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Evolving germs

Antibiotic resistance and natural selection in
education and public communication

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Abstract

Bacterial resistance to antibiotics threatens modern healthcare on a global scale. Several actors in society, including the general public, must become more involved if this development is to be countered. The conveyance of relevant information provided through education and media reports is therefore of high concern. Antibiotic resistance evolves through the mechanisms of natural selection; in this way, a sound understanding of these mechanisms underlies explanations of causes and the development of effective risk-reduction measures. In addition to natural selection functioning as an explanatory framework to antibiotic resistance, bacterial resistance as a context seems to possess a number of qualities that make it suitable for teaching natural selection – a subject that has been proven notoriously hard to teach and learn. A recently suggested approach for learning natural selection involves so-called threshold concepts, which encompass abstract and integrative ideas. The threshold concepts associated with natural selection include, among others, the notions of randomness as well as vast spatial and temporal scales. Illustrating complex relationships between concepts on different levels of organization is one, of several, areas where visualizations are efficient. Given the often-imperceptible nature of threshold concepts as well as the fact that natural selection processes occur on different organizational levels, visual accounts of natural selection have many potential benefits for learning.

Against this background, the present dissertation explores information conveyed to the public regarding antibiotic resistance and natural selection, as well as investigates how these topics are presented together, by scrutinizing media including news reports, websites, educational textbooks and online videos. The principal method employed in the media studies was content analysis, which was complemented with various other analytical procedures. Moreover, a classroom study was performed, in which novice pupils worked with a series of animations explaining the evolution of antibiotic resistance. Data from individual written assignments, group questions and video-recorded discussions were collected and analyzed to empirically explore the potential of antibiotic resistance as a context for learning about evolution through natural selection.

Among the findings are that certain information, that is crucial for the public to know, about antibiotic resistance was conveyed to a low extent through wide-reaching news reporting. Moreover, explanations based on natural selection were rarely included in accounts of antibiotic resistance in any of the examined media. Thus, it is highly likely that a large proportion of the population is never exposed to explanations for resistance development

during education or through newspapers. Furthermore, the few examples that were encountered in newspapers or textbooks were hardly ever visualized, but presented only in textual form. With regard to videos purporting to explain natural selection, it was found that a majority lacked accounts of central key concepts. Additionally, explanations of how variation originates on the DNA-level were especially scarce. These and other findings coming from the content analyses are discussed through the lens of scientific literacy and could be used to inform and strengthen teaching and scientific curricula with regards to both antibiotic resistance and evolution. Furthermore, several factors of interest for using antibiotic resistance in the teaching of evolution were identified from the classroom study. These involve, among others, how learners' perception of threshold concepts such as randomness and levels of organization in space and time are affected by the bacterial context.

Swedish summary

Antibiotikaresistens är ett stort hot mot samtidens och framtidens hälsa och sjukvård. På grund av resistensutvecklingen riskerar många vanliga infektionssjukdomar att bli omöjliga att behandla i framtiden. Dessutom är stora delar av den moderna sjukvården, såsom cellgiftsbehandlingar, transplantationer eller vård av tidigt födda barn, beroende av fungerade antibiotika för att kunna utföras säkert. För att vända den negativa utvecklingen krävs åtgärder på många samhällsnivåer. Även allmänheten spelar en viktig roll, framförallt när det handlar om förväntningar i samband med läkarbesök och huruvida man fullföljer behandlingar som föreskrivet. Det är därför angeläget att information som når allmänheten om antibiotikaresistens genom allmänna kanaler såsom nyhetsförmedling eller utbildning är korrekt och relevant.

Bakteriers motståndskraft gentemot antibiotika utvecklas genom naturligt urval, en av de starkaste evolutionära drivkrafterna. En förståelse för hur naturligt urval inverkar på bakteriers resistensutveckling utgör därmed en möjlighet att härleda både orsaker till spridning och nyttan med föreslagna åtgärder. Antibiotikaresistens lyfts därför ibland fram för att motivera vikten av evolutionsundervisning i skolan. Förutom att naturligt urval kan förklara resistensutveckling hos bakterier tyder mycket på att det även finns förtjänster med det omvända förhållandet – att bakterier och antibiotikaresistens är ett användbart exempel för att lära sig om naturligt urval.

Evolution genom naturligt urval är i sig ett ämne som har visat sig vara svårt att lära sig och som är förknippat med många missuppfattningar. Forskningen kring lärande av naturligt urval handlar vanligtvis om viktiga nyckelbegrepp som tillsammans förklarar naturligt urval. Ett relativt nytt angreppssätt är att även fokusera på så kallade tröskelbegrepp. För naturligt urval har till exempel slump, sannolikhet och tid- och rumsskalor föreslagits vara viktiga tröskelbegrepp. Dessa har en integrerande funktion och är till sin natur mer abstrakta jämfört med de mer innehållsbundna nyckelbegreppen.

Visualisering av vetenskap i lärande- och kommunikationssyfte har en lång historia av både praktik och teori och kan vara ett kraftfullt verktyg för att förstå både abstrakta och konkreta resonemang. Med hjälp av visualisering kan komplexa samband, som till exempel hur begrepp som befinner sig på olika skalor förhåller sig till varandra, göras tydligare. Då evolution spänner över extrema skalnivåer och innefattar flera olika sorters begrepp som behöver sättas i relation till varandra finns många tänkbara fördelar med visualisering av evolution i lärandesyfte.

Mot denna bakgrund undersökte tre av studierna i denna avhandling informationen som når ut till både elever och medborgare med avseende på både antibiotikaresistens och naturligt urval samt relationen mellan dessa.

Källor som användes i det här hänseendet innefattade nyhetsartiklar, webbsidor, biologiläromedel anpassade för årskurs 7-9 och förklarande videor som kan ses direkt i webbläsare på internet. I den fjärde studien utforskades möjligheterna att använda animationer som beskriver antibiotikaresistens i undervisning om naturligt urval med en grupp åttondeklassare. Avhandlingen bygger på studier som presenterats i fyra artiklar. Innehållet i de ingående artiklarna presenteras kortfattat nedan.

I *artikel I* studerades specifikt hur antibiotikaresistens förmedlas genom svenska dagstidningar under en treårsperiod. Resultaten, som tolkas utifrån teorier inom riskkommunikation, visade bland annat att informationen snarare riktar sig mot samhällseliga aktörer än till individuella läsare/patienter. Vidare finns klart utrymme för en ökad rapportering av fakta och råd som skulle hjälpa medborgare att utveckla en mer nyanserad förståelse av antibiotikaresistens. En föreslagen strategi för att åstadkomma detta vore att inkludera evolutionära förklaringar till hur antibiotikaresistens uppstår.

Därav följer studien i *artikel II* som undersökte till vilken grad evolutionära förklaringar användes i samband med beskrivningar av antibiotikaresistens. Denna studie tittade både på information som förmedlas genom dagstidningar och på sidor som kommer upp vid sökningar på internet. Men studien undersökte också i vilken grad detta samband tas upp i biologiläromedel för årskurs 7-9. Denna biologikurs innefattar enligt läroplanen både evolution och antibiotikaresistens och det är också den sista obligatoriska biologikursen i svenska skolan. Resultaten visade entydigt att sambandet mellan naturligt urval och antibiotikaresistens sällan lyfts fram och att det därigenom är troligt att en stor del av befolkningen inte får detta samband berättat för sig genom någon av dessa kanaler. Vid de tillfällen som sambandet togs upp så var det i regel förmedlat i textform utan stöd av bilder.

Artikel III tittade specifikt på naturligt urval och hur detta presenteras genom videor som kan ses direkt i webbläsare på internet. Denna studie tog avstamp i fyra huvudsakliga innehållskategorier: nyckelbegrepp, tröskelbegrepp, kända missuppfattningar samt vilka organismtyper som används som exempel. Resultaten visade på att innehållsliga begrepp togs upp till väldigt olika grad samt att endast en liten andel av de analyserade videorna tog upp tre viktiga grundprinciper. En generell tendens var att förklaringar ofta utelämnade beskrivningar av hur variation uppstår slumpmässigt på DNA-nivå.

Artikel IV beskriver en studie utförd med 32 åttondeklassare som inte studerat evolution tidigare. Möjliga fördelar med att introducera antibiotikaresistens som ett första exempel på naturligt urval undersöktes genom att

eleverna gruppvis fick interagera med en serie animationer som beskrev resistensutveckling. Data samlades in både individuellt (genom skriftliga uppgifter före och efter animationerna) och gruppvis (genom uppgifter som de fick besvara skriftligt tillsammans under animationerna). Dessutom videofilmades grupperna och deras diskussioner transkriberades och analyserades. Resultaten visade att de flesta elever, efter den förhållandevis korta interventionen, lyckades göra evolutionära förutsägelser om utveckling av antibiotikaresistens. Vidare tyder resultaten på att bakteriers korta generationstid och möjligheten att rymma stora populationer på liten yta möjliggör elevers acceptans för förekomsten av ovanliga punktmutationer och dessas spridning inom populationen.

Sammanfattningsvis ger avhandlingen svar på frågor om vilka aspekter som förmedlas och vilka som utelämnas med avseende på både antibiotikaresistens och naturligt urval genom ett flertal olika kanaler. Vetskap om vilka aspekter som är underrepresenterade i kommunikation som når ut brett till allmänheten kan användas vid utveckling av både undervisning och läroplansarbete. Tydligare förklaringar av hur naturligt urval ligger till grund för antibiotikaresistens kan både hjälpa allmänheten att förstå föreslagna åtgärder mot antibiotikaresistens och underlätta delar av evolutionsundervisningen. Visuella hjälpmedel har stor outnyttjad potential för dessa ändamål, särskilt när det gäller att representera viktiga tröskelbegrepp.

Preface

A question that continuously gives me a stimulating (and nerve-wrecking) headache is why we should actually know any science. For real. Of course, this question can be addressed in many ways and from many perspectives, but is nevertheless a crucial part of the foundation for any research carried out within the fields of science education and science communication. A truthful response could be to admit that scientific knowledge doesn't actually need to be in every person's possession. Without a doubt, it would be perfectly possible to live a delightful life without any special insights in, for example, physics or biology. When travelling through narrow academic corridors it is easy to forget that there are other values and insights that *people* actually care more about. What will my pension look like? Who will I share my life with? What art makes me laugh or cry? The list goes on and on.

So why should one care at all? And why should I, as well as other researchers, receive a salary to ponder questions surrounding this topic? During my academic career, I have spent several hours considering, and trying to warrant, why insights into scientific issues should be of real importance to the broader public. In the end, I find myself reaching two lines of argument that have become important foundations in the justification of my own work. The first is as a democratic principle. The majority of all research that is undertaken in Sweden is financed by public funds. Thereby, it is the taxpayers that pay for the research, whether they like it or not. Science is by nature inaccessible. Primary scientific literature is often hidden behind expensive walls and requires exorbitant fees to access if you are not linked to a university library. Furthermore, understanding and valuing what you read is a task that requires extensive conceptual understanding of numerous words, mechanisms and conventions. However, if we are to utilize a system in which our shared resources finance the undertaken research, then there should be a possibility for the funder (the public) to be able to follow what is happening and, in a next step, perhaps have something to say about it. Note that democratic arguments are highly relevant also beyond funding issues, as scientific discoveries (regardless of where the money comes from) tend to impact the societies in which we all need to function as responsible citizens. For a public engagement with science to be possible, a well-functioning educational system in which adequate grounds are laid - as well as relevant and accurate reporting from media and other informal learning resources - is crucial.

The second argument is about quality of life. If we agree that the most important human needs include food on the table, the possibility to be warm and dry and to have access to love and friendship, then scientific knowledge

naturally becomes a lesser concern. However, it is still important. Life simply becomes more intriguing with knowledge about how nature and people are constituted. It may concern anything from how a small seed grows into a flower or a tree to how the latter constitutes the basis for a table or bed. It may concern why plants, animals and bacteria look like and act like they do. It may concern using previously unknown theoretical perspectives to contemplate human behavior, for example, why wars are fought or why people are drawn to religion and what they are willing to sacrifice for it. In other words, science has the power to make life, as well as our thoughts, more complex and beautiful.

The work underlying this doctoral thesis was motivated by this background. Nevertheless, this dissertation also follows the rules applying to all knowledge production: it is narrow, inaccessible to the majority and directly affects only a few people. Still, it is a small cog in a larger wheel that I am convinced has the capacity to drive development further towards increased scientific literacy and public understanding of science.

And at least my world has become more complex and beautiful during these years. But this would naturally not have been possible without the help and collaboration of a large number of people. I would therefore like to use the following section to humbly express my gratitude to all of you who have crossed my life during these years.

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First, I want to sincerely thank *Lena Tibell* (my main supervisor) and *Gunnar Höst* (my co-supervisor) for taking on the task of guiding my development through these years. You complement each other beautifully in your competencies and you have formed a supervisory team that no superlative could adequately describe. Your sharp minds and critical eyes have improved everything that I have written. Next, I am very thankful to *Carl-Johan Rundgren* who has read and commented on my complete works on two different occasions during my studies. Your comments have been invaluable to the progression of this dissertation. I have worked closely within the VLC-group where former and present members all have contributed with comments, reflections and friendship during the years. Thank you *Konrad, Caroline, Mari, Daniel, Johanna, Jennifer, Helena, Andreas, Jörgen, Henry* and *Alma*. A special thanks is due to *Andreas* who has worked closely with me in several research and development projects. Three additional persons that have enriched our group with their intellect and personalities are *Nalle Jonsson, Jan Anward* and *Marie Rådbo*. I am not a native English-speaker and am for this reason indebted to *John Blackwell*

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Stockholm
September 2017

List of papers

- I. Bohlin, G., & Höst, G. E. (2014). Is it my responsibility or theirs? Risk communication about antibiotic resistance in the Swedish daily press. *Journal of Science Communication*, 13(3), A02.
- II. Bohlin, G., & Höst, G. E. (2015). Evolutionary explanations for antibiotic resistance in daily press, online websites and biology textbooks in Sweden. *International Journal of Science Education, Part B: Communication and Public Engagement*, 5(4), 319-338.
- III. Bohlin, G., Göransson, A., Höst, G. E., & Tibell, L. (2017). A conceptual characterization of online videos explaining natural selection. *Re-submitted to Science & Education*.
- IV. Bohlin, G., Göransson, A., Höst, G. E., & Tibell, L. (2017). Insights from introducing natural selection to novices using animations of antibiotic resistance. *Journal of Biological Education*. Advance online publication. DOI: 10.1080/00219266.2017.1368687

Other journal publications not included in this dissertation:

- V. Höst, G. E., & Bohlin, G. (2015). Engines of creationism? Intelligent design, machine metaphors and visual rhetoric. *Leonardo*, 48(1), 80-81.

The papers are referred to by their roman numerals throughout the dissertation. Published papers are distributed in the printed version of this dissertation with permission from the respective journal or publisher.

Author's contribution to the papers

The research presented in the included papers is the result of collaboration with other researchers. This section will attempt to unravel my personal contribution to the different papers in order to demonstrate the research that I have performed during my doctoral studies.

For papers I and II, I planned the studies as well as collected and coded all of the source material. I also performed the reliability calculations. Gunnar Höst coded the reliability samples and we interpreted the results together. I wrote two complete drafts of the papers that we then re-wrote together in a joint effort. The criteria catalogue in Paper III was deduced from previous literature through a selection process by a group of researchers comprising myself, Professor Lena Tibell, Professor Ute Harms, Professor Nalle Jonsson, Professor Jan Anward, Dr. Konrad Schönborn, Dr. Gunnar Höst and Daniel Orraryd. The videos that were used as the source material were collected in a database by the same group of researchers with the addition of Andreas Göransson, Dr. Jennifer Härting, Jörgen Stenlund and Anja Nordbruch. Andreas Göransson and I performed the coding of the videos independently and I performed the initial reliability calculations. I wrote the first drafts of Paper III, with Andreas Göransson, Gunnar Höst and Lena Tibell all contributing comments, reflections and written revisions. Andreas Göransson and Gunnar Höst produced the figures in this paper and Gunnar Höst performed the cluster analysis procedures. I initiated the study presented in Paper IV while the research design planning was a joint effort by all the authors. The animation used in the study was designed and produced by Andreas Göransson following a storyboard written by Andreas Göransson, Professor Lena Tibell and myself. The data collection was a joint effort by all the authors, and I later transcribed all the videos. I led the data analysis and writing of Paper IV with significant contributions by all co-authors, particularly Andreas Göransson, who wrote the parts concerning the animations.

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1. Introduction

This dissertation concerns perspectives from education and communication on evolution, particularly natural selection, and antibiotic resistance. The former is a scientific theory that provides general principles to explain the diversity of all life-forms on earth while the latter is a biological phenomenon that arises as a consequence of natural selection mechanisms. The studies underlying this dissertation explore how different aspects of antibiotic resistance and natural selection, as well as how they relate to each other, are conveyed through different channels and how these findings can be utilized for educational purposes. Among the conclusions are that neither textbooks nor the popular press provide adequate evolutionary explanations for antibiotic resistance, and that certain threshold concepts such as randomness are underrepresented in explanations of natural selection. Support is also found for using antibiotic resistance as a context for teaching natural selection in introductory classes. This chapter will detail how the dissertation is structured. The motivation for the research is also presented along with a brief discussion of how the dissertation is situated within a broader research context.

1.1 Structure of the dissertation

This is a compilation thesis consisting of four individual papers and a comprehensive summary. The introductory chapter, which also presents the purpose and positioning of the dissertation, is followed by a description of the theoretical framework in Chapter 2. Natural selection and antibiotic resistance are first presented individually, with the communicational benefits of explaining the two subjects together discussed in a separate section. This is followed by a section that focuses on visualizations as mediators of scientific knowledge. The theoretical background chapter concludes with a section on scientific literacy, a topic that is introduced to further elaborate on the significance of the presented research and results. The aims and research questions are presented in Chapter 3, while Chapter 4 describes the methodological choices that have been made during the course of the doctoral studies, including a discussion of validity and reliability. Chapter 5 summarizes the results from each paper and concludes by highlighting the most relevant results pertaining to each research question. Chapter 6 provides a discussion of the results in light of previously

published literature, including the perspective of scientific literacy. The discussion ends with potential implications and future research directions.

1.2 Purpose of the dissertation

Increasing antibiotic resistance is considered one of the greatest threats to human health. Not only are many illnesses at risk of being rendered untreatable, but there could be wider repercussions given that functional antibiotics are a prerequisite for most of today's advanced healthcare. Transplantations, chemotherapy and prenatal health care all rely on functional antibiotics, and will therefore be gravely affected unless efficient solutions to bacterial resistance to antibiotics are found soon. Many actors – not only medical professionals and scientists – have important roles in solving this problem. The general public plays a pivotal role in terms of the demand and use of antibiotic drugs. Sufficient public knowledge and awareness of the problem is crucial, with media reports and high-quality education being key sources of information.

Bacterial resistance to antibiotics evolves through natural selection. This concept comprises a general set of principles that forms one of the major mechanisms of evolution that all living organisms abide by. A sound understanding of natural selection is therefore highly relevant not only in light of antibiotic resistance, but also for other pressing societal issues such as the implications of climate change, biodiversity management and other natural phenomena. However, the concept of natural selection is notoriously hard to teach, and misconceptions about its mechanisms are abundant. This is partly due to the extensive temporal and spatial scales that evolution works over, as well as misunderstandings about the role of randomness in evolution. Visualizations such as animations may be a robust way to help learners mediate between symbolic models and physical phenomena. In this way, visualizations, which are useful in making previously imperceptible concepts tangible to learners, could be pivotal to disseminating the correct knowledge about natural selection throughout contemporary society.

The purpose of the studies underlying this dissertation is two-fold: first, the research aims to explore the nature of the information concerning antibiotic resistance and natural selection that is conveyed to members of society; second, the research aims to empirically investigate the potential value of teaching natural selection in light of antibiotic resistance. Furthermore, special focus is given to visual modes in explanations as well as the role and inclusion of so-called threshold concepts. The research also concentrates on two aspects of communication: the communication that is widely accessible in the public realm and what educational standards that facilitate the correct comprehension of this communication. Scientific

literacy provides an appropriate theoretical lens for this purpose. However, scientific literacy remains a rather elusive concept that has been interpreted in multiple ways since its introduction. The results from the studies are discussed through the perspectives of some of these meanings.

The three main themes that characterize the work presented in this dissertation are biological evolution (specifically natural selection), antibiotic resistance and the use of visualizations. These themes are considered to varying extents in the included papers, as seen in Table 1.1.

Table 1.1. Distribution of the main themes in the included papers.

<i>Paper no.</i>	Evolution	Antibiotic resistance	Visualizations
I		X	
II	X	X	
III	X		X
IV	X	X	X

1.3 Positioning of the dissertation

The research underlying this dissertation can be considered to be situated in and between two related research fields. These are *science education* and *science communication* (also referred to as *public communication of science and technology* (PCST)). Although these fields are similar in many aspects, they both have unique elements. Science education is a more mature field which, by nature, focuses on education and the learning of science content (including both products and processes of science). Science communication is a younger field that is more concerned with questions surrounding engagement with science (Baram-Tsabari & Osborne, 2015, Ogawa, 2011). However, both fields share many similarities and research directions; for example, attitudes toward science and informal learning in public settings are pursued within both fields. A published book that aims to build bridges and initiate dialogue between the fields (van der Saanden & de Vries 2016) and a special issue of the *Journal of Research in Science Teaching* (Baram-Tsabari & Osborne 2015) demonstrate recent initiatives towards increased cooperation between the fields.

A natural link between these two fields is the concept of scientific literacy. Basically, scientific literacy concerns the goal of science education, namely, whether it is to prepare future scientists or to prepare citizens for the future in a society heavily impinged by science (e.g. Roberts, 2007). To put it simplistically, education research provides us with the tools necessary to properly inform and develop teaching while communication research can

function to highlight critical areas, based on knowledge and attitudes among the general public(s), where further teaching is needed.

Additionally, the two fields have somewhat different theoretical starting points, as education researchers see scientific ideas as being embedded in disciplinary structures whereas communication researchers tend to perceive them as being embedded within social concerns (Feinstein, 2015). Therefore, it is logical that science education would see antibiotic resistance as a way to illustrate natural selection whereas science communication would rather introduce bacterial resistance with the concepts of health and illness (Feinstein, 2015). The presented research has been produced in the boundaries between these research fields. Consequently, the included papers adopt multiple theoretical viewpoints, such as risk communication, threshold concepts, visualization research and evolution education. In practice, Paper I is published in a journal firmly situated within the PCST-community, Paper II is published in a journal that considers publications from both fields of research (Ogawa, 2011), whereas Paper III is under consideration by, and Paper IV is published in, traditional science education journals.

2. Theoretical framework

This chapter presents the theoretical underpinnings of the included studies. Antibiotic resistance and evolution are initially covered separately, but these topics are later viewed in light of each other in a section that includes a consideration of how these two topics could be brought together in a synergistic way for communication and education. This is followed by a brief discussion of the use of visualizations in science education. The notion of scientific literacy, which is used to connect the four included papers and critically discuss the presented findings, is introduced in the last section of this chapter.

2.1 Antibiotic resistance

Bacterial resistance to antibiotics has been labeled one of the greatest threats to human health (World Health Organization, 2011; World Economic Forum, 2016). At least 25,000 lives are lost annually in Europe as a result of antibiotic resistance, exerting a societal burden worth as much as 1.5 billion Euro (WHO, 2011). According to a review on antimicrobial resistance funded by the Wellcome Trust and the UK government, global annual mortality could rise to 10 million lives and the cumulative costs between now and 2050 would be an astounding 100 trillion US Dollar, corresponding to the entire UK economy each year, if actions are not taken (O'Neill, 2015). Not only does antibiotic resistance carry the risk of making infectious diseases untreatable, it also has far wider implications. Functional antibiotics are a prerequisite for numerous advanced medical treatments such as chemotherapy, transplantations, premature care and invasive surgery; thus, antibiotic resistance also threatens the efficacy of treatments we consider standard (Blair et al., 2015; Cars et al., 2008; Levy & Marshall, 2004).

The terms *antimicrobial* (that also include viruses, parasites and fungi) - and *antibiotic* resistance are sometimes used interchangeably. Mendelson and colleagues (2017) advise against the use of the term antimicrobial resistance due to that antimicrobials also include medicines that are necessary in sustaining food security, such as anticoccidial medicines that are crucial for poultry production (and do not contribute to resistance in bacteria). There is also a lack of conventional translations for antimicrobial resistance in many languages, including Swedish, which may impede public awareness (Mendelson et al., 2017). For these reasons, the term antibiotic resistance will be the used in the following text.

Given the widespread use of antibiotics not only in human medicine, but also in animal care, horticulture, beekeeping, antifouling paints (paint that is used on the bottom of ships to prevent growth of marine organisms) and genetic laboratories, there is strong evolutionary pressure for resistance-development in bacteria (Blair et al., 2015). Resistance to antibiotics is not a completely modern phenomenon. The majority of our functional antibiotic drugs have been developed through antibiotic-producing microorganisms that have dwelled on the planet for billions of years. In this way, the evolution of antibiotic resistance is a natural ecologic process. In fact, ancient bacteria with resistance to certain antibiotics have been found in permafrost and isolated caves – far from human activity (D’Costa et al., 2011; Blair et al., 2015). In his acceptance speech for the Nobel Prize in Physiology or Medicine in 1945, Alexander Fleming warned us about the effects of resistance in future antibiotics (Fleming, 1945). Unfortunately, the evolutionary aspect of resistance development has not been particularly emphasized or considered during the history of antibiotic drugs. Bull and Wichman (2001) speculate that this might be due to the seemingly limitless supply of new drugs. However, the influx of new antibiotic drugs on the market has decreased dramatically in recent years (Brown & Wright, 2016). Unless significant action is taken to combat the problem of bacterial resistance to antibiotics, there is a real possibility that we will no longer be able to treat bacterial infections (Watkins, 2016).

There is large variation in antibiotic resistance among European countries, and although the problem has been acknowledged for many years - with efforts to limit prescription rates - there are still resistant bacterial strains that continue to rise in all countries (European Centre for Disease Prevention and Control, 2015). Significant efforts at multiple levels of society are required to overcome the problem of resistant bacterial strains. In addition to working with diverse societal stakeholders and producing new medicines, the general public needs to become more involved (Davey, Pagliari & Hayes, 2002; McNulty et al., 2007; O’Neill, 2016). It is also important to note that antibiotic resistance is a global problem, with migration and travelling habits (both of which have increased during recent times) providing an infrastructure for the international spread of resistant bacteria.

2.1.1 Public knowledge and awareness about antibiotic resistance

The importance of increased public awareness and understanding regarding antibiotic resistance has been emphasized by numerous scholars (e.g.

Davey, Pagliari & Hayes, 2002; McNulty, Boyle, Nichols, Clappison & Davey, 2007) and non-governmental organizations (e.g. World Economic Forum, 2016; WHO, 2011). One of the most important factors is lowering patient expectations for receiving antibiotics when visiting a medical practitioner. Studies have shown that there is a clear relationship between patient expectations and prescription outcome after physician consultation (Davey, Pagliari & Hayes, 2002; Scott et al., 2001). On a population level, there seems to be an inverse correlation between public awareness of antibiotic resistance and prevalence of resistant strains (Grigoryan et al., 2007).

An American study by Carter, Sun and Jump (2016) showed that respondents were aware of a relationship between antibiotic overuse and antibiotic resistance, but a majority did not recognize it as a big problem. The same study also identified confusion regarding the biological background of resistance, for example, whether resistance develops in bacteria or patients as well as the (non)-effectiveness against viruses (Carter, Sun & Jump, 2016). Gualano and colleagues concluded that more educational initiatives are needed following a systematic review of knowledge and attitudes towards antibiotics among the general American population (Gualano et al., 2015). This conclusion is supported by another systematic review, which revealed that the public in several countries does not believe that they are contributing to the development of increased resistance (McCullough et al., 2016).

The Swedish population was shown to possess favorable attitudes and behavior for combating antibiotic resistance in a European comparison (Grigoryan et al., 2007), a situation that might be partly due to the organization STRAMA (Swedish Strategic Programme against Antibiotic Resistance), which has worked with different stakeholders, including the public, since 1995 (Grigoryan et al., 2007; Molstad et al., 2008). A population-based survey from 2010 found that although Swedish attitudes towards antibiotic resistance rank highly in a European comparison, the knowledge levels of Swedes do not differ considerably from those of other Europeans. For example, about 25 % of Swedes agreed with the claim that antibiotics are effective against viral infections, and 85 % agreed that humans may become resistant to antibiotics (André et al., 2010). A follow-up study showed a slight improvement in knowledge levels. However, there is still clear room for improvement, especially among groups such as the elderly and poorly educated. The study also found a correlation between high knowledge levels and restrictive attitudes toward antibiotics (Vallin et al., 2016).

Reasons for cross-national differences in antibiotic behavior - such as the relative numbers of, and compliance with, prescriptions - are numerous and hard to isolate. According to Deschepper and collaborators (2008), one important factor is cultural differences in attitudes to authorities. Although Swedes generally exhibit relatively high trust in physicians and official agencies, this trust will only positively impact the fight against antibiotic resistance if the authorities (such as prescribing doctors) are accessible and provide meaningful advice. However, a study on perceptions of antibiotic prescribing among Swedish hospital physicians identified five qualitatively different perceptions, with antibiotic resistance only considered in two. The authors provided several reasons that physicians do not consider resistance to antibiotics, for example, a dominating focus on patient care, uncertainty about how to manage infectious diseases or pressure from the healthcare organization (Björkman et al., 2010).

2.1.2 Antibiotic resistance in school curricula

During the compulsory years (1-9) of the Swedish school system, antibiotic resistance is listed among the learning goals of the biology course for years 7-9 (The Swedish National Agency For Education, 2011). Therefore, it is a topic that all Swedish students will encounter during their educational years. This course is also where evolution is first introduced to the Swedish pupils. The overall aims of this biology course include “to use concepts of biology, its models and theories to describe and explain biological relationships in the human body, nature and society.” Specific aims include “evolutionary mechanisms and their outcomes” (The Swedish National Agency for Education, 2011). In secondary school, antibiotic resistance does not appear in any of the national courses, but may be covered in occasional local courses. Evolution is only covered within the natural science program, which accepts approximately 10 % of pupils. Thus, the biology course for years 7-9 should equip every Swedish school pupil with the knowledge necessary to deal with antibiotic resistance. The studies in this dissertation are situated in a Swedish context, but antibiotic resistance is also present in several other European curricula at both junior and senior levels (Lecky et al., 2011).

With regard to higher education, a concept inventory revealed several misconceptions commonly held by students prior to attending a microbiology course. These preconceptions included that antibiotics only work on bacteria that cause disease and that antibiotic resistance is a physical coat or skin that protects bacteria (Stevens et al., 2017). Richard, Coley and Tanner (2017) investigated three forms of intuitive reasoning

associated with antibiotic resistance - teleological, anthropocentric and essentialist - in students at various levels, as well as in biological faculty. Their findings show that all three forms of intuitive reasoning were prevalent in all student groups (including advanced biology majors) and significantly correlated to misconceptions on antibiotic resistance (Richard, Coley & Tanner, 2017).

The Swedish national agency for education (Skolverket) produces annual national tests in different subjects that are distributed to all of the pupils in various age groups. The national tests for biology (school year 9) included items concerning antibiotic resistance in both 2014 and 2015. The exact formulations of the items are classified, but the producers of the test annually release a report that includes general reflections on the results. In 2014, there was a multiple-choice item concerning antibiotic resistance. This item proved to be very difficult for all pupils, including those with a high general test-score (Lind Pantzare et al., 2014). The following year's test included an open-ended item in which pupils were asked to explain the relationship between infections and antibiotic resistance. This was also found to be difficult for pupils on all performance levels. The test producers concluded that the pupils were not able to explain why the effect of antibiotics is lost as a consequence of more frequent usage. A common misconception was that the human body, rather than bacteria, becomes resistant to antibiotics (Lind Pantzare et al., 2015), a result that is consistent with population-based surveys (e.g. André et al., 2010).

Overall, antibiotic resistance is a crucial part of the biology curriculum that all Swedish pupils need to learn. It appears together with evolution, which presents teachers with the opportunity to teach these two topics simultaneously. However, antibiotic resistance seems to be among the more problematic contents of the course for both high and low achievers nationwide. Outside of the educational system, there are several sources from which citizens can receive information about antibiotic resistance. These sources include, for example, friends and family, Internet, and science centers. But the main source of health information, which also strongly influences the previously mentioned sources, is news media, which is the focus of the following section.

2.1.3 Newspaper reporting on antibiotic resistance

Newspaper content has been found to significantly influence readers' behavior with regard to health risks (Trumbo, 2012), and also affects trust in local health care actors (Van der Schee, de Jong & Groenewegen, 2012). An identified correlation between the use of media and both factual and

procedural scientific knowledge (Nisbet et al., 2002), along with the observation that media and the press become the primary source of scientific information after formal education (e.g. Dunwoody, 2008), demonstrate that the media is an important study object within science communication.

Although physical newspapers now boast a significantly smaller audience than 20 years ago, they were considered to be a valuable data source in two of the included papers. This decision was based on that there exists a lot of previous scholarly work based on print newspapers, providing a possibility to compare methodological choices as well as results. Also, both of these studies focused on the Swedish context, in which print newspapers were still read relatively frequently in 2011 and maintain a high ranking in terms of public trust compared to, for example, Internet sources (Weibull, Oscarsson & Bergström, 2011). For a more elaborated discussion of this issue, see Section 4.6 or Paper I.

Studies that investigate news reports of infectious diseases commonly adopt a risk communication perspective (e.g. Dudo, Dahlstrom & Brossard, 2007; Evensen & Clarke, 2012; You et al., 2017) and apply theory-based concepts such as magnitude or efficacy to interpret their findings based on risk communication models. Given the subjective nature of risk information and how it could be interpreted, Dudo and colleagues (2007) suggested a conceptual definition of what “quality information” should constitute with regard to media-reported risks. Their definition of quality information includes, *inter alia*, a high degree of quantitative information (in relation to qualitative statements) concerning a risk’s magnitude along with specific information concerning possible risk-reduction measures for individuals to undertake.

Most studies on news reports of antibiotic resistance have been situated in English-speaking contexts. Desilva, Muskavitch and Roche (2004) looked at coverage in the United States and Canada and found that newspapers generally lacked important information on measures available to the general public. Two British studies on the coverage of methicillin-resistant *Staphylococcus aureus* (MRSA) concluded that information in articles was more often based on governmental agency press releases than research reports, as well as that the source of the problem was commonly cited as “dirty hospitals” (Boyce, Murray & Holmes, 2009; Chan et al., 2010). Bie, Tang and Treise (2016) compared the coverage of NDM-1 in Indian, British and American newspapers and found that reporting in the UK and US contained higher levels of dread (emotionally loaded words, infection consequences) and controllability (by providing personal protection measures) than the reporting in Indian newspapers. A study that applied a linguistic transitivity analysis to UK press concluded that no sense of

individual responsibility was reported, but rather that the problem was directed to society as a whole (Collins, Jaspal & Nerlich, 2017).

In general, comparable data are available from English-speaking countries, but no information regarding how antibiotic resistance is conveyed through Swedish media currently exists. Given that the Swedish population is characterized by more favorable attitudes but similar knowledge levels when compared to other nationalities in terms of antibiotic resistance, the differences between Swedish media and reporting from other countries are of potential interest. For example, what background knowledge is conveyed and what is implicitly presumed to be known by the readers? This also raises the issue of scientific literacy which, according to one definition, refers to a level of understanding at which citizens can read and understand the reporting of scientific matters in a daily newspaper (e.g. Rughinis, 2011).

2.2 Evolution

Evolution is defined as the change in heritable traits of biological populations over generations. It forms the basis for the development of all present and extinct replicating life forms on earth, and, as such, evolutionary processes are at the heart of biology (Dobzhansky, 1973). Given its strong explanatory power with respect to biological phenomena, evolution can be considered to form part of scientific literacy (e.g. Fowler, 2009; Olander, 2013; Smith, 2010b). Three of the processes through which evolution takes place are natural selection, gene flow (migration) and genetic drift. This dissertation predominantly focuses on natural selection, which is presented in the following section. However, it is important to note that genetic drift also underlies many biological phenomena and therefore receives deserved interest from the education community (e.g. Price et al., 2014). Although there are no elements of selection in genetic drift, specific mechanisms such as the bottleneck effect or the founder effect can stimulate dramatic changes in populations.

2.2.1 Natural selection – the basic steps

Natural selection was first introduced by Charles Darwin and Alfred Russell Wallace, with an elaboration in Darwin's book "On the origin of species" in 1859 (Darwin, 1859). Basically, natural selection explains, through general mechanisms framed as three inferences based on five observations/facts, how certain variations within species accumulate over generations (Mayr, 1982). These mechanisms are summarized in Table 2.1.

Table 2.1. Natural selection as explicated by Ernst Mayr (1982).

Fact #1	All species have such great potential fertility that their population size would increase exponentially if all individuals that are born would again reproduce successfully.
Fact #2	Except for minor annual fluctuations and occasional major fluctuations, populations normally display stability.
Fact #3	Natural resources are limited. In a stable environment they remain relatively constant.
Inference #1	Since more individuals are produced than can be supported by the available resources but population size remains stable, it means that there must be a fierce struggle for existence among the individuals of a population, resulting in the survival of only a part, often a very small part, of the progeny of each generation.
Fact #4	No two individuals are exactly the same; rather, every population displays enormous variability.
Fact #5	Much of this variation is heritable.
Inference #2	Survival in the struggle for existence is not random but depends in part on the hereditary constitution of the surviving individuals. This unequal survival constitutes a process of natural selection.
Inference #3	Over the generations this process of natural selection will lead to a continuing gradual change of populations, that is, to evolution and to the production of new species.

Note that Mayr's original compilation does not account for how variation originates, only that we can observe variation in all populations. Nevertheless, the explication in Table 2.1 has been referred to and elaborated on (for example with regard to origin of variation) in an impressive amount of subsequent work within the field of science education (e.g. Anderson et al. 2002; Gregory, 2009; Smith, 2010b). When Darwin initially presented the mechanisms of natural selection, there was limited evidence surrounding the details of the theory. Mendelian genetics was only

merged with Darwinian ideas about evolution in the 1930s and 1940s. This gave rise to the so-called *modern synthesis*. Today, we know much more about how variation arises and the mechanisms behind inheritance (Gregory, 2009). This knowledge has been a result of advances in molecular biology, beginning with the discovery of DNA as the carrier of heredity. Inheritance works through replication of DNA-molecules within cells. During this process, it is possible for the original information to get altered through errors (mutations) or the reshuffling of larger portions of the genome (genetic recombination). This gives rise to variation in both the genotype and phenotype of all individuals in any given population. Furthermore, mutations appear randomly, and are thus unbiased with regard to potential implications for the organism (positive, negative or neutral). However, even though the variation-generating process is random, the next step in natural selection is not. Selection works on all individuals, with those that are better adapted to their environment enjoying a higher probability of surviving to a reproductive age, and ultimately procreating, than those that are poorly adapted.

2.2.2 Research in evolution education

Even though evolution is vital to understanding biology, and thus features prominently in biology curricula worldwide, research has shown that it remains notoriously difficult to teach (e.g. Smith, 2010b). Numerous misconceptions have been identified in students at all stages of education, including biology majors (Nehm & Reilly, 2007) and even prospective teachers (Nehm, Kim & Sheppard, 2009). The challenge of research and practice in evolution education is two-fold: one aim is to increase the “understandability” of the subject and to battle misconceptions, the other is to increase the “acceptability” and argue in favor of evolution with respect to creationism and intelligent design. Although the latter is not usually a curricular demand, a lot of scholarly work has nevertheless been dedicated to this problem (e.g. Infanti et al., 2014; Smith & Siegel, 2016). These challenges are naturally intertwined, but one can notice that the first focuses more on *knowledge* whereas the other concerns *attitudes*. However, acceptance and understanding do not seem to be specifically correlated (Bishop & Anderson, 1990; Shtulman, 2006). Bishop and Anderson (1990) even state that: “*it appears that a majority on both sides of the evolution-creation debate do not understand the process of natural selection or its role in evolution.*” Kampourakis and Strasser suggest that science educators and communicators should rather direct their attention towards the “unsure” group, which generally constitutes around 30 % of students, than focusing

on those that oppose evolution for religious reasons. It has been suggested that the “unsure” group could be reached more successfully by focusing on the conceptual understanding of evolution rather than by arguing for its relevance (Kampourakis & Strasser, 2015).

Academic literature on the teaching of evolution began to increase in the 1970s (according to a search in the database *ERIC*). However, Cummins and colleagues still lamented the lack of research within the area as late as 1994 (Cummins, Demastes & Hafner, 1994). That same year, the *Journal of Research in Science Teaching* published a special issue on the teaching and learning of biological evolution, and since then, there has been extensive work in the field (for an overview, see e.g. Smith, 2010a). Building on the work of, for example, Mayr (1982) (Table 2.1), natural selection has traditionally been compartmentalized into a number of interrelated concepts that are crucial to understand and relate to each other. For example, Mayr’s first observation translates into *biotic potential*, and the fourth into *individual variation*. Most conceptual compilations in the literature build on Mayr’s first summary and vary somewhat with regard to add-ons and exceptions. The concepts stemming from Mayr’s first summary has often been used in the development of assessment tests (e.g. Bishop & Anderson, 1990; Anderson et al., 2002; Nehm & Reilly, 2007). Tibell and Harms (2017) use the term key concepts for these content-oriented concepts and organize them into three overarching principles: variation, inheritance and selection (cf. Godfrey-Smith, 2007). Tibell and Harms also relate the key concepts to so-called *threshold concepts* (see Section 2.2.3).

According to Nieswandt and Bellomo (2009), the problem with a strict focus on these key concepts is that understanding evolution does not only consist of factual knowledge, but also relies on procedural, schematic and strategic knowledge. This means that students should be able to know when, where, how and why to apply the knowledge. Another problem is how the key concepts relate to each other. Biological concepts are generally multi-leveled, with explanations for an observation on one level often applying to observations at other levels (Wilensky & Resnick, 1999). For example, the route from origin of variation in an individual’s genotype to the gradual increase in phenotypic traits in a population over generations requires thinking across multiple levels of organization (so-called *vertical coherence*) (Jördens et al., 2013). Specifically, it has been suggested that the integration and clarification of processes that occur on the genetic level is important for both successful teaching and a satisfactory public understanding of evolution (Jördens et al., 2013; Smith et al., 2009; White et al., 2013).

It is also important to note that evolution education research traditionally has treated natural selection as being almost synonymous with evolution, and omitted other evolutionary principles such as genetic drift and migration (Catley, 2006). If a population is not well suited to compete for resources in its environment, then natural selection is a powerful evolutionary mechanism that can drive the gradual adaptation of the population. In contrast, natural selection will impede changes (i.e. evolution) in a population that is perfectly adapted to a certain environment.

The scientific community has identified many erroneous understandings, or misconceptions, as to how evolution works (e.g. Gregory, 2009; Smith, 2010b). Some scholars prefer the term ‘alternative conceptions’ to describe these ideas, and although they are used synonymously, there is an ongoing debate about what term that should be used by the research community (see e.g. Maskiewicz & Lineback, 2014; Leonard, Kalinowski & Andrews, 2014). For the sake of clarity, the term ‘misconceptions’ will be used consistently throughout the rest of this dissertation. Many of the misconceptions seem to develop in early childhood as part of a practical understanding of how the world functions. Unfortunately, intuitive interpretations are often contradictory to scientific principles (Gregory, 2009), and learning natural selection is therefore less a question of adding new knowledge as helping students to revise what they already know (Sinatra, Brem & Evans, 2008). Common misconceptions include, for example, that evolution is driven by an organism’s need or that all organisms in a population evolve together (Bishop & Anderson, 1990). Other common misconceptions are that traits that are acquired during a lifetime are inherited (Nehm & Schonfeld, 2008) or that only the traits that are favorable for the individual are passed on to the offspring (Gregory, 2009). Misconceptions are usually related to key concepts discussed above and are often integrated as false alternatives in test items (e.g. Anderson, Fischer & Norman, 2002).

2.2.3 Threshold concepts in evolution

The notion of threshold concepts has received attention from many scientific fields since being first introduced by Meyer and Land (2003; 2005). A threshold concept is commonly likened to a portal that, once passed, provides access to new ways of thinking (Meyer & Land, 2005). Definitions of threshold concepts vary slightly between different sources, but they are usually described as being *transformative*, *irreversible* and *integrative* in relation to their subject (Meyer & Land, 2005). Transformative in this sense means that they transform the way the subject is being perceived.

Irreversible means that once the concept is learned, it cannot be unlearned, while integrative signifies that learning a specific concept will reveal previously unknown relationships in the subject's content. An example from literature studies is the use of irony in text. Meyer and Land quote a lecturer who states: *"Initially, they just don't get it, but once they realize what irony is and how it is used by writers, whole areas open up, and perceptions, in terms of the various layers of meaning and structure that might be operating within a work at one time. But it's a hard concept to teach."* (Meyer & Land, 2005).

Within the scope of science education, threshold concepts differ from more content-oriented concepts in that they are generally of a more abstract character. Although content-oriented concepts may be conceptually difficult, they generally receive ample attention in biology teaching. Threshold concepts are not necessarily as troublesome to learn as content-oriented concepts, but receive less classroom attention even if they might provide students with specific skills, or perspectives, that would help them understand content concepts (Ross et al. 2010a). Scholars have identified threshold concepts in a wide variety of subjects such as engineering education (Baillie, Goodhew & Skryabina, 2006), biochemistry (Loertscher et al., 2014) and economics (Davies & Mangan, 2007). The notion of threshold concepts has also been criticized, with the argument that they are hard to isolate based on their definition (Rowbottom, 2007). Nevertheless, the subject is receiving more and more research attention, and has also been applied to integrated models that aim to bring threshold concepts closer to teaching practice (e.g. Barradell & Kennedy-Jones, 2015).

Within biology, threshold concepts have been suggested to be related more with processes and abstract ideas than content-focused key concepts (Ross et al., 2010b; Taylor, 2006). Furthermore, certain researchers have suggested that biological threshold concepts are treated as tacit or assumed understanding in biology teaching (Davies, 2006; Ross et al., 2010b). Dobzhansky's (1973) claim that "nothing in biology makes sense except in the light of evolution" can be extended to mean that evolution would be a threshold concept for the whole field of biology. However, understanding the concept of evolution seems to depend on the mastery of several threshold concepts (Kinchin, 2010; Ross et al., 2010b). Based on previous work on threshold concepts in biology, Tibell and Harms (2017) propose four threshold concepts that are important for understanding natural selection. These are *randomness*, *probability*, *spatial scale* and *temporal scale*. These four concepts are interrelated, and their relationships to the previously mentioned key concepts are described in the following paragraph. Tibell and Harms suggest a two-dimensional model for

organizing threshold concepts, key concepts and the three overarching evolutionary principles (Fig. 2.1) (Tibell & Harms, 2017).

Fig. 2.1. The relationship between threshold concepts, key concepts and evolutionary principles, as suggested by Tibell and Harms (2017).

The mechanisms underlying natural selection work on multiple levels. For example, variation-generating processes occur within the cell and rely on random events on the molecular level. Variation manifests on DNA or protein structure on the subcellular level and through multiple features such as height or skin color on the phenotypic level. Moreover, differential survival and the gradual change within populations can result in a bacterial population occupying a cubic millimeter or animals inhabiting a landmass as large as an entire continent. Just as the spatial scale of evolution shows an almost immeasurable range, the time frames involved in the different steps of evolution can range from nanoseconds to billions of years. It is important to emphasize these scales to students because they are not likely to be apparent if a teacher only focuses on the key concepts (Tibell & Harms, 2017). Several conceptual problems can arise due to the spatial and temporal width of evolutionary processes. Geological, or deep, time in itself is hard for most students to grasp (Catley & Novick, 2009; Cheek, 2010), and research tells us that students have trouble moving between different organizational levels in space and time (Johnstone, 1982; Jørgens et al., 2016; Lewis & Kattman, 2004). There are also practical problems associated with using linear scales to depict events that occur on vast temporal scales.

This is often solved by using logarithmic scales, which, unfortunately, have been found to be especially problematic for students to interpret correctly (Swarat et al., 2011).

Mutations are one of the main mechanisms through which new variations are introduced into a population, and therefore, provide the basis for both genetic drift and natural selection. As mentioned at the end of Section 2.2.1, mutations (origin of variation) are random in the sense that they do not occur as a response to an organism's need and are just as likely to exert a negative effect as a positive effect for the individual (although they are mostly neutral). However, the selection processes that affect individuals of a population are most definitely not random. The individuals with traits that confer a higher probability of survival and reproduction (higher fitness) will, by definition, be more likely to procreate and pass on their genes than individuals with lower fitness. There are of course certain random factors at play, such as individuals dying due to uncontrollable events, but statistically, the favorable traits will accumulate in subsequent generations.

There are several problems associated with comprehending random processes in biology (e.g. Mead & Scott, 2010). Garvin-Doxas and Klymkowsky (2008) reported that students found the noticeably efficient biological systems very hard to combine with the notion of randomness, which evoked a counter-intuitive paradox among learners. Fiedler, Tröbst and Harms (2017) developed instruments for measuring the understanding of randomness in the context of both evolution and mathematics, and determined that these two concepts involve different competencies. Moreover, they found pre-service biology teachers to have both significantly lower understanding of randomness in the context of evolution and conceptual evolutionary knowledge than biology majors (Fiedler, Tröbst & Harms, 2017). Evolution education studies have found that many misconceptions are based on underlying confusion regarding randomness (Gregory, 2009). Among these are that mutations are always harmful (Cho, Kahle & Nordland, 1985) and that evolution is driven by the needs of an organism (Bizzo, 1994). Consequently, Robson and Burns (2011) found interventions that directly target students' understanding of randomness in mutations to enhance learning and comprehension.

Randomness can be defined as unpredictability in the outcome of a single event. Analogously, probability determines the distribution of possible outcomes. For example, the probability of receiving a specific homozygous genotype from a heterozygous crossing (where at least one allele is shared by the parents) is one in four (25 %). The resulting genotype in a unique progeny is random in the sense that we cannot know what the result will be although it is more probable that the progeny will also acquire a

heterozygous genotype (Mead & Scott, 2010). Thus, an outcome with a low probability is unlikely to happen given one single opportunity. However, as the number of events increases, so do the chances that at least one of the events will result in a specific outcome. Thus, by using evolution as an example it becomes clear that probability is also closely related to both spatial (large populations) and temporal scales (many generations). A rare and beneficial mutation always has a low probability of occurring during the reproduction of one individual, but within a large population and over many generations the same mutation is almost certain to appear at some point. In other words, even if the probability of an event is the same (i.e. highly unlikely), it is more plausible that the specific event will occur as the sample size and/or number of repetitions grows.

2.3 Antibiotic resistance and evolution in light of each other

Evolution and natural selection are general mechanisms that affect all living organisms, including bacteria. The development and spread of bacterial resistance to antibiotics happens through natural selection (e.g. Andersson & Levin, 1999), with resistance providing bacteria with strong relative fitness. Genereux and Bergstrom (2004) provide an account of how a single resistant mutant can progress from a relative frequency of 0,01 % to 99,9 % in only 24 hours. The following two sections will discuss incentives for emphasizing the links between evolution and the development of antibiotic resistance from two perspectives: first, how evolutionary reasoning can, and has been used to, promote a better understanding of antibiotic resistance, and second, the potential benefits that arise from using antibiotic resistance as a context in which to teach evolution. To put the relationship in perspective, the following quotation provides an account of how antibiotic resistance abides by some of the key concepts of natural selection (also present in Paper II).

“Bacteria have an average generation time of approximately 20 minutes, providing them with an extreme biotic potential. In fact, one single bacterial cell could give rise to a bacterial population with the same mass as the earth in about 36 hours under ideal circumstances. Fortunately, this does not happen because of limited resources in terms of the available space and necessary nutrients, leading to population stability. For example, the composition of bacterial strains in the intestines is usually more or less constant over time. An inference from these observations is

that individuals in a dividing bacterial population clearly have limited survival. Moreover, the individuals in a bacterial population are not identical to each other but exhibit a degree of individual variation due to relatively frequent (e.g. compared to human cells) random mutations during cell division (origin of variation). The generated variation is inherited by successor cells or other cells through horizontal gene transfer. A mutation that turns out to be beneficial in a particular environment (e.g. a gene for antibiotic resistance in the presence of an antibiotic drug) affects survival probability, leading to a differential chance of survival among the individuals in the population. Since individuals with a resistance gene are more likely to survive, a cumulative change in population over generations will occur as the resistance gene(s) accumulates and becomes a trait in the majority of the bacterial population. These mechanisms form the basis of natural selection and explain what is commonly referred to as microevolution, or changes in the distribution of traits within a population. The same principles, together with other evolutionary mechanisms such as genetic drift, apply to the origin of species. However, longer periods of time combined with geographical separation are typically required for new species to evolve” (Bohlin & Höst, 2015).

2.3.1 Antibiotic resistance in light of evolution

There are essentially two, partly overlapping, lines of reasoning regarding the potential impact of evolutionary knowledge on the understanding of antibiotic resistance. The first regards how evolutionary reasoning can improve policy, medical research as well as hospital care management (e.g. Carroll et al., 2014; Futuyma, 1995; Meagher, 2007). The other concerns how patients, individual medical practitioners and the general public could benefit from a better understanding of evolution. In addition, the decision to teach antibiotic resistance and evolution together could be supported by the claim that understanding evolution provides an explanatory framework for grasping the appearance, spread and problems associated with resistant bacteria. This would help fulfill the requirements of curricula that include antibiotic resistance (e.g. Bull & Wichman, 2001; Krist & Showsh, 2007; Cloud-Hansen et al., 2007). However, Burmeister and Smith (2016), note that evolution is often missing from microbiology teaching. They identify several challenges concerning successful integration of evolution in microbiology. These challenges include confusing terminