therefore see no restrictions for an increasing use of modelling in biology education to emphasize its scientific meaning.

Instructional Efficiency and Educational Implications

Mid-term knowledge increase and the mental effort of the model phase are related to the calculated instructional efficiency. The higher mid-term knowledge increase of the *model viewers* was the main factor leading to the significant results. We confirm that similar mental effort leads to different performance, shown by the positive effects of the *model viewing* approach. As the approach of *model elaboration* in earlier studies has been shown as fruitful method, its successful implementation may just need additional planning and preparation (Justi and Gilbert 2002b; Svoboda and Passmore 2013).

We suggest two adjustments to educational practice: Firstly, an additional pre-modelling phase before applying the model elaboration phase, thus promoting the development of several modelling skills (e.g. methods to generate mental models and transfer them into physical ones on a selected teacher-introduced example) and, secondly, concluding a more detailed model evaluation which appears to be another solution to overcome discrepancies between the modelled outcomes. Following Justi (2009) we consider the four main stages of the 'Model of Modelling' (Justi and Gilbert 2002b): collecting information about the entity that is being modelled (1), producing a mental model (2), expressing that

model in an adequate representation form (3), testing and evaluating its scope and limitations (4). We agree that an introductory phase regarding the 'Model of modelling' in our module could be important for the *modellers*, especially in aspects like linking ideas, data and mental models by taking into account the purpose of the model. Alternatively, evaluate the models in a subsequent group discussion to identify and correct misconceptions about DNA structure.

Finally, we note, in agreement with Justi and Gilbert (2002b), that teachers themselves need to be competent in modelling. As shown earlier, many teachers had a less than satisfactory understanding of models (Justi and Gilbert 2002a), although they seem at least to be aware of the need for competence in model learning. Consequently, modelling strategies should be a subject of in-service (or, better still, pre-service) teacher education.

Limitation of the Study

With regard to Rotbain et al. (2006) our findings are typically for closed, factual knowledge questions when learning the issue of genetics. Evaluating the benefit of physical models of molecular structures, Roberts et al. (2005) found an improvement in students' responses to content questions: When working with three-dimensional models more focused answers were given aligned with reasoning in appropriate language. However, the focus of our study is on the comparison regarding students' cognitive achievement (during the model phases) and mental effort (cognitive load) to receive instructional efficiency. We agree that further research including more open-ended conceptual questions would be useful to get a more detailed picture of students' achievement.

Conclusion

In summary, our findings clearly demonstrate the potential of model-supported teaching in out-of-school labs in addition to classic experimental tasks in supporting cognitive achievement. Based on our comparison of two different student-centred as well as model-supported teaching approaches, *model viewing* turned out to be significantly more instructional efficient than *model elaboration* in terms of sustainable mid-term knowledge. Nevertheless, neither model-based approach showed differences concerning cognitive load. Modelling as a complex suite of strategies provides further benefits such as offering multiple ways for learning science and understanding routes to historical discoveries (Svoboda and Passmore 2013) in contrast to simple visualization, which is why adaptions for current *model elaboration* approaches are needed. We recommend the 'Model of Modelling' (Justi and Gilbert 2002b) approach, which suggests a pre-modelling phase to explain and train necessary modelling skills. On the other hand, a more detailed model evaluation after modelling, e.g. within a teacher-guided group discussion, could prevent misconceptions of DNA structure. Modelling as a student-centred activity, though praised in theory for years, needs further research before it can be established as an up-to-date and widely used approach to scientific learning.

Acknowledgements

This article reflects only the author's views and the European Union as well as BMBF are not liable for any use that might be made of information contained herein. Special thanks go to teachers and students involved in this study for their cooperation. We also thank Michael Wiseman for discussing earlier stages of our paper.

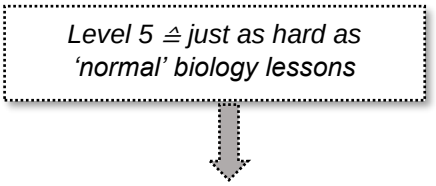
Funding Information

This study was supported by the 'CREATIONS' project funded by the European Union's HORIZON 2020-SEAC-2014-1 Program (Grant: 665917), by the 'Qualitätsoffensive Lehrerbildung' Program funded by the German Federal Ministry of Education and Research (BMBF; Grant: 01JA160) and by the University of Bayreuth.

Appendix

Items of the cognitive load questionnaire monitoring the mental effort during task performance in our gene technology module.

Please appreciate retrospectively your mental effort for the phases of the module on a scale of 1 *(very, very low ≙ it was very easy for me)* ***to 9*** *(very, very high ≙ it was very difficult for me)!*



My mental effort during the module's phases was …		**very, very low**	→	→	→	→	→	→	→	**very, very high**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1.	… in the pre-laboratory phase	□	□	□	□	□	□	□	□	□
2.	… in the experimental phase 1 (theory)	□	□	□	□	□	□	□	□	□
3.	… in the experimental phase 1 (practice)	□	□	□	□	□	□	□	□	□
4.	… in the experimental phase 2 (theory)	□	□	□	□	□	□	□	□	□
5.	… in the experimental phase 2 (practice)	□	□	□	□	□	□	□	□	□
6.	… in the model phase (theory)	□	□	□	□	□	□	□	□	□
7.	… in the model phase (practice)	□	□	□	□	□	□	□	□	□
8.	… in the interpretation phase	□	□	□	□	□	□	□	□	□

References

Ayres, P. (2006). Using subjective measures to detect variations of intrinsic cognitive load within problems. *Learning and Instruction* 16, 2006 (5), 389–400.

Baddeley, A. (1992). Working memory. *Science* 255, 556–559.

Baek, H., Schwarz, C., Chen, J., Hokayem, H., & Zhan, L. (2011). Engaging elementary students in scientific modeling: the MoDeLS fifth-grade approach and finding. In M. S. Khine & I. M. Saleh (Eds.), Models and modeling: cognitive tools for scientific enquiry (pp. 195–220). Heidelberg: Springer.

Barab, S. A., Hay, K. E., Barnett, M., & Keating, T. (2000). Virtual solar system project: Building understanding through model building. *Journal of Research in Science Teaching* 37(7), 719-756.

Bavarian Ministry of Education (2007). *Lehrplan für das Gymnasium G8* [*Curriculum for Gymnasium G8*]. Munich, Germany: ISB.

Beckmann, J. F. (2010). Taming a beast of burden – On some issues with the conceptualisation and operationalisation of cognitive load. *Learning and Instruction* 20 (3), 250–264. doi: 10.1016/j.learninstruc.2009.02.024.

Ben-Nun, M. S., & Yarden, A. (2009). Learning molecular genetics in teacher-led outreach laboratories. *Journal of Biological Education* 44 (1), 19–25. doi: 10.1080/00219266.2009.9656187.

Bryce, T., & Robertson, I. (1985). What can they do? A review of practical assessment in Science. *Studies in Science Education* 12, 1–24.

Buckley, B. C. (2000). Interactive multimedia and model-based learning in biology. *International Journal of Science Education* 22 (9), 895–935. doi: 10.1080/095006900416848.

Chittleborough, G. D., & Treagust, D.F. (2009). Why models are advantageous to learning science. *Educación química* 20 (1), 12–17.

Cohen, J. (1992). A power primer. *Psychological bulletin* 112 (1), 155–159.

Cokelez, A., Dumon, A., & Taber, K. S. (2008). Upper secondary French students, chemical transformations and the "Register of models": A cross-sectional study, *International Journal of Science Education*, 30 (6), 807-836. doi: 10.1080/09500690701308458.

Cokelez, A. (2012). Junior high school students' ideas about the shape and size of the atom. *Research in Science Education*, 42 (4), 673-686. doi: 10.1007/s11165-011-9223-8.

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education* 90 (6), 1073–1091. doi: 10.1002/sce.20164.

Döring, N., & Bortz, J. (2016). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften* [*Research methods and evaluation in social and human sciences*] (5th ed.). Berlin Heidelberg, Germany: Springer-Verlag.

Ferk, V., Vrtacnik, M., Blejec, A., & Alenka, G. (2003). Students' understanding of molecular structure representations. *International Journal of Science Education* 25 (10), 1227–1245. doi: 10.1080/0950069022000038231.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics* (4th Ed.). London: SAGE.

Franke, G., & Bogner, F. X. (2011). Cognitive influences of students' alternative conceptions within a hands-on gene technology module. *The Journal of Educational Research* 104, 2011, 158–170.

Gerstner, S., & Bogner, F. X. (2010). Cognitive achievement and motivation in hands-on and teacher-centred science classes: Does an additional hands-on consolidation phase (concept mapping) optimise cognitive learning at work stations? *International Journal of Science Education* 32 (7), 849–870. doi: 10.1080/ 09500690902803604.

Giere, R. (1988). *Explaining science*. Chicago: University of Chicago Press.

Gilbert, J. K. (2004). Models and modelling: Routes to more authentic science education. *International Journal of Science and Mathematics Education* 2, 115–130.

Gilbert, J. K., Boulter, C., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. Gilbert & C. Boulter (Eds.), *Developing models in science education* (pp. 3–17). Dordrecht: Kluwer.

Gilbert, J. K., Boulter, C., & Rutherford, M. (1998). Models in explanations, Part 1: Horses for courses? *International Journal of Science Education* 20 (1), 83–97. doi: 10.1080/0950069980200106.

Girwidz, R., Robitzko, T., Schaal, S., & Bogner, F.X. (2006). Theoretical concepts for using multimedia in science education. *Science Education International*, 17(2), 77-93.

Goldschmidt, M., Scharfenberg, F.-J., & Bogner, F. X. (2015). Instructional efficiency of different discussion approaches in an outreach laboratory: Teacher-guided versus student-centered. *The Journal of Educational Research* 109 (1), 27–36. doi: 10.1080/00220671.2014.917601.

Griffiths, K. A., & Preston, R. K. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. *Journal of Research in Science Teaching*, 29(6), 611–628.

Grosslight, L., Unger, C., Jay, E., & Smith, C. L. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching* 28 (9), 799–822.

Grünkorn, J., Upmeier zu Belzen, A., & Krüger, D. (2014). Assessing students' understandings of biological models and their use in science to evaluate a theoretical framework. *International Journal of Science Education* 36 (10), 1651–1684. doi: 10.1080/09500693.2013.873155.

Harrison, A. G., & Treagust, D. F. (1996). Secondary students' mental models of atoms and molecules: Implications for teaching chemistry. *Science Education*, 80(5), 509–534.

Harrison, A. G., & Treagust, D. F. (2000). A typology of school science models. *International Journal of Science Education* 22 (9), 1011–1026. doi: 10.1080/095006900416884.

Henze, I., & Van Driel, J. H. (2011). Science teachers' knowledge about learning and teaching models and modeling in public understanding of science. In M. S. Khine & I. M. Saleh (Eds.), *Models and modeling: cognitive tool for scientific inquiry* (pp. 239–261). Heidelberg: Springer.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2006). Scaffolding and Achievement in Problem-Based and Inquiry Learning: A Response to Kirschner, Sweller, and Clark. *Educational Psychologist* 42 (2), 99–107.

Hodson, D. (1998). *Teaching and learning science: Towards a personalized approach.* Buckingham, PA: Open University Press.

ISB [State Institute for School Quality and Educational Research, Munich] (2004). *Lehrplan im Fach Chemie für das Gymnasium in Bayern* [*Curriculum in Chemistry for the Gymnasium in Bavaria*]. Wolnzach, Germany: Kastner.

Justi, R. S. (2009). Learning how to model in science classroom: key teacher's role in supporting the development of students´ modelling skills. *Educación química* 20 (1), 32–40.

Justi, R. S., & Gilbert, J. K. (2002a). Science teachers' knowledge about and attitudes towards the use of models and modelling in learning science. *International Journal of Science Education* 24 (12), 1273–1292. doi: 10.1080/09500690210163198.

Justi, R. S., & Gilbert, J. K. (2002b). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education* 24 (4), 369–387. doi: 10.1080/09500690110110142.

Kester, L., Kirschner, P. A., & Van Merriënboer, J. J. G. (2006). Just-in-time information presentation: Improving learning a troubleshooting skill. *Contemporary Educational Psychology*, 31, 167-185.

Kindfield, A. C. (1991). Confusing chromosome number and structure: A common student error. *Journal of Biological Education* 25, 1991 (3), 193–200.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist* 41 (2), 75–86. doi: 10.1207/s15326985ep4102_1.

KMK (2005). Beschlüsse der Kultusministerkonferenz – Bildungsstandards im Fach Biologie für den Mittleren Bildungsabschluss [Resolution of the Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany - Standards of biology education for secondary school]. Munich, Germany: Luchterhand.

Krajcik, J., & Merritt, J. (2012). Engaging students in scientific practices: what does constructing and revising models look like in the science classroom? The Science Teacher, 79(3), 38–41.

Langheinrich, J., & Bogner, F. X. (2015). Student conceptions about the DNA structure within a hierarchical organizational level: Improvement by experiment- and computer-based outreach learning. *Biochemistry and Molecular Biology Education* 43 (6), 393–402. doi: 10.1002/bmb.20888.

Langheinrich, J., & Bogner, F. X. (2016). Computer-related self-concept: The impact on cognitive achievement. *Studies in Educational Evaluation* 2016 (50), 46–52.

Linn, M. (2003). Technology and science education: Starting points, research programs, and trends. *International Journal of Science Education* 25(6), 727– 758.

Louca, L. T., & Zacharia, Z. C. (2012). Modeling-based learning in science education: Cognitive, metacognitive, social, material and epistemological contributions. *Educational Review*, *64*(4), 471–492.

Maia, P.F., & Justi, R. (2009). Learning of chemical equilibrium through modelling-based teaching. *International Journal of Science Education* 31 (5), 603–30.

Malacinski, G. M., & Zell, P. W. (1996). Manipulating the 'invisible': Learning molecular biology using inexpensive models. *American Biology Teacher* 58, 1996 (7), 428–432.

Marbach-Ad, G., & Stavy, R. (2000). Students' cellular and molecular explanations of genetic phenomena. *Journal of Biological Education* 34 (4), 200–205. doi: 10.1080/00219266.2000.9655718.

Mayer, R. E. (2001). *Multimedia learning*. Cambridge, UK: Cambridge University Press.

Mayer, R. E., & Wittrock, M. C. (1996). Problem-solving transfer. *Handbook of educational psychology*, 47–62.

Meissner, B., & Bogner, F. X. (2011). Enriching students' education using interactive workstations at a salt mine turned science centre. *Journal of Chemical Education* 88 (4), 510–515. doi: 10.1021/ed1006103.

Mierdel, J., & Bogner, F. X. (2019a). Is creativity, hands-on modeling and cognitive learning gender-dependent? Thinking Skills and Creativity 31, 91–102, doi:10.1016/j.tsc.2018.11.001.

Mierdel, J., & Bogner, F. X. (2019b). Comparing the Use of Two Different Model Approaches on Students' Understanding of DNA Models. *Education Sciences*, 9(2), 115.

NGSS Lead States (2013). Next generation science standards: for states, by states; The National Academies Press: Washington, DC.

Oh, P. S., & Oh, S. J. (2011): What teachers of science need to know about models: An overview. *International Journal of Science Education* 33 (8), 1109–1130. doi: 10.1080/09500693.2010.502191.

Paas, F. G. (1992). Training strategies for attaining transfer of problem-solving skill in statistics: A cognitive-load approach. *Journal of Educational Psychology*, 84(4), 429–434.

Paas, F. G. W. C., Renkl, A., & Sweller, J. (2003b). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, 38(1), 1–4.

Paas, F. G. W. C., Tuovinen, J., Tabbers, H., & Van Gerven, P. W. (2003a). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist*, 38(1), 63–71.

Paas, F. G. W. C., & Van Merriënboer, J. J. G. (1993). The efficiency of instructional conditions: An approach to combine mental effort and performance measures. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 35(4), 737–743.

Paas, F. G., Van Merriënboer, J. J., & Adam, J. J. (1994). Measurement of cognitive load in instructional research. *Perceptual and Motor Skills*, 79(1), 419–430.

Peebles, P., & Leonard, W. H. (1987). A hands-on approach to teaching about DNA structure and function. *The American Biology Teacher* 49, 1987 (7), 436–438.

Randler, C., & Bogner, F. X. (2006). Cognitive achievements in identification skills. *Journal of Biological Education* 40 (4), 161–165. doi: 10.1080/00219266.2006.9656038.

Roberts, J.R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education*, 33, 105–110. doi: 10.1002/bmb.2005.494033022426

Rost, J. (2004). *Lehrbuch Testtheorie – Testkonstruktion* [*Textbook test theory – test construction*] (2nd Ed.). Bern, Switzerland: Verlag Hans Huber.

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2006). Effect of bead and illustrations models on high school students' achievement in molecular genetics. *Journal of Research in Science Teaching* 43 (5), 500–529. doi: 10.1002/tea.20144.

Scharfenberg, F.-J., Bogner, F. X., & Klautke, S. (2007). Learning in a gene technology laboratory with educational focus: Results of a teaching unit with authentic experiments. *Biochemistry and Molecular Biology Education* 35 (1), 28–39. doi: 10.1002/bmb.1.

Scharfenberg, F.-J., & Bogner, F. X. (2011). A new two-step approach for Hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene technology lab. Research in Science Education 41 (4), 505–523. doi: 10.1007/s11165-010-9177-2.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., & Fortus, D. (2009). Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners. Journal of Research in Science Teaching, 46(6), 632–654. doi:10.1002/tea.20311.

Sellmann, D., & Bogner, F. X. (2013). Climate change education: Quantitatively assessing the impact of a botanical garden as an informal learning environment. *Environmental Education Research* 19, 2013 (4), 415–429.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of experimental psychology: General*, 125(1), 4.

Sins, P. H., Savelsbergh, E. R., van Joolingen, W. R., & van Hout-Wolters, B. H. (2009). The relation between students' epistemological understanding of computer models and their cognitive processing on a modelling task. *International Journal of Science Education* 31 (9), 1205–29. doi: 10.1080/09500690802192181.

Sotiriou, S., & Bogner, F. X. (2008). Visualizing the invisible: Augmented reality as an innovative science education scheme. *Advanced Science Letters* 1 (1), 114–122. doi: 10.1166/asl.2008.012.

Steiner, G. (2006). Lernen und Wissenserwerb [Learning and knowledge acquisition]. In A. Krapp, & B. Weidemann (Eds.), *Pädagogische Psychologie. Ein Lehrbuch* [*Educational Psychology. A Textbook*] (pp. 166-170). Weinheim, Germany: Beltz.

Stull, A. T., Gainer, M. J., & Hegarty, M. (2018). Learning by enacting: The role of embodiment in chemistry education. *Learning and Instruction*, 55, 80-92. doi: 10.1016/j.learninstruc.2017.09.008.

Stull, A. T., & Hegarty, M. (2016). Model manipulation and learning: Fostering representational competence with virtual and concrete models. *Journal of Educational Psychology*, 108(4), 509-527. doi: 10.1037/edu0000077.

Svoboda, J., & Passmore, C. (2013). The strategies of modeling in biology education. *Science & Education* 22 (1), 119–142. doi: 10.1007/s11191-011-9425-5.

Sweller, J. (2006). Discussion of 'emerging topics in cognitive load research: using learner and information characteristics in the design of powerful learning environments'. *Applied Cognitive Psychology* 20 (3), 353–357. doi: 10.1002/acp.1251.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory. Explorations in the Learning Sciences, Instructional Systems and Performance Technologies, Volume 1*. New York, Springer. doi: 10.1007/978-1-4419-8126-4

Sweller, J., Van Merriënboer, J. J. G., & Paas, F. G. W. C. (1998). Cognitive architecture and instructional design. *Educational Psychology Review* 10 (3), 251–296.

Taber, K. S. (1998). An alternative conceptual framework from chemistry education. *International Journal of Science Education*, 20(5), 597–608.

Templin, M. A., & Fetters, M. K. (2002). A working model of protein synthesis using LegoTM building blocks. *The American Biology Teacher* 64, 2002 (9), 673–678.

Tobin, K. (1990). Research on science laboratory activities: In pursuit of better questions and answers to improve learning. *School Science and Mathematics*, 90, 403–418.

Treagust, D. F., Chittleborough, G., & Mamiala, T. (2002). Students' understanding of the role of scientific models in learning science. *International Journal of Science Education* 24 (4), 357–368. doi: 10.1080/09500690110066485.

Upmeier zu Belzen, A. (2013). Modelle [Models]. In H. Großengießer, U. Harms, & U. Kattmann (Eds.), *Fachdidaktik Biologie* [*Biology education*] (pp. 325–334). Freising: Aulis Verlag.

Van Gog, T., Paas, & F. G. W. C. (2008). Instructional efficiency: Revisiting the original construct in educational research. *Educational Psychologist* 43, 2008, 16–26.

Van Merriënboer, J. J. G., & Ayers, P. (2005). Research on cognitive load theory and its design implications for e-learning. *Educational Technology Research and Development* 53 (3), 5–13.

Watson, J.D. (1968). *The double helix*. London: Penguin Books.

Watson, J. D., & Crick, F. H. C. (1953). Molecular structure of nucleic acids. A Structure for Deoxyribose Nucleic Acid. *Nature* (171), 737–738.

Werner, S., Förtsch, C., Boone, W., von Kotzebue, L., & Neuhaus, B. J. (2017). Investigating how German Biology teachers use three-dimensional physical models in classroom instruction: A video study. *Research in Science Education* 1-27. doi: 10.1007/s11165-017-9624-4.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education* 92, 941–67. doi: 10.1002/sce.20259.

5.6 Teilarbeit D

Education Sciences

Vol. 9(2), pp. 115, 2019

First published online Mai 2019. https://doi.org/10.3390/educsci9020115

Comparing the use of two different model approaches on students' understanding of DNA models

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Abstract

As effective methods to foster students' understanding of scientific models in science education are needed, increased reflection on thinking about models is regarded as a relevant competence associated with scientific literacy. Our study focuses on the influence of model-based approaches (modeling vs. model viewing) in an out-of-school laboratory module on the students' understanding of scientific models. A mixed method design examines three subsections of the construct: (1) students' reasoning about multiple models in science, (2) students' understanding of models as exact replicas, and (3) students' understanding of the changing nature of models. There were 293 ninth graders from Bavarian grammar schools that participated in our hands-on module using creative model-based tasks. An open-ended test item evaluated the students' understanding of "multiple models" (MM). We defined five categories with a majority of students arguing that the individuality of DNA structure leads to various DNA models (modelers = 36.3%, model viewers = 41.1%). Additionally, when applying two subscales of the quantitative instrument Students' Understanding of Models in Science (SUMS) at three testing points (before, after, and delayed-after participation), a short- and mid-term decrease for the subscale "models as exact replicas" (ER) appeared, while mean scores increased short- and mid-term for the subscale "the changing nature of models" (CNM). Despite the lack of differences between the two approaches, a positive impact of model-based learning on students' understanding of scientific models was observed.

Keywords

genetics, model-based learning, student understanding, creative modeling, hands-on experimentation, outreach learning

1. Introduction

Genetics, as a key aspect in modern biology, provides access to many fields such as the decryption of specific disease patterns in medicine, the development of customized and effective medication, and increased understanding of genetic conditions on our behaviors [1]. Models and modeling play a significant role in the research process as they may help to explain experimental observations by revealing essential relationships that bridge theoretical knowledge to build a basis for further scientific predictions [2]. It is important for researchers to develop complex genetic models to describe and understand the molecular basis of observed phenomena, for example, for gene cascades that can explain the basics of learning and memory [3,4].

Years ago, one of the most revolutionary events for modern genetics was inspired by the creative process of modeling and finally helped in the interpretation of experimental data [5]. In 1953, Francis Crick wrote to his then 12-year-old son about "a most important discovery" and described the "beautiful" structure of DNA [6] as a molecule that carries the most genetic information in all organisms from bacteria to humans. In 1962, he and his colleagues, James Watson and Maurice Wilkinson, were awarded with the Nobel Prize. Nevertheless, it is often forgotten that the decoding of the DNA structure by modeling was also largely facilitated by the innovative crystallographic studies from Rosalind Franklin and Raymond Gosling. Their research was essential for determining the structure of DNA. Franklin recognized that an adequate model of DNA structure must have phosphate groups on the outside of the molecule [7], also, identified two distinct configurations of DNA (A and B form), and was able to show that a double helix was consistent with the X-ray patterns of both forms [8].

1.1. Teaching Genetics: The Role of Outreach Laboratories and Model-Support

Modeling and experimentation go hand in hand in the description and explanation of genetic phenomena. However, as the understanding of invisible molecular processes and abstract concepts still poses numerous questions, transposing this knowledge into classrooms is a challenge for learning genetics at school [9,10]. To counteract learning difficulties caused by inaccessible working spaces of real scientist connected with incomprehensible research contents, outreach laboratories at universities may help students to get in touch with realistic learning scenarios by offering special material resources as compared with the regular biology lessons [11,12]. Many studies have investigated the effects of student-centered learning in outreach laboratories on students' cognitive achievement and have demonstrated further benefits as compared with conventional teacher-centered science classes due to the combination of newly acquired knowledge with autonomous hands-on learning [13,14,15]. Another advantage of out-of-school labs is that participants are actively involved in the learning content as they slip into the role of scientists when working cooperatively on student-centered hands-on tasks [16,17]. Discussing socio-scientific issues in an outreach laboratory, the authors [18] showed that student-centered approaches provide an appropriate means to establish students' own opinions, even though

they have been shown to be associated with a higher cognitive load than that of teacher-guided approaches. An important strategy for a classroom discussion seems to be the promotion of students' ability to ask their own research questions while performing inquiry-based tasks [19]. From another perspective, the participation in a teacher-led lab activity that focuses on DNA manipulations to reveal the connection between gene and phenotype significantly improved students' mental models of DNA as well as their procedural understanding of DNA manipulations [20]. Nevertheless, authentic first-hand experiences may help to increase scores on wellbeing when students have the opportunity to work like real scientists [21].

One of our aims was to innovate traditional outreach programs in learning genetics by arousing students' creativity and transferring enthusiasm from arts to science classes. We developed a STEAM teaching approach (STEAM = science, technology, engineering, arts and mathematics) for an out-of-school lab setting, combining creative model-based learning with classical hands-on experimentation [22]. Visual representations are regarded as essential to understand complex (molecular) contents and especially models that are highly relevant for exemplification in teaching genetics [23]. For chemistry education it is known that enacting with hand-held molecular models can reduce the demand of imaging concepts and processes in the mind by lowering the cognitive load [24]. Models and modeling may help students to learn, structure. and integrate newly acquired information with their previous knowledge, since the mere mental transformation of novel representations is very memory intense [25]. The students' understanding of three-dimensional molecular structures also seems to be dependent on the type of representation used. The application of concrete three-dimensional models or pseudo-concrete computer-generated models leads to better results than more abstract kinds of representations (e.g., schematic representations and stereochemical formulas) [26].

Models and modeling occupy various roles in scientific practice and there are also many different ways to use models and modeling in science classrooms [27,28]. A general distinction can be drawn between "model-based teaching" (the use of existing models by students) and "modeling-based teaching" (the creation and use of models by students) [29]. The work of Odenbaugh defines five major applications of models in biology: (1) to explore unknown possibilities, (2) to explore complex systems by using simplified models, (3) to develop conceptual frameworks, (4) to make accurate predictions, and (5) to generate causal explanations [30]. In consequence, modeling or model-based inquiry can also help students to explore their own ideas and to refine their conceptual understanding [28]. However, common model-based approaches include models primarily as teaching tools, for example, as illustrative objects to explain specific processes and structures. In contrast, student-centered modeling activities have the potential to engage students in developing, evaluating, and improving their own models which finally helps them to reflect on how scientists use models to study natural phenomena [31,32]. When comparing influences on cognitive achievement, cognitive load, and instructional efficiency model viewers achieved significantly higher mid-term knowledge increases than modelers, while individual cognitive load scores remained similar. Accordingly, model viewing produced

significantly higher scores for instructional efficiency, pointing to enhanced cognitive achievement [33]. The correct understanding of the three genetics concepts (DNA, gene, and chromosome) may have hindered the development of correct and complete DNA models from the modelers [17,33]. We also evaluated students' model quality and monitored potential influences on individual creativity and knowledge levels [34]. Girls created significantly better structured models than boys, and girls' model quality also significantly correlated with short- and mid-term knowledge levels and to the creativity subscale "flow". Modeling seems to provide stronger support for female students and is a suitable approach for emphasizing creativity in science education to overcome the negative perceptions of traditional science [35].

1.2. Empirical Findings on Students' Understanding of Scientific Models

As models and modeling play a key role in scientific inquiry and communication, the Next Generation Science Standards (NGSS, [36]) emphasize the meta-level of thinking about models as an essential learning goal in science curricula with the aim of promoting understanding of the nature of science and developing scientific literacy [37]. However, in classrooms, the use of models as learning tools to gain conceptual and theoretical knowledge often predominates the role of models as part of the nature of science [32,38]. It is not surprising that empirical studies have indicated that both teachers and learners mainly associate models with descriptive characteristics and their role as equipment for teaching visualize abstract concepts [39,40]. Biology teachers, in particular, mentioned primarily descriptive entities of models as compared with other science teachers who were able to give more accurate definitions of models consistent with scientific explanations [40]. In consequence, students' appreciation of models is often limited and naïve, when they describe models as physical copies and do not understand their role as mediators between theory and observation [39,41]. A recent study investigated students' understanding of the nature and purpose of biological models confirmed these earlier findings [42] and reported that across grades the majority of students still considered models as idealized representations of an original with the purpose to illustrate or to explain this original. One reason could be the frequency of introducing passive models in classrooms, although the active involvement and handling of models seemingly may better support a perception of models as interpretive and predictive tools [24,43]. This is in line with current research on the uses of three-dimensional physical models in biology classroom instruction [27]. Werner and colleagues found that several categories of scientific reasoning were rarely applied during an extensive use of models in biology lessons. Furthermore, they revealed a lack of critical reflection on the applied models unless they were regarded as essential for developing a general understanding of science and scientific reasoning skills.

Additionally, the demand for defined descriptions of students' understanding of models with regard to either grade- or context-specific aspects became greater. In order to promote students' meta-knowledge of models and modeling, more investigations on context-specific teaching approaches are in the interest of research, as well as an accompanying evaluation of students' understanding of models

[44]. In addition, the activity of argumentation is considered important in modeling of a phenomenon, since scientific modeling is inherently an argumentative act. Furthermore, students can remain focused on the role of the model while arguing with their classmates about it. Herein, arguments can be mental, written or verbal with the intention of judging and understanding ideas, communicating them to others, and convincing oneself or others that the ideas and views to explain a phenomenon are useful [45]. However, science teachers themselves need modeling skills as well as an elaborated understanding of models and modeling to apply modeling practices appropriately in the classroom (e.g., [46]). According to Justi and Gilbert's model of modeling [47], four main stages for successful modeling in science classrooms should be taken into account: (1) collecting information about the entity that is being modeled, (2) producing a mental model, (3) expressing that model in an adequate representation form, (4) testing and evaluating its scope and limitations. Furthermore, Krell and colleagues recently saw the need to develop an instrument to analyze and describe modeling activities of (preservice) science teachers and to derive modeling strategies [48].

Empirical research of students' understanding of models is widespread as well as the number of potential assessment instruments is high [38,49-51]. On the basis of their individual life experiences, students built up personal and alternative concepts of the role of scientific models, which, in addition, do not have to match the teacher's assumptions about the students' perceptions. Treagust and colleagues [38] designed the quantitative instrument Students' Understanding of Models in Science (SUMS) that measures the following five aspects: (1) scientific models as multiple representations, (2) models as exact replicas, (3) models as explanatory tools, (4) the uses of scientific models, and (5) the changing nature of scientific models. On the one hand, their results for secondary science students revealed that the majority of students think that new ideas and research findings can lead to changes of existing scientific models (factor 5). On the other hand, answers were different for models as exact replicas (factor 2) emphasizing, in particular, that descriptive entities of scientific models depend on the level of abstraction [38].

A second approach applied open-ended test items to evaluate a theoretical framework that concentrated on five partly similar aspects of students' understandings. Two biological models which were nature of models and multiple models, and their use in science which included purpose of models, testing, and changing models [41,51]. Empirical data supported a subdivision of each scale into three levels (I–III) and confirmed that these levels reflect an increasing degree of difficulty [44]. As expected, students' answers could be more frequently classified as level I and II as compared with far fewer answers at the highest level III. Taking into account that Grünkorn and colleagues defined learners' understanding as competencies, these results are assigned to the specific domain of biology [41]. However, the underlying framework is applicable to evaluate students' understanding of scientific models in general [51]. This offers the advantage to assess multidisciplinary topics as well, for example in the context of molecular instruction. Especially in terms of molecular biochemical content, an overlapping is often given as well as an application of adequate models makes sense [23].

A third study used the instrument Students' Views of Scientific Models and Modeling (VSMM) and focused on three main aspects of representational characteristics of models and students' educational levels [52]. The applied subscales were: (1) nature of models, (2) nature of modeling, and (3) purpose of models, and each included modality, dimensionality, and dynamics. Their major findings were that high school students more frequently understood textual representations and pictorial representations as models (model identification), while they also more often perceived differences between two-dimensional and three-dimensional models (utility of multiple models) as compared with middle school students [52]. These findings support the assumption that the students' age and educational level are additional relevant factors which explain their interactions with different representative forms [53].

1.3. Objectives of the Study

The present research compares the influence of a model-based and a modeling-based approach in an out-of-school laboratory module on students' understanding of the role of scientific models. To follow the demand on more context-specific evaluations, both approaches relate to the topic of DNA structure and investigate three sub-aspects as follows: are there differences between the two approaches in students' reasoning about multiple models in science (RQ1); to what extent do the two approaches affect students' understanding of scientific models as exact replicas (RQ2); how do model-based activities influence students' understanding of the changing nature of scientific models, if at all (RQ3).

2. Materials and Methods

2.1. Educational Intervention

A one-day module (270 min) on DNA structure for ninth graders at a university out-of-school lab was implemented by the same teacher. The hands-on learning activity was embedded in an inquiry-based setting where students worked in pairs, and used a workbook as a guide to encourage problem-solving as well as collaborative skills (for a detailed description of the module's phases see [22,34]). The contents of the lab day were adapted to follow the guidelines set by the Bavarian grammar school syllabus [54]. With regard to abstraction capability and the promotion of logical thinking, students dealt with challenging, application-oriented questions that required interdisciplinary networked thinking based on fundamental biological knowledge. Working with model concepts as well as frequent changes between different organizational levels (e.g., cells, organs, organisms, ecosystems) promoted the ability to abstract and train multi-perspective and logical thinking. On the basis of the traits observed, ninth graders gained an overview of the path from genetic information to traits. They got to know DNA as an information carrier and could describe a simplified DNA model.

The intervention started with a pre-lab phase (50 min) to introduce the laboratory bench and practice essential working techniques (e.g., micro pipetting, decantation, and centrifugation). The two

experimental phases, DNA isolation from oral mucosal cells for 60 min and agarose gel electrophoresis for 85 min, were connected by a model phase (60 min), where students followed the footsteps of Watson and Crick to solve the molecular puzzle of DNA structure. The model phase was the key activity as it provided the theoretical basis for the experimental findings (Figure 1). After reading about the discovery of the DNA structure, students answered comprehension questions. They internalized essential background information as they mentally began to develop a model of DNA structure. On the basis of the text, the following important components should be considered, for example, the phosphate-sugar chains as DNA backbone, names and arrangement of the bases, possible base pairings, hydrogen bonds between base pairings, and the right-handed double helix structure. For the subsequent model-based activities participants were randomly assigned to two subsamples: (A) The modelers (md) who creatively generated a DNA model with no instructions provided except DNA-modeling kits containing various handcrafting materials (e.g., colored beads, pipe cleaners, scissors, scotch tape, plasticine, and paper cards). (B) The model viewers (mv) who worked instead with a completed but unlabeled commercially available school model and compared the substructures of this model with their mental models. In order to consider the scope and limitations of the models both treatments had to make a labelled drawing to explain the elements of their models'. During this model evaluation students could explicitly reflect their modeling process and the nature of models while they were arguing with their partners about their ideas and whether the representation of DNA might be appropriate as recommended by Passmore and Svoboda [45]. In the final interpretation phase, both groups discussed and compared the findings of the model phase with previously formulated hypotheses and with the experimental results. Additionally, students had to consider the scope and limitations of the models.

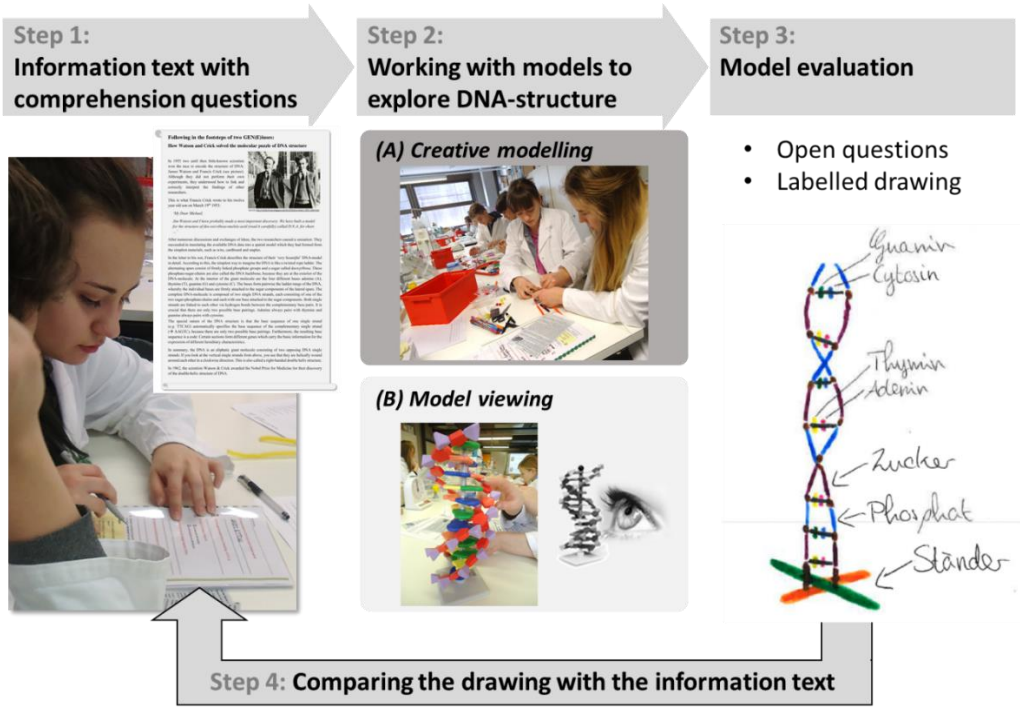

Figure 1. Overview of student activities in the model phase.

2.2. Participants

In 2017, twelve classes from eight different Bavarian grammar schools ('Gymnasium') participated in our laboratory module. Class sizes ranged from 20 to 34 students. Data were collected from 293 ninth graders (59.04% female, age M ± SD = 14.51 ± 0.69, novices). The classes were randomly assigned to two treatments: 120 modelers (md) creatively elaborated a DNA model and 134 model viewers (mv) identified DNA substructures on a commercially available school model. To control for the effect of repeated measurement, a test-retest sample was also taken from students in grammar schools (n = 39), who completed the SUMS questionnaire (Students' Understanding of Models, [38]) without having participated in the module or receiving any instruction on the topic during data collection.

Participation was voluntary. The parents of all students gave their written consent for students' participation. The study was conducted in accordance with the Declaration of Helsinki [55]. The Bavarian State Ministry for Education and Cultural Affairs approved the questionnaire. Data collection was pseudo-anonymous. Students could not be identified from the data used.

2.3. Test design and instruments

Our study followed a quasi-experimental mixed-method design with pre-test (T0), post-test (T1) and retention-test (T2). The data were gathered using paper-and-pencil questionnaires. Students were never aware of any testing schedules. For qualitative assessment of students' reasoning about "multiple models" (MM) in science, we used an open-ended test item directly after participation in the lab module (T0, "Explain why there can be different models of one biological original (like the DNA structure)!" adapted from [41]). A single decider categorized students' answers by using qualitative content analysis [56]. Although we considered the framework of Grünkorn et al. [41] to be appropriate, it was only partially transferable to our study. Firstly, the measurement design differed between the studies, and the applicability of the proposed category system to classify our student responses was too extensive and complex. In addition, our participants often argued contextually, which would have required an extension of the existing framework. Consequently, we developed an alternative system by inspecting the variety of explanations with regard to students' understanding of multiple models as compared with one biological original and we identified five different categories: MM1, various ideas/concepts; MM2, individuality of DNA; MM3, different model design; MM4, different focus; and MM5, different research states). Detailed descriptions of the categories as well as examples from students' answers are shown in Table 1. In order to examine reliability, we randomly selected 15% of the students' answers for intra- and inter-rater categorization. The dataset was reanalyzed by the first author after six months to estimate intra-rater statistics and by a nonpartisan third person to obtain independent inter-rater reliability. Cohen's Kappa coefficient [57] yielded reliability scores for intra-rater reliability of kappa = 0.826 and for inter-rater reliability of kappa = 0.651. These scores were rated as almost perfect or rather substantial indicating that the assessment was independent of the raters [58]. Consequently, a high

observer agreement was interpreted as an indication that the category system used was easily applicable and led to measurement accurate data [59].

Table 1. Category system to evaluate students' understanding of models with regard to the aspect of "multiple models" with an open-ended test item (Q: *Explain why there can be different models of one biological original (like the DNA structure)!)*

Categories		Description	Example(s) from the Students' Answers
MM0	missings	no or inadequate answer	-
MM1	various ideas/concepts	There can be various ideas about the original; different models are valid at the same time. Differing concepts lead to different interpretations of the data.	*'Because everyone has different interpretations of a representation, e.g., everyone presents things/components etc. differently.'*
MM2	individuality of DNA	The complexity and the individuality of the original DNA structure result in diverse model versions, especially regarding the representation of possible base sequences.	*'Every human being is different, so the bases in each person are also arranged differently.'*
MM3	different model design	Differing methods of presentation (*e.g.*, 2D or 3D, different colors, large or small, separated elements or one piece).	*'Because it can be displayed in different sizes and proportions.'* *'Each one represents the individual components differently, e.g., in different colors.'*
MM4	different focus	The complexity of the original allows different perspectives or variations of focusing on the original (interior or exterior, different sections or states of the original, etc.)	*'To explain various 'properties', there are for example models where you only see the base pairings, and others where you can see the right-handed double helical structure, etc.'*
MM5	different research states	Integrating new findings about the original into the model; improved technology leads to new findings about the original.	*'There are more and more new research findings.'*

Students completed the SUMS questionnaire (Students' Understanding of Models, [33]) three times: two weeks before participation (T0), immediately after the module (T1), and six weeks after participation (T2). We applied a shortened version of the SUMS questionnaire using the subscales ER (models as exact replicas) and CNM (the changing nature of models), as these subscales adequately fit the intent of the model-based learning sequences. For the subscale ER we concentrated on items with high factor loadings (≥0.64) and dropped those with cross loadings from the original questionnaire (see Section 3.2.1 below). The Cronbach's alpha values of the internal consistency of each scale are presented in Table 2. Although acceptable values are normally above 0.70 [60], values between 0.70 and 0.60 can

be rated as still reasonable if the factors have only a few items [61]. It became clear that reliabilities increased to more acceptable levels over the three test times. This can be explained by the fact that the response patterns of the individual students over the test period became more homogeneous and more strongly divided opinion patterns existed on the construct examined. The SUMS instrument used a 5-point Likert-type scale with the following answer options: strongly disagree (1), disagree (2), not sure (3), agree (4), and strongly agree (5). Item order was changed randomly for each test schedule.

Table 2. Number of items and Cronbach's *alpha* scores of the SUMS questionnaire (Students' understanding of models, [38]) for the subscales models as exact replicas (ER) and the changing nature of models (CNM). Cronbach's alpha scores are calculated for pre- (T0), post- (T1) and retention-test (T2).

	Subscale	*Number of items*	α_{T0}	α_{T1}	α_{T2}
ER	Models as exact replicas	4	0.609	0.633	0.663
CNM	The changing nature of models	3	0.699	0.682	0.791

2.4. Statistical Analysis

Statistical tests were conducted using SPSS Statistics 24. The mean scores of the SUMS scale were normally distributed as assessed by the Shapiro–Wilk test, ($p > 0.05$) and according to the QQ-Plots [62]. Consequently, we used parametric testing methods. Pearson's chi-square test was applied for comparing observed frequencies of the categorical variables with the treatment groups [63,64]. An explanatory factor analysis with subsequent orthogonal rotation (varimax) was conducted on the SUMS item set to inspect the similarity to the original scale. To assess the suitability of the sample, the Kaiser–Meyer–Olkin test (KMO) [65] and Bartlett's test of sphericity were applied. The Kaiser–Guttman criterion was used to determine the number of factors to be extracted [66]. Between-group differences were analyzed using a one-way ANOVA at each testing point and within-group comparisons by using a repeated-measures ANOVA based on mean scores for each subscale. Pairwise comparisons at the different testing points used the Bonferroni correction. We reported the effect size using partial eta squared, considering values of 0.01 as a small effect, 0.06 as a medium effect, and 0.14 as a large effect [67].

3. Results

3.1. Qualitative Assessment

To evaluate students' understanding of multiple models (MM) to one biological original with an open-ended test-item, several categories were extracted ($N_{Student\ pairs}$ =189; $N_{Statements}$ =153; n_{md} =80; n_{mv} =73). The frequency is based on all students' answers and all statements add up to 100% (Figure 2). For the category MM1, more modelers (md = 17.5%) as compared with model viewers (mv = 8.2%) justified the existence of multiple models with various ideas about the original that lead to different representations of a phenomenon, some also maintain that those different models are valid at the same time. The majority of students for both treatments argue that the individuality of DNA structure (category MM2) explains the variety of DNA models (md = 36.3%, mv = 41.1%). A different model design (category MM3), for example, the choice of the material used to build the model or the decision whether to present the DNA in 2D or 3D, is also given by the students as justification, regardless of the treatment (md = 28.6%, mv = 30.1%). Less frequently, students in both treatments name the focus of the model (category MM4) as a reason for different forms of representation, for example, to illustrate certain relationships in detail like the different base pairings or the double-helical structure of the DNA (md = 15.0%, mv = 15.1%). Only very few students related the existence of different models to the original (category MM5) with new research leading to a change in the model (md = 2.6%, mv = 5.5%). Nonetheless, no frequencies showed statistically significant association between the type of treatment and students' argumentation about elaborating multiple models for DNA structure (chi-square (4) = 3.77, n.s.).

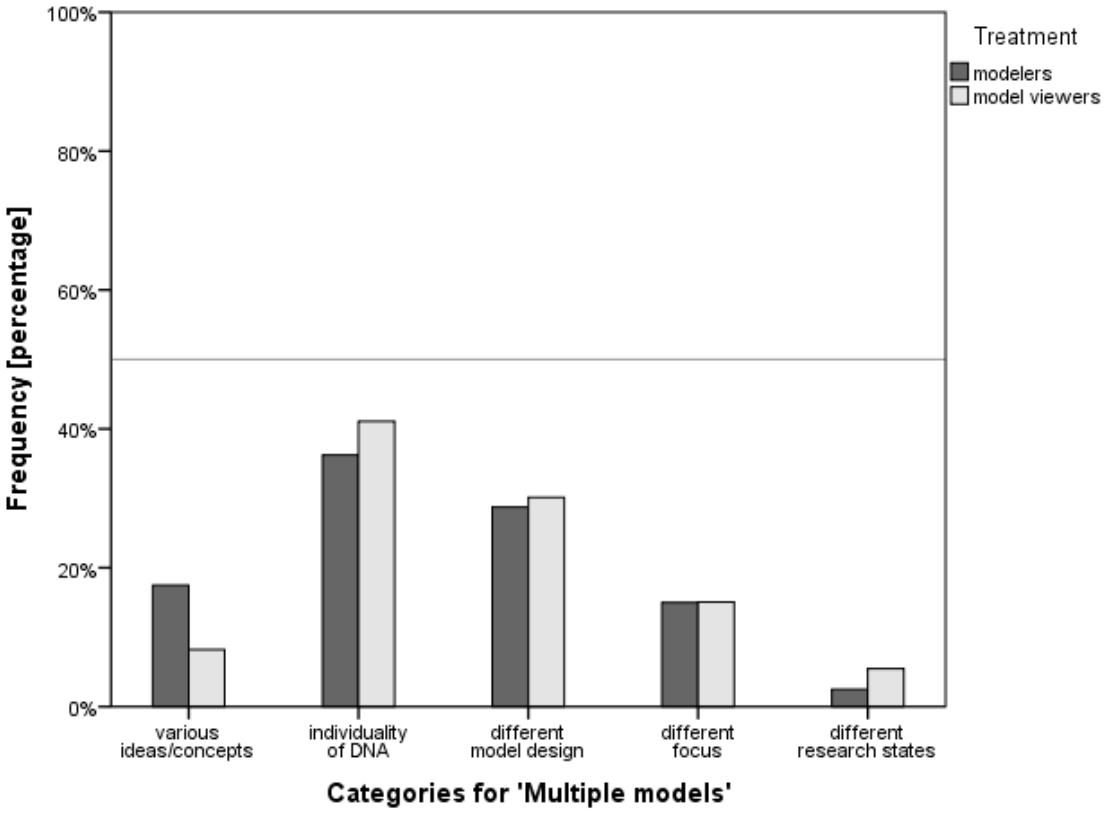

Figure 2. Frequency and distribution of student' answers split by treatments on the open-ended item "Explain why there can be different models of one biological original (like the DNA structure)!" to evaluate students' understanding with regard to the aspect of multiple models. Note. Open question with categories formed from answers given.

3.2. Quantitative Assessment

3.2.1 Factor Analysis

Principal component analysis (PCA) on 7 items of the SUMS (T1) with orthogonal rotation (varimax) yielded two factors on the basis of eigenvalues >1.0. The Kaiser–Meyer–Olkin measure verified the sampling adequacy (KMO = 0.667), which is well above the acceptable limit of 0.5 [68]. Bartlett's test of sphericity (chi-square = 241.578, $p < 0.001$) indicated that correlations between items were sufficiently large for performing a PCA [59]. Examination of the Kaiser–Guttman criterion yielded empirical justification for retaining two factors, which explained 55.14% of the total variance. The scree plot and the component plot in rotated space (Figure 3) supported our two-factor solution and confirmed the original subscales. Among other factor solutions, the varimax-rotated two-factor solution yielded the most interpretable result, with items loading highly on only one of the two factors (Table 3, scores under 0.35 are suppressed). The percent of variance explained by models as exact replicas (ER) was 29.46%, and 25.67% for the changing nature of models (CNM).

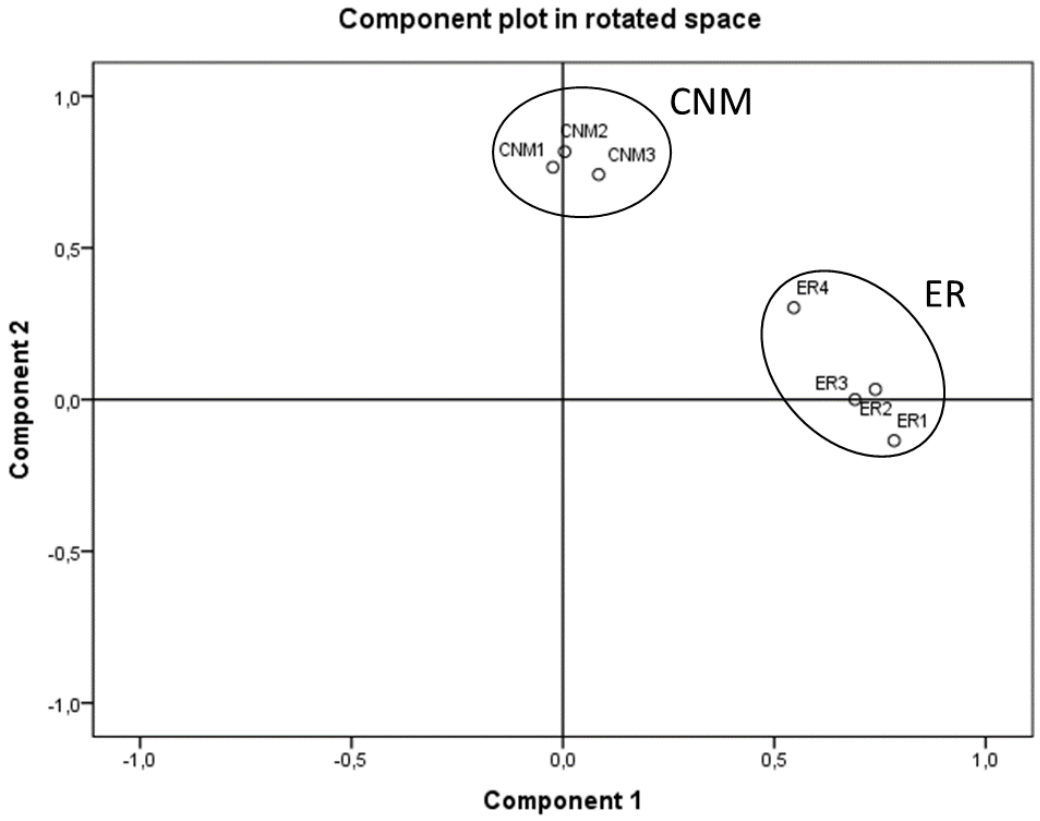

Figure 3. Component plot in rotated space with applied 7 Items of the SUMS (Students' Understanding of Models; [38]) indicating two factors (Items ER1-4, models as exact replicas and items CNM1-3, the changing nature of models).

Table 3. Factor loadings from the principal factor analysis of the post-test (T1) values of two subscales of the SUMS (Students' Understanding of Models [38]).

	Item	*Components*	
		Factor 1 (ER)	*Factor 2 (CNM)*
ER1	A model should be an exact replica.	.783	
ER2	A model needs to be close to the real thing.	.739	
ER3	A model needs to be close to the real thing by being very exact, so nobody can disprove it.	.691	
ER4	Everything about a model should be able to tell what it represents.	.546	
CNM2	A model can change if there are new findings.		.817
CNM1	A model can change if there are new theories or evidence prove otherwise.		.766
CNM3	A model can change if there are changes in data or belief.		.742

Note. N = 220; ER (models as exact replicas); CNM (the changing nature of models); scores under .35 are suppressed.

3.2.2 Influences of the Model-Based Approaches on Two Subscales of the SUMS

The subscale ER (models as exact replicas, Figure 4A) revealed significant differences in the repeated measurement ANOVA ($F(1.89, 424.30) = 103.80$, $p < 0.001$, partial eta squared = 0.32). The Mauchly's test indicated that the assumption of sphericity had been violated (chi-square (2) = 14.87, $p < 0.001$). Therefore, degrees of freedom were corrected by using Huynh-Feldt estimates of sphericity (epsilon = 0.947). The ER mean scores dropped from T0 (M ± SD = 3.49 ± 0.71) to T1 (2.86 ± 0.71) and increased to testing point T2 (3.01 ± 0.75). Post hoc pair-wise comparison with Bonferroni correction showed similar results. The ER mean scores dropped short-term (T0 to T1, $p < 0.001$) and increased again at testing point T2 (T1 to T2, $p = 0.001$). The testing points T0 and T2 also revealed a significant decrease of ER mean scores (T0 to T2, $p < 0.001$).

The subscale ER was also analyzed for differences between the treatments (Figure 4A). There was no significant treatment effect ($F(1.90, 424.28) = 0.123$, $p = 0.875$, partial eta squared = 0.001) which indicated that the mean scores from modelers and model viewers were similar (M ± SD: md = T0 (3.47 ± 0.72), T1 (2.82 ± 0.65), T2 (2.99 ± 0.69); mv = T0 (3.50 ± 0.70), T1 (2.89 ± 0.76), T2 (3.00 ± 0.75)).

The repeated measurement ANOVA for the subscale CNM (the changing nature of models, Figure 4B) also showed a statistically significant difference between testing points ($F(1.72, 379.97) = 33.72$, $p < 0.001$, partial eta squared = 0.13). The Mauchly's test revealed violation of the assumption of sphericity for the subscale CNM (chi-square (2) = 41.36), and therefore degrees of freedom were corrected by using Huynh–Feldt estimates of sphericity (epsilon = 0.860). In contrast to subscale ER, the CNM mean scores increased from T0 (M ± SD = 3.94 ± 0.79) to T1 (4.35 ± 0.59) and dropped to

testing point T2 (4.18 ± 0.69). Post hoc pairwise comparison with Bonferroni correction showed similar results. CNM mean scores increased short-term (T0 to T1, $p < 0.001$) and decreased again at testing point T2 (T1 to T2, $p < 0.001$). The testing points T0 and T2 also showed a significant increase of CNM mean scores (T0 to T2, $p < 0.001$).

The subscale CNM also showed no statistical differences between modelers and model viewers (Figure 4B; F(1.73, 379.69) = 1.137, $p = 0.316$; partial eta squared = 0.01), indicating similar mean scores for both treatments (M ± SD: md = T0 (3.97 ± 0.69), T1 (4.36 ± 0.55); T2 (4.12 ± 0.72) and mv = T0 (3.93 ± 0.87), T1 (4.35 ± 0.62), T2 (4.22 ± 0.67)).

Observing effects of repeated measures of all applied SUMS items, a non-participant test-retest group yielded no statistical differences in a repeated measurement ANOVA (M ± SD = T0 (3.54 ± 0.41), T1 (3.62 ± 0.43); T2 (3.75 ± 0.36); F (2, 0 48) = 2.889; $p = 0.065$; partial eta squared =0.11).

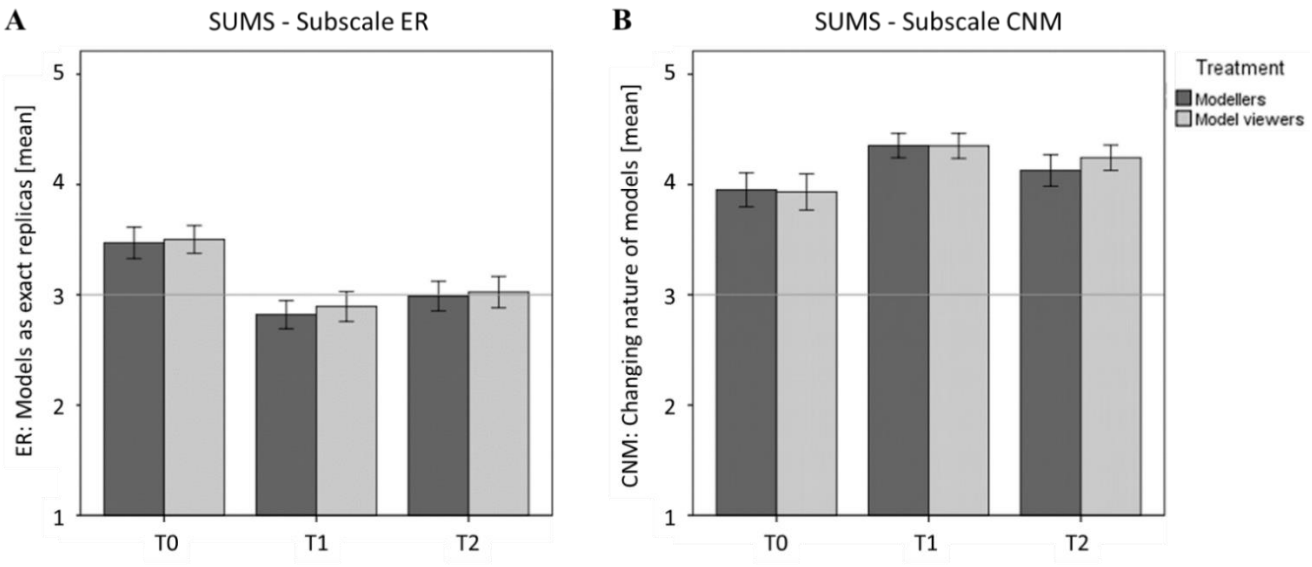

Figure 4. Mean scores for the SUMS sub-scales (A) ER (models as exact replicas) and (B) CNM (the changing nature of models) to testing points T0, T1 and T2 split by treatment. Bars are 95% confidence intervals.

4. Discussion

Over the years increasing efforts have been undertaken to establish models and modeling as integral parts of science curricula and several national education standards highlight their importance for scientific literacy [36,69]. The application of models and the implementation of modeling in science classrooms has been well described and has produced a long series of studies as both are supposed to introduce and engage students in authentic scientific inquiry [2,39,43]. We have shown that a hands-on module in an outreach laboratory is a successful approach for bridging abstract scientific theory with experimental observations through two kinds of model support (modeling vs. model viewing). A

review of modeling-based learning (MbL) approaches specifies five areas that are closely linked to students' learning outcomes which are contributing to cognitive, metacognitive, social, material, and epistemological aspects [70]. We investigated students' cognitive achievement and reported that short- and mid-term knowledge increases after participation in a hands-on laboratory module with modeling tasks [34].

However, as earlier studies have already investigated the effects of inquiry-based modeling on students' understanding of scientific models, especially over multiple testing points [71,72], we follow the demand for further effective implementations of MbL and give an example in the context of molecular DNA models [70]. The findings are in line with previous research and clearly demonstrate a significant improvement of students' understanding of scientific models. Gobert and Pallant used a pre- and post-test design and scaffolded modeling tasks in which students developed their own models, then critiqued peers' models, and finally reflected upon revised models in order to identify improved characteristics. Gobert and Pallant's approach on authentic model-based learning also indicates a deeper understanding of content knowledge as well as an improved understanding of models and their use in science [71]. Another study from organic chemistry education demonstrated that combining two types of three-dimensional molecular models (physical vs. virtual) may foster students' understanding of the model concept as well as the spatial understanding of molecular structures [72]. Therefore, even short-term interventions with adequate inquiry-based tasks seem to have the potential to foster students' understanding of scientific models.

4.1. Influences of the Model-Based Approaches on Students' Understanding of Multiple Models

The aspect of students understanding of multiple models (MM) refers to one original that is represented by different model objects [39,40]. The framework developed by Grünkorn et al. is complex and for reasons already mentioned (see Section 2.3) could not be adequately transferred to students' answers. Nevertheless, some of our categories are comparable to those of Grünkorn et al. and their detailed category system is helpful in assessing students' understanding of multiple models [41].

Quantitative comparison revealed no significant differences between treatments. This result, at first, was surprising because the two approaches lead to different ways of perceptions of the way to describe and simplify the theoretical background of DNA structure. The model viewers explore the DNA structure more passively through a didactically prepared representation (commercially available school model) as compared with the modelers that strengthen important modeling abilities such as actively designing individual models of DNA after mental modeling and modifying their models [28,32]. This implies that all model viewers have acquired the scientific background on identical models, while modelers constructed multiple models of differing model quality [34]. Therefore, we had expected differences in students' responses to the treatments of at least two categories. As modelers might have experienced inspiring thoughts during creative modeling, more justifications about the existence of

multiple models with various ideas about the original (MM1) would have been coherent. Additionally, we hypothesized that the category MM3 (different model design) could be assigned more often to the modelers' answers because they were free to choose by themselves the material and design of their models from a modeling kit. However, both assumptions could not be statistically confirmed and suggest that the different treatments do not affect students' reasoning.

Focusing on the comparison between our results and the framework of Grünkorn et al. our findings are partially in line with their categories in terms of multiple models [41]. First, category MM3 (different model design) is comparable to Level 1 [41], pointing to a low level of understanding, as many students only relate to material and design properties of model objects and consider models as teaching tools. Second, student answers on category MM4 (different focus) could be assigned to Level 2 [41], which corresponds to a medium level of understanding. According to Grosslight et al. [39], students with a median understanding realize that the construction of a model is connected to a specific purpose. Consequently, models are not seen as exact duplicates of an original but rather as a medium of something [73]. Third, remarkably less students argued about the existence of multiple models with various ideas and concepts (MM1) that can be classified as responses on highest Level 3 [41]. Herein, students mentioned, for example, different assumptions, differing interpretations, and their recognition that different models of an original can be valid at the same time [41,52]. The different frequency distribution between the levels as compared with our study could be explained by varying grades (seventh to eleventh grade), different contexts (biomembrane structures, human gullet structures, taste maps of the human tongue), and treatments [41]. These findings are in line with earlier research showing that students' age, educational level, as well as the biological context are relevant factors in students' understanding of models [44,51]. However, it is noticeable that most participants state the individuality of DNA (category MM2) as a reason for the existence of multiple models. Furthermore, some others argue that different research states could lead to different representation forms (category MM5). These two alternative categories are much more content-oriented than the others as students use newly acquired knowledge from the module for their explanations (e.g., arrangement of DNA bases cause different models, a DNA model could be changed in the future due to new findings). Category MM2 highlights typical biological properties of the original and MM5 multiple models caused by the process of scientific discovery. Both categories are apparent to students when they follow the historical discovery route of DNA structure during the module. In summary, arguments in the category MM2 emphasize a lower understanding of models from a medial perspective as an illustration of something [31,32]. This is also true for students' answers in category MM5 since their reasoning indicates an initial understanding. According to Grünkorn et al. students understand only one model as the final model and are unaware that multiple models can be valid contemporaneously [41]. Finally, future research that focuses on investigations of students' reasoning about multiple models over several test times would be of interest.

4.2 Influences of the Model-Based Approaches on Two Subscales of the SUMS

We clearly replicated the original factor structure of the quantitative instrument Students' Understanding of Models in Science (SUMS), with the sub-aspects models, exact replicas (ER) and the changing nature of models (CNM), indicating a good fit of the instrument [38]. Additionally, our findings show significant positive influences for both of our approaches on both subscales, demonstrating that even short-term interventions could contribute to a deeper understanding of the role of models and modeling in science. This can also be confirmed by the measured effect sizes: For the differences in understanding between the three test times, a large effect can be reported for the subscale ER (0.32) and a medium effect for the subscale CNM (0.13). As there are multiple frameworks and assessment instruments, the relationship between our results and existing literature is presented for each sub-aspect [39,40,52].

The ER subscale investigates the students' understanding of how close a model needs to be to the real thing. The observed mean scores (T0) are slightly lower but comparable to the original values from Treagust et al. on secondary school students (eighth to tenth grade) [38]. The empirical data confirms the common perception of models as simple copies in the pre-test. This understanding is considered naïve because it describes models primarily through accuracy and matching details which result in being very similar to the original [39,41]. However, many students are unaware that models can be defined as constructed representations with different theoretical perspectives, focusing on different aspects of an original to explain complex or unknown entities [39]. This is in line with other frameworks that also assign a majority of students to an understanding at lowest Level 1 under the sub-aspects such as kinds of models [39] or nature of models [41]. Reasons for this might be that students appreciate models primarily as visual objects in the classroom (medial perception, e.g., a heart model with detailed anatomical structures) and even teachers more often seem to neglect modeling as a typical method of science in the classroom [32,41]. The teachers' views on models and modeling in learning science could explain these results. According to Justi and Gilbert, teachers know the value of models in the learning of science but often do not realize their value in learning about science [31]. Furthermore, many biology teachers seem to define models as reproductions and to ignore the idea of a model being a subjective mental image of something [40].

It is therefore encouraging that both methods lead to a short- and mid-term decrease of students' understanding of models as exact replicas (ER). Consequently, our participants perceive models less as simple copies because they might have learned through the module that scientists use models and modeling when the actual appearance is not known yet. Both approaches also make students aware that an abstract model of DNA structure can still provide accurate insights even if some details are missing because they are irrelevant for the selected representation form.

The CNM subscale examines how strongly the students perceived models as always valid or appreciated that changes in scientific thinking can lead to adjusted models. Measured mean scores (T0)

are slightly higher as compared with those from the Treagust et al. study [38], pointing to an agreement with the changing nature of models due to new findings or advanced technologies. Although mean scores were already relatively high in the pre-test, the observed short- and mid-term increases indicate further positive influences on students' understanding of the changing nature of models (CNM) regardless of the treatment. This result makes sense, as our module concentrates on the discovery path of DNA structure when combining hands-on experiments with model-based tasks, and therefore our participants themselves follow the typical route of scientific inquiry. However, an evolved understanding of CNM might further be encourage by biology teachers if they stimulate critical thinking about the effectiveness of models and modeling for scientific reasoning [27].

4.3 Limitations of the Study

Nevertheless, our study might have the following limitations: Due to the design of the study, the modelers constructed their own model, whereas the model viewers investigated a regular school model. In consequence, we could have reported a greater variability of DNA models and model quality among the modelers, which is why the potential complexity of the models between the two treatments was partly different. Second, an additional pre-modeling phase that provides meta-modeling knowledge to all participants could be helpful for a further development of students' modeling skills and in consequence for students' understanding of models. Third, our participants were from the highest stratification secondary school level ('Gymnasium'). Therefore, the results could not be generalize to other school types or other grades. As genetics is a complex and specific field, it receives less attention in other school types or is taught in higher classes so that comparability would be difficult.

5. Conclusions

Following the demand for effective model-based strategies with regard towards a more authentic science education [74], we have shown that combining hands-on experimentation with model-based tasks in an outreach laboratory (modeling vs. model viewing) successfully promotes students' understanding of scientific models. Initially, the investigation of students' reasoning about multiple models provided a typical cross-section for the age group surveyed and showed that a majority justified model differences with varying properties of the original (DNA) or with regard to the model design. According to the literature this corresponds more to a lower understanding of multiple models and emphasizes the medial perspective in which models are mainly regarded as teaching tools [32,39,41]. Furthermore, most student responses to this aspect were related to the inquiry-based setting about DNA structure (individuality of DNA and different research states). In consequence, transferability of established frameworks was difficult and alternative categories were formed. This demonstrates, that a specific biological context might play a decisive role in the students' argumentation and could make it difficult to evaluate the model's understanding within a standardized framework. Earlier studies also

have reported that students' understanding of models might be influenced by educational levels and biological contexts [44,51].

We could clearly reproduce the original factor structure of two subscales of the SUMS (Students' Understanding of Models in Science [38]). Furthermore, our pre-, post- and retention-design provided interesting insights into the influences of model-based strategies under the sub-aspects models as exact replicas (ER) and the changing nature of models (CNM). We observed a short- and mid-term decrease for the subscale ER, which indicates that many participants diverged from a naïve perception of models as simple copies. In contrast, a short- and mid-term increase for the subscale CNM, points to a heightened awareness that new research findings could lead to changes and adaptions of existing scientific models. It is encouraging that even a one-day module has the power to improve students' understanding towards a more scientific point of view. Therefore, we conclude that the context of DNA structure provides a fruitful example for combining hands-on experimentation with model-based learning in an out-of-school laboratory by offering access to an exciting path of discovery of molecular phenomena using student-centered hands-on tasks [22].

In summary, both student-centered approaches positively affect students' understanding of models. However, creative modeling can be time-intense both in preparation and in classroom implementation, and this might sometimes even result in students' misconceptions [34] Whereas, learning through model viewing offers an alternative way that can be realized much more easily in biology classrooms.

Nevertheless, there is still a dearth of investigations of innovative and working model applications in science classes. Moreover, future research needs to focus on the role of teachers, and to examine further facets of students' understanding of models such as testing models and purpose of models. Even though our knowledge has come a long way towards successfully integrating models and modeling into science curricula, there are still some milestones to achieve until they are established educational practice.

Author Contributions: Conceptualization, J.M.; Formal analysis, J.M.; Funding acquisition, F.X.B.; Investigation, J.M.; Methodology, J.M.; Supervision, F.X.B.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review & editing, F.X.B.

Funding: This study was supported by the 'CREATIONS' project funded by the European Union's HORIZON 2020-SEAC-2014-1 Program (Grant: 665917) and by the 'Qualitätsoffensive Lehrerbildung' Program funded by the German Federal Ministry of Education and Research (BMBF; Grant: 01JA160). This publication was also funded by the German Research Foundation (DFG) and the University of Bayreuth in the APC funding program 'Open Access Publishing'.

Acknowledgments: Special thanks to the teachers and students involved in this study for their cooperation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in

the decision to publish the results. This article reflects only the authors' views; the European Union as well as the BMBF and the DFG are not liable for any use that might be made of information contained herein.

References

1. Graw, J. *Genetik [Genetics]*, 6th Ed.; Springer Spektrum: Berlin, 2015, ISBN 9783662448168.
2. Gilbert, J. K., Boulter, C., Rutherford, M. Models in explanations, Part 1: Horses for courses? *Int. J. Sci. Educ.* **1998**, *20*, 83–97, doi:10.1080/0950069980200106.
3. Matynia, A., Kushner, S. A., Silva, A. J. Genetic approaches to molecular and cellular cognition: a focus on LTP and learning and memory. *Ann. Rev. Genet.* **2002**, *36*, 687–720, doi:10.1146/annurev.genet.36.062802.091007.
4. Plomin, R., Walker, S. O. Genetics and educational psychology. *Br. J. Educ. Psychol.* **2003**, *73*, 3–14, doi:10.1348/000709903762869888.
5. Watson, J. D., Crick, F. H. C. Molecular structure of nucleic acids. A structure for deoxyribose nucleic acid. Nature **1953**, 171, 737–738.
6. Usher, S. *Letters of note*. *Correspondence deserving of a wider audience;* Canongate: Edinburgh, 2013, ISBN 9781782112235.
7. Klug, A. Rosalind Franklin and the discovery of the structure of DNA. *Nature* **1968**, *219*, 808–810.
8. Elkin, L.O. Rosalind Franklin and the double helix. *Phys. Today* **2003**, *56*, 42–48, doi:10.1063/1.1570771.
9. Longden, B. Genetics—are there inherent learning difficulties? *J. Biol. Educ.* **1982**, *16*, 135–140, doi:10.1080/00219266.1982.9654439.
10. Kindfield, A.C.H. Confusing chromosome number and structure: a common student error. *J. Biol. Educ.* **1991**, *25*, 193–200, doi:10.1080/00219266.1991.9655206.
11. Euler, M. The role of experiments in the teaching and learning of physics; pp 175–221.
12. Scharfenberg, F.-J., Bogner, F. X., Klautke, S. Learning in a gene technology laboratory with educational focus: Results of a teaching unit with authentic experiments. *Biochem. Mol. Biol. Edu.* **2007**, 35, 28–39, doi:10.1002/bmb.1.
13. Franke, G., Bogner, F. X. Cognitive influences of students' alternative conceptions within a hands-on gene technology module. *J. Educ. Res.* **2011**, 104, 158–170.
14. Scharfenberg, F.-J., Bogner, F. X. Teaching Gene Technology in an Outreach Lab: Students' Assigned Cognitive load clusters and the clusters' relationships to learner characteristics, laboratory variables, and cognitive achievement. *Res. Sci. Educ.* **2013**, 43, 141–161.
15. Langheinrich, J., Bogner, F. X. Computer-related self-concept: The impact on cognitive achievement. *Stud. Educ. Eval.* **2016**, 50, 46–52.
16. Scharfenberg, F.-J., Bogner, F. X. A new two-step approach for hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene technology lab. *Res. Sci. Educ.* **2011**, 41, 505–523.
17. Langheinrich, J., Bogner, F. X. Student conceptions about the DNA structure within a hierarchical organizational level: Improvement by experiment- and computer-based outreach learning. *Biochem. Mol. Biol. Edu.* **2015**, 43, 393–402, doi:10.1002/bmb.20888.
18. Goldschmidt, M., Scharfenberg, F.-J., Bogner, F. X. Instructional efficiency of different discussion approaches in an outreach laboratory: Teacher-guided versus student-centered. *J. Educ. Res.* **2016**, 109, 27–36, doi:10.1080/00220671.2014.917601.
19. Bielik, T., Yarden, A. Promoting the asking of research questions in a high-school biotechnology inquiry-oriented program. *IJ STEM Ed.* **2016**, *3*, 397, doi:10.1186/s40594-016-0048-x.
20. Ben-Nun, M. S., Yarden, A. Learning molecular genetics in teacher-led outreach laboratories. *J. Biol. Educ.* **2009**, *44*, 19–25, doi:10.1080/00219266.2009.9656187.
21. Meissner, B., Bogner, F. X. Enriching students' education using interactive workstations at a salt mine turned science center. *J. Chem. Educ.* **2011**, 88, 510–515, doi:10.1021/ed1006103.
22. Mierdel, J., Bogner, F. X. Simply inGEN(E)ious! How creative DNA-modeling can enrich classic hands-on experimentation. *submitted* **2019**.
23. Rotbain, Y., Marbach-Ad, G., Stavy, R. Effect of bead and illustrations models on high school students' achievement in molecular genetics. *J. Res. Sci. Teach.* **2006**, *43*, 500–529, doi:10.1002/tea.20144.

24. Stull, A. T., Gainer, M. J., Hegarty, M. Learning by enacting: The role of embodiment in chemistry education. *Learn. Instr.* **2018**, *55*, 80–92, doi:10.1016/j.learninstruc.2017.09.008.
25. Stull, A.T., Hegarty. Model manipulation and learning: Fostering representational competence with virtual and concrete models. *J. Educ. Psychol*. **2016**, *108(4)*, 509-527. doi:10.1037/edu0000077.
26. Ferk, V., Vrtacnik, M., Blejec, A., Gril, A. Students' understanding of molecular structure representations. *Int. J. Sci. Educ.* **2003**, *25*, 1227–1245, doi:10.1080/0950069022000038231.
27. Werner, S., Förtsch, C., Boone, W., von Kotzebue, L., Neuhaus, B. J. Investigating how german biology teachers use three-dimensional physical models in classroom instruction: A video study. *Res. Sci. Educ.* **2017**, *1*, 195, doi:10.1007/s11165-017-9624-4.
28. Svoboda, J., Passmore, C. The strategies of modeling in biology education. *Sci. & Educ.* **2013**, *22*, 119–142, doi:10.1007/s11191-011-9425-5.
29. Gilbert J.K., Justi R. *Learning Scientific Concepts from Modelling-Based Teaching*. In: j. k. Gilbert & R. Justi (Eds.), Modelling-based Teaching in Science Education. Models and Modeling in Science Education, Vol 9; Springer: Cham, 2016.
30. Odenbaugh, J. Idealized, inaccurate but successful: A pragmatic approach to evaluating models in theoretical ecology. *Biol. Philos*. **2005**, 20, 231-255, doi:10.1007/s10539-004-0478-6.
31. Justi, R., Gilbert, J. K. Science teachers' knowledge about and attitudes towards the use of models and modelling in learning science. *Int. J. Sci. Educ.* **2002a**, *24*, 1273–1292, doi:10.1080/09500690210163198.
32. Oh, P. S., Oh, S. J. What teachers of science need to know about models: An overview. *Int. J. Sci. Educ.* **2011**, *33*, 1109–1130, doi:10.1080/09500693.2010.502191.
33. Mierdel, J., Bogner, F. X. Investigations of modellers and model viewers in an out-of-school gene technology laboratory. *submitted* **2019**.
34. Mierdel, J., Bogner, F. X. Is creativity, hands-on modeling and cognitive learning gender-dependent? *Think. Skills Creat.* **2019**, 31, 91–102, doi:10.1016/j.tsc.2018.11.001.
35. Runco, M. A., Acar, S., Cayirdag, N. A closer look at the creativity gap and why students are less creative at school than outside of school. *Think. Skills Creat.* **2017**, *24*, 242–249, doi:10.1016/j.tsc.2017.04.003.
36. NGSS Lead States. *Next generation science standards: for states, by states;* The National Academies Press: Washington, DC, 2013.
37. Halloun, I.A. Mediated modeling in science education. *Sci. & Educ.* **2007**, *16*, 653–697, doi:10.1007/s11191-006-9004-3.
38. Treagust, D. F., Chittleborough, G. D., Mamiala, T. L. Students' understanding of the role of scientific models in learning science. *Int. J. Sci. Educ.* **2002**, *24*, 357–368, doi:10.1080/09500690110066485.
39. Grosslight, L., Unger, C., Jay, E., Smith, C. L. Understanding models and their use in science: Conceptions of middle and high school students and experts. *J. Res. Sci. Teach.* **1991**, *28*, 799–822, doi:10.1002/tea. 3660280907.
40. Justi, R., Gilbert, J. K. Teachers' views on the nature of models. *Int. J. Sci. Educ.* **2003**, *25*, 1369–1386, doi:10.1080/0950069032000070324.
41. Grünkorn, J., Upmeier zu Belzen, A., Krüger, D. Assessing students' understandings of biological models and their use in science to evaluate a theoretical framework. *Int. J. Sci. Educ.* **2014**, *36*, 1651–1684, doi:10.1080/ 09500693.2013.873155.
42. Gogolin S., Krüger, D. Students' understanding of the nature and purpose of models. *J. Res. Sci. Teach.* **2018**, *55*, 1313-1338, doi:10.1002/tea.21453.
43. Chittleborough, G. D., Treagust, D. F. Why models are advantageous to learning science. *Educ. quím.* **2009**, *20*, 12–17.
44. Krell, M., Upmeier zu Belzen, A., Krüger, D. Students' understanding of the purpose of models in different biological contexts. *Int. J. Biol. Educ.* **2012**, *2*, 1–34.
45. Passmore, C. M., Svoboda, J. Exploring opportunities for argumentation in modelling classrooms. Int. J. Sci. Educ. **2012**, *34(10)*, 1535-1554, doi: 10.1080/09500693.2011.577842.
46. Günther, S., Fleige, J., Upmeier zu Belzen, A., & Krüger, D. *Interventionsstudie mit angehenden Lehrkräften zur Förderung von Modellkompetenz im Unterrichtsfach Biologie [Intervention study with pre-service teachers*

for fostering model competence in biology education]. In C. Gräsel & K. Trempler (Eds.), Entwicklung von Professionalität pädagogischen Personals; Springer: Wiesbaden, 2017, 215–236.

47. Justi, R. S., Gilbert, J. K. Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *Int. J. Sci. Educ.* **2002b**, 24(4), 369–387, doi:10.1080/09500690110110142.
48. Krell, M., Walzer, C., Hergert, S., Krüger, D. Development and application of a category system to describe pre-service science teachers' activities in the process of scientific modelling. *Res. Sci. Educ*. **2017**, 1-27, doi:10.1007/s11165-017-9657-8.
49. Treagust, D. F., Chittleborough, G. D., Mamiala, T. L. Students' understanding of the descriptive and predictive nature of teaching models in organic chemistry. *Res. Sci. Educ.* **2004**, *34*, 1–20, doi:10.1023/B:RISE.0000020885.41497.ed.
50. Krell, M., Upmeier zu Belzen, A., Krüger, D. Students' levels of understanding models and modelling in biology: Global or aspect-dependent? *Res. Sci. Educ.* **2014**, *44*, 109–132.
51. Upmeier zu Belzen, A., Krüger, D. Modellkompetenz im Biologieunterricht [Model competence in biology education]. *ZfDN* **2010**, *16*, 41–57.
52. Wen-Yu Lee, S., Chang, H.-Y.; Wu, H.-K. Students' views of scientific models and modeling: Do representational characteristics of models and students' educational levels matter? *Res. Sci. Educ.* **2017**, *47*, 305–328, doi:10.1007/s11165-015-9502-x.
53. Ainsworth, S. DeFT: A conceptual framework for considering learning with multiple representations. *Learn. Instr.* **2006**, *16*, 183–198.
54. ISB (Staatsinstitut für Schulqualität und Bildungsforschung – *Bavarian Syllabus Gymnasium G8;* Kastner: Wolnzach, Germany, 2007.
55. World Health Organization. Declaration of Helsinki. *Bull. World Health Organ* **2001**, *79*, 373–374.
56. Mayring, P. *Qualitative Inhaltsanalyse: Grundlagen und Techniken (Beltz Pädagogik) Taschenbuch 2;* Beltz: Weinheim, Germany, 2015.
57. Cohen, J. Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. *Psychol. Bull.* **1968**, *70*, 213–220.
58. Landis, R. J., Koch, G. G. The measurement of observer agreement for categorical data. *Biometrics* **1977**, *33*.
59. Döring, N., & Bortz, J. *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften [Research methods and evaluation in social and human sciences]*, 5th Ed.; Springer-Verlag: Berlin, Heidelberg, Germany, 2016.
60. Kline, P. (2000): The handbook of psychological testing. 2nd Ed.; Routledge: London, 2000.
61. Hair, J., Black, W., Babin, B., Anderson, R., & Tatham, R. (2006). Multivariate Data Analysis, 6th Ed.; Pearson Educational: New Jersey, 2006.
62. Field, A.P. *Discovering statistics using IBM SPSS statistics (and sex and drugs and rock' n' roll)*, 4th Ed.; SAGE: London, UK, 2013.
63. Fisher, R.A. On the interpretation of chi square from contingency tables, and the calculation of P. *J. Royal Stat. Soc.* **1922**, *85*, 87–94.
64. Pearson, K. On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can be reasonably supposed to have arisen from random sampling. *Philos. Mag.* **1900**, *50*, 157–175.
65. Kaiser, H.F. A second generation little jiffy. *Psychometrika* **1970**, *35*, 401–415.
66. Kaiser, H.F. Consequently perhaps. *Measurement* **1960**, *XX*, 141–151.
67. Bühner, M., Ziegler, M. *Statistik für Psychologen und Sozialwissenschaftler [Statistics for psychologists and social scientists]*, 3rd Ed.; Pearson Studium: München, 2012, ISBN 9783827372741.
68. Field, A.P. *Discovering statistics using SPSS (and sex and drugs and rock' n' roll)*, 3rd Ed.; SAGE: London, UK, 2009.
69. KMK. *Beschlüsse der Kultusministerkonferenz - Bildungsstandards im Fach Biologie für den Mittleren Bildungsabschluss [Resolution of the Standing Conference of the Ministers of Education and Cultural Affairs of the Länder in the Federal Republic of Germany - Standards of biology education for secondary school];* Luchterhand: Munich, Germany, 2005.

70. Louca, L. T., Zacharia, Z. C. Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. *Educ. Rev.* **2012**, *64*, 471–492, doi:10.1080/00131911.2011.628748.
71. Gobert, J. D., Pallant, A. Fostering students' epistemologies of models via authentic model-based tasks. *J. Sci. Educ. Technol.* **2004**, *13*, 7–22.
72. Dori, Y. J., Barak, M. Virtual and physical molecular modeling: Fostering model perception and spatial understanding. *Educ. Technol. Soc.* **2001**, *4*, 61–74.
73. Mahr, B. Information science and the logic of models. *Software & Systems Modeling*. **2009**, *8*, 365–383.
74. Gilbert, J.K. Models and Modelling: Routes to More Authentic Science Education. *Int. J. Sci. Math. Educ.* **2004**, *2*, 115–130, doi:10.1007/s10763-004-3186-4.

ANHANG

Fragebögen

A Schülerfragebogen

Exemplarisch wird der Vortest-Fragebogen gezeigt, der die Wissensitems, die Items zum Modellverständnis (Teilskalen des SUMS; Treagust et al. 2002) und zur Kreativität (Conradty & Bogner 2018) sowie einige allgemeine Fragen zur Modellerfahrung im Unterricht umfasst. Korrekte Antworten zu den Wissensfragen werden *kursiv* abgedruckt, Items mit der Kennzeichnung ‚L' überprüfen das Wissen zu den Laboraktivitäten und ‚M' kennzeichnet Items zu den Modellaktivitäten. Im Nach- und Behaltenstest wurden die Itemreihenfolge bei den Wissensfragen einschließlich der Antwortoptionen sowie die Itemreihenfolge der Modellverständnisskala zufällig getauscht. Die Kreativitätsskala wurde nur im Vortest gefragt.

B Fragebogen zur kognitiven Belastung

Der Fragebogen zur kognitiven Belastung wurde von den Schülern im Verlauf des Unterrichtsmoduls ausgefüllt, wobei die Schüler durch das Lehrpersonal regelmäßig nach den einzelnen Unterrichtsabschnitten dazu aufgefordert waren ihre geistige Anstrengung zu notieren. Der Mittelpunkt der Skala (5) steht hierbei für die durchschnittliche Schwierigkeit einer Biologiestunde in der Schule.

C Fragebogen zum DNA-Modell

Nachdem die Schüler die Verständnisfragen zur DNA-Struktur an ihren selbst gebauten Modellen bzw. an den Schulmodellen (mündlich) in Partnerarbeit überprüft haben, erstellten sie in den Tandems eine beschriftete Skizze des Modells und beantworteten eine offene Frage zur Erhebung des Modellverständnisses über ‚Alternative Modelle'.

A Schülerfragebogen

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Fragebogen zum Demonstrationslabor Bio-/ Gentechnik der Universität Bayreuth im Kontext „Kreatives Modellieren zur DNA-Struktur"

Liebe Schülerin, lieber Schüler,

dieser Fragebogen ist Teil einer wissenschaftlichen Untersuchung und **streng vertraulich**.

Er wird **nicht von deiner Lehrkraft eingesehen oder benotet**.

Bitte bearbeite **alle** Fragen alleine, sorgfältig und wahrheitsgemäß.

Bitte fülle den Fragebogen mit einem **dunklen Stift** aus (keine hellen Stifte, Neonfarben oder Bleistifte verwenden).

Wenn du fertig bist, **kontrolliere** bitte, ob du alle Seiten ausgefüllt hast.

Vielen Dank, dass du an dieser Befragung teilnimmst!

Datum								
					2	**0**		
	TT		**MM**		**JJJJ**			

Persönlicher Code:

Durch diesen Code können wir nicht mehr nachvollziehen wer diesen Fragebogen ausgefüllt hat, jedoch die Fragebögen untereinander zuordnen.

Kürze dein Geschlecht mit **M** (männlich) bzw. **W** (weiblich) ab.
Trage den Monat deines Geburtstages ein (z.B. **08** für August, **12** für Dezember).
Trage das Jahr deiner Geburt ein (z.B. **99** für 1999, **00** für 2000).
Trage die zwei ersten Buchstaben des Vornamens deiner Mutter ein (z.B. **CL** für Claudia).
Trage die Hausnummer ein, in der du wohnst (z.B. **003** für Hausnummer 3).

Geschlecht	**Geburtsmonat**		**Geburtsjahr**		**Mutter**		**Hausnummer**		

Beispiel: Maximilian ist männlich, geboren im September 2001, seine Mutter heißt Andrea und er wohnt in Hausnummer 61. ****Sein Code lautet:* ***M0901AN061*******

Diese Studie wurde vom Bayerischen Staatsministerium für Unterricht und Kultus genehmigt X.7-BO5106/149/10.

A) Beantworte die folgenden Fragen zu deinem Wissen.

Es gibt immer nur 1 richtige Antwort, deshalb setze bitte nur 1 Kreuz pro Frage.

Wenn du die Antwort nicht weißt, kreuze die Frage nicht an!

L1	**Ein positiv geladenes Teilchen wandert im elektrischen Feld …**
☐	zwischen beiden Polen hin und her.
☐	zum positiven Pol.
☐	*zum negativen Pol.*
☐	überhaupt nicht.

M2	**Welcher der folgenden Bestandteile ist nicht in der DNA enthalten?**
☐	Adenin
☐	*Ribose*
☐	Guanin
☐	Desoxyribose

L3	**Was stimmt nicht? Die Wanderungsgeschwindigkeit eines Moleküls durch das Elektrophoresegel ist abhängig von …**
☐	der angelegten Spannung.
☐	*der Dichte der Probe.*
☐	der Dichte des Elektrophoresegels.
☐	der Größe der Moleküle.

M4	**1962 erhielten James Watson und Francis Crick den Nobelpreis für Medizin für die Entdeckung …**
☐	der DNA im Zellkern.
☐	der Bestandteile der DNA.
☐	der Gelelektrophorese.
☐	*der Doppelhelixstruktur der DNA.*

M5	**Was stimmt nicht? Die DNA des Menschen…**
☐	ist Träger der Erbinformation.
☐	ist ein langes Kettenmolekül.
☐	*ist aus Aminosäuren aufgebaut.*
☐	ist ein Makromolekül.

L6	**Mit Hilfe der Gelelektrophorese lassen sich Aussagen treffen über …**
☐	*die Molekülmasse.*
☐	die Anzahl der Bindungen eines Moleküls.
☐	die Bestandteile eines Moleküls.
☐	die Atome eines Moleküls.

M7	Welche Basenpaarung ist korrekt?
☐	*Adenin paart mit Guanin.*
☐	Thymin paart mit Cytosin.
☐	Guanin paart mit Cytosin.
☐	Cytosin paart mit Adenin.

L8	Um 20 µl einer Flüssigkeit zu einer Probe zu geben, verwendet man …
☐	eine Pasteur-Pipette.
☐	einen Messzylinder.
☐	*eine Mikropipette.*
☐	eine Messpipette.

L9	Mit Hilfe einer Zentrifuge …
☐	wird die Probe durchmischt.
☐	werden die Moleküle in Schwingung gebracht.
☐	können einzelne Moleküle isoliert werden.
☐	*werden feste Stoffe von Flüssigkeiten getrennt.*

M10	Spricht man vom „Rückgrat der DNA“, dann meint man damit …
☐	die ringförmige Struktur der DNA.
☐	die zum Schutz der DNA gebundenen Fettsäuren.
☐	die Paarung der DNA-Basen.
☐	*die Kette aus Phosphat abwechselnd mit Desoxyribose als Bestandteil der DNA.*

M11	Die DNA-Basen befinden sich …
☐	*im Inneren des DNA-Moleküls an den Zucker gebunden.*
☐	im Inneren des DNA-Moleküls an Phosphat gebunden.
☐	an der Außenseite des DNA-Moleküls an Phosphat gebunden.
☐	an der Außenseite des DNA-Moleküls an den Zucker gebunden.

M12	Die beiden DNA-Stränge sind …
☐	versetzt voneinander.
☐	identisch.
☐	unabhängig voneinander.
☐	*gegenläufig.*

L13	Die Auftrennung der DNA-Moleküle bei der Elektrophorese beruht auf dem DNA-Bestandteil…
☐	Thymin
☐	*Phosphat*
☐	Zucker
☐	Cytosin

L14	Was stimmt <u>nicht</u>? Die DNA ist in kaltem Alkohol …
☐	unlöslich.
☐	als fädige Struktur zu erkennen.
☐	ein weißer Feststoff.
☐	*löslich.*

M15	Die molekulare Struktur der DNA lässt sich am besten vergleichen mit …
☐	einer Pappröhre.
☐	*einer eingedrehten Strickleiter.*
☐	einer Bahnschiene.
☐	einem Bindfaden.

L16	Ein sogenannter „DNA-Längenstandard“ dient …
☐	*der Messung der Länge eines DNA-Fragments.*
☐	der Verlängerung der DNA-Bereiche.
☐	der Reparatur von DNA-Abschnitten.
☐	dem Anfärben von DNA-Strängen.

M17	Die Abkürzung DNA steht für …
☐	Desoxynukleinsäure.
☐	Oxyribonukleinsäure.
☐	*Desoxyribonukleinsäure.*
☐	Didesoxyribonukleinsäure

M18	Wie viele verschiedene DNA-Bausteine gibt es?
☐	2
☐	4
☐	*6*
☐	8

M19	**Ein DNA-Einzelstrang hat folgende Basenabfolge: AATGGG** *(Großbuchstabe = Anfangsbuchstabe der jeweiligen Base, z.B. „A“ für Adenin)* **Wie lautet die Basenabfolge des gegenüberliegenden, paarenden DNA-Einzelstrangs?**
☐	TTGCCC
☐	*TTACCC*
☐	TTGAAA
☐	GGACCC

M20	Der Zusammenhalt der beiden DNA-Stränge entsteht durch Ausbildung von …
☐	*Wasserstoffbrückenbindungen.*
☐	Atombindungen.
☐	Schwefelbrückenbindungen.
☐	Ionischen Wechselwirkungen.

L21	Die Gesamtlänge der menschlichen DNA pro Zelle beträgt etwa …
☐	200 m.
☐	*2 m.*
☐	20 m.
☐	2 cm.

M22	Die Erbinformation der DNA wird verschlüsselt durch die …
☐	*Abfolge der einzelnen Basen.*
☐	Bildung verschiedener Chromosomen.
☐	Verschmelzung von Ei- und Spermienzelle bei der Befruchtung.
☐	Windungen des DNA-Stranges.

M23	**Einen DNA-Abschnitt, der die Grundinformation für die Ausbildung eines bestimmten Merkmals trägt, nennt man …**
☐	Plasmid.
☐	Genom.
☐	Chromosom.
☐	*Gen.*

L24	**Die DNA ist Träger der Erbinformation bei …**
☐	*allen Organismen.*
☐	den Menschenaffen.
☐	allen Organismen außer Bakterien.
☐	den Wirbeltieren.

L25	**In welchem Zellorganell befindet sich die DNA?**
☐	im Ribosom
☐	*im Zellkern*
☐	im Zellplasma
☐	in der Vakuole

M26	**Bei der Analyse eines DNA-Abschnittes ergibt sich einen Anteil von Guanin mit 30 %. Der Anteil von Adenin ist somit …**
☐	nicht bestimmbar.
☐	ebenfalls 30%.
☐	70 %.
☐	*20 %.*

M27	**Das Verhältnis von Zucker zu Phosphat im DNA-Molekül beträgt …**
☐	2:1
☐	3:1
☐	*1:1*
☐	1:2

M28	**Die DNA besteht aus folgenden Atomsorten:**
☐	Wasserstoff, Schwefel, Phosphor, Kohlenstoff und Stickstoff
☐	Wasserstoff, Sauerstoff, Phosphor, Schwefel und Stickstoff
☐	*Wasserstoff, Sauerstoff, Phosphor, Kohlenstoff und Stickstoff*
☐	Wasserstoff, Sauerstoff, Schwefel, Kohlenstoff und Stickstoff

M29	**Die räumliche Struktur der DNA …**
☐	ist eine linksgängige Doppelhelix.
☐	*ist eine rechtsgängige Doppelhelix.*
☐	besitzt keine Drehrichtung.
☐	ist eine abwechselnd rechts- und linksgängige Doppelhelix.

L30	**Was stimmt <u>nicht</u>? Das Sichtbarmachen der DNA-Moleküle bei der Gelelektrophorese wird möglich durch …**
☐	*den blau eingefärbten Auftragspuffer.*
☐	einen Farbstoff, der an DNA-Moleküle bindet.
☐	einen Farbstoff, der im UV-Licht leuchtet.
☐	die Farbstoff-Zugabe in das Gel.

B) Bewerte die folgenden Aussagen zu Modellen, indem du im entsprechenden Kästchen <u>1 Kreuz</u> setzt.

	Folgender Aussage stimme ich …	**absolut nicht zu**	**nicht zu**	**weder Zu-stimmung noch Ablehnung**	**zu**	**stark zu**
1.	Ein Modell sollte eine exakte Kopie sein.	☐	☐	☐	☐	☐
2.	Ein Modell muss nah am Realobjekt sein.	☐	☐	☐	☐	☐
3.	Ein Modell muss nah am Realobjekt sein, sodass es niemand widerlegen kann.	☐	☐	☐	☐	☐
4.	Alles an einem Modell sollte erkennen lassen, was es abbildet.	☐	☐	☐	☐	☐
5.	Modelle werden benutzt, um etwas physisch oder visuell zu repräsentieren.	☐	☐	☐	☐	☐
6.	Modelle helfen dabei, sich wissenschaftliche Geschehnisse gedanklich besser vorzustellen.	☐	☐	☐	☐	☐
7.	Modelle werden zur Erklärung wissenschaftliche Phänomene benutzt.	☐	☐	☐	☐	☐
8.	Modelle werden verwendet, um eine Idee aufzuzeigen.	☐	☐	☐	☐	☐
9.	Modelle werden zur Formulierung von Ideen und Theorien über wissenschaftliche Ereignisse benutzt.	☐	☐	☐	☐	☐
10.	Modelle werden benutzt, um ihre Funktion in wissenschaftlichen Untersuchungen aufzuzeigen.	☐	☐	☐	☐	☐
11.	Modelle werden benutzt, um Prognosen über ein wissenschaftliches Ereignis anzufertigen und zu testen.	☐	☐	☐	☐	☐
12.	Ein Modell kann sich ändern, wenn neue Theorien oder Beweise etwas anderes besagen.	☐	☐	☐	☐	☐
13.	Ein Modell kann sich ändern, wenn neue Erkenntnisse vorliegen.	☐	☐	☐	☐	☐
14.	Ein Modell kann sich ändern, wenn neue Änderungen der Daten oder Ansichten auftreten.	☐	☐	☐	☐	☐

C) Bewerte die folgenden Aussagen, indem du im entsprechenden Kästchen 1 Kreuz setzt.

	Im vergangenen Schuljahr …	**niemals**	**manchmal**	**oft**	**sehr oft**
1.	… habe ich bei einer neuen Aufgabe versucht, so viele Ideen wie möglich zu entwickeln.	☐	☐	☐	☐
2.	… habe ich andere um Hilfe gebeten, um mögliche Lösungen für ein Problem zu entwickeln.	☐	☐	☐	☐
3.	… habe ich ein Problem oder eine Aufgabe aus einem anderen Blickwinkel betrachtet, um eine Lösung zu finden.	☐	☐	☐	☐
4.	… habe ich verschiedene Ideen zusammengefügt, um eine neue Idee zu entwickeln.	☐	☐	☐	☐
5.	… habe ich eine alte / bewährte Lösung genutzt, um damit einen neuen Weg einzuschlagen.	☐	☐	☐	☐
6.	… habe ich eine Verbindung hergestellt zwischen einem aktuellen Problem (Aufgabe) und einer ähnlichen Situation, die ich schon meisterte.	☐	☐	☐	☐
7.	… habe ich mir eine mögliche Lösung vorgestellt, um ihre Brauchbarkeit in Gedanken zu erforschen.	☐	☐	☐	☐
8.	… bin ich komplett in meine Arbeit an einem Problem (Aufgabe) versunken.	☐	☐	☐	☐
9.	… habe ich komplett die Zeit aus den Augen verloren, wenn ich intensiv an etwas gearbeitet habe.	☐	☐	☐	☐
10.	… habe ich gefühlt, dass die Arbeit automatisch und mühelos war, während ich eine angenehme Aufgabe erledigte.	☐	☐	☐	☐

D) Beantworte zum Schluss noch einige allgemeine Fragen!

1. Welchen Schulzweig besuchst du?

NTG	SG	WSG	MuG
☐	☐	☐	☐

2. Welche Note hast du aktuell im Fach Biologie? Meine Biologie-Note: .....

		niemals	**selten**	**gelegent-lich**	**oft**	**immer**
3. Wie häufig hast du bisher in folgenden Fächern Experimente **selbst** durchgeführt?	Biologie	☐	☐	☐	☐	☐
	Chemie	☐	☐	☐	☐	☐
	Physik	☐	☐	☐	☐	☐
4. Wie häufig wurden bisher in folgenden Fächern Modelle im Unterricht von der Lehrkraft eingesetzt?	Biologie	☐	☐	☐	☐	☐
	Chemie	☐	☐	☐	☐	☐
	Physik	☐	☐	☐	☐	☐
5. Wie häufig hast du bisher in folgenden Fächern **selbst** Modelle hergestellt?	Biologie	☐	☐	☐	☐	☐
	Chemie	☐	☐	☐	☐	☐
	Physik	☐	☐	☐	☐	☐

B Cognitive Load Fragebogen

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Datum ☐☐ ☐☐ 20☐☐
TT MM JJJJ

Persönlicher Code:
Durch diesen Code können wir nicht mehr nachvollziehen wer diesen Fragebogen ausgefüllt hat, jedoch die Fragebögen untereinander zuordnen.

☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Geschlecht	Geburtsmonat		Geburtsjahr		Mutter		Hausnummer		

Beispiel: Maximilian ist männlich, geboren im September 2001, seine Mutter heißt Andrea und er wohnt in Hausnummer 61. ***Sein Code lautet: ***M0901AN061*****

Stufe 5 ≙ genau so schwer wie „normaler" Biologie-Unterricht

Meine geistige Anstrengung war während …	**sehr, sehr gering** → → → → → → → → **sehr, sehr hoch**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1. … der experimentellen Einführungsphase	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. … der ersten theoretischen Erarbeitungsphase	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. … des DNA-Isolations-Experiments	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. … der zweiten theoretischen Erarbeitungsphase	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. … des Gelelektrophorese-Experiments	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. … der dritten theoretischen Erarbeitungsphase	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. … der DNA-Modell-Phase	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. … der Auswertungsphase	☐	☐	☐	☐	☐	☐	☐	☐	☐

Vielen Dank für deine Mitarbeit!

C Fragebogen zum DNA-Modell

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										Gruppenmitglied 1
										Gruppenmitglied 2

Geschlecht | Geburtsmonat | Geburtsjahr | Mutter | Hausnummer

Beispiel: Maximilian ist männlich, geboren im September 2001, seine Mutter heißt Andrea und er wohnt in Hausnummer 61. ***Sein Code lautet: ***M0901AN061******

1. Beschriftete **Skizze** des Modells:

2. Erklärt, weshalb es zu einem biologischen Original (wie der DNA) verschiedene Modelle geben kann!

Danksagung

Mein erster Dank gilt meinem Doktorvater Herrn Prof. Dr. Franz X. Bogner, der es mir ermöglicht hat mein Promotionsvorhaben am Lehrstuhl der Didaktik der Biologie durchführen zu können. Vielen Dank für das Vertrauen, die Anleitung zum selbstständigen Arbeiten und das konstruktive Feedback beim Verfassen wissenschaftlicher Literatur. Besonders bedanken möchte ich mich auch für die Möglichkeit zum Mitwirken in europäischen Projekten, die Teilnahme an nationalen und internationalen Konferenzen und das Anvertrauen von Lehrveranstaltungen.

Des Weiteren möchte ich mich herzlich bei Herrn Dr. Franz-Josef Scharfenberg bedanken, für die gute Kooperation im Demonstrationslabor Bio-/Gentechnik, die Zusammenarbeit und den Austausch innerhalb der universitären Lehre und die kompetente Unterstützung bei vielen methodischen und statistischen Fragen. Auch Frau Sabine Hübner danke ich herzlich für ihre Unterstützung und Ratschläge in allen Lebenslagen. Mit ihrer Hilfe ließ sich für fast jedes kleinere oder größere Problem eine Lösung finden.

Meinen lieben Kolleginnen möchte ich für die angenehme Arbeitsatmosphäre, den konstruktiven Austausch und die erheiternden Gespräche danken. Die geselligen Stunden zur Kaffeezeit und beim Stammtisch werde ich schon bald vermissen! Besonderer Dank gilt Jennifer Schneiderhan-Opel, Mona Schönfelder-Beer und Sarah Schmid, die ich neben der Arbeit als gute Freundinnen kennenlernen durfte. Michaela Marth danke ich für das Korrekturlesen dieser Arbeit.

Danke sage ich Frau Petra Feuerstein für die Bewältigung der bürokratischen und organisatorischen Hürden.

Ich möchte mich bei allen Schulen, Lehrkräften, Schülern und Schülerinnen bedanken, die mit Begeisterung und Engagement an der Intervention teilgenommen und somit diese Studie erst möglich gemacht haben.

Ein herzlicher Dank geht an Frau Tamara Roth, die mir als zuverlässige Studierende im Schülerlabor zur Seite stand und tatkräftig bei der Durchführung sowie der Vor- und Nachbereitung der Intervention geholfen hat.

Zu guter Letzt danke ich herzlich meinem Ehemann Konstantin Mierdel, meiner Familie und meinen engsten Freunden für die emotionale Unterstützung während der Promotionszeit. Nur durch eure immerwährende Unterstützung hatte ich den Mut, die Motivation und das Vertrauen, die für das Gelingen dieser Arbeit nötig waren.

(Eidesstattliche) Versicherungen und Erklärungen

(§ 8 Satz 2 Nr. 3 PromO Fakultät)

Hiermit versichere ich eidesstattlich, dass ich die Arbeit selbstständig verfasst und keine anderen als die von mir angegebenen Quellen und Hilfsmittel benutzt habe (vgl. Art. 64 Abs. 1 Satz 6 BayHSchG).

(§ 8 Satz 2 Nr. 3 PromO Fakultät)

Hiermit erkläre ich, dass ich die Dissertation nicht bereits zur Erlangung eines akademischen Grades eingereicht habe und dass ich nicht bereits diese oder eine gleichartige Doktorprüfung endgültig nicht bestanden habe.

(§ 8 Satz 2 Nr. 4 PromO Fakultät)

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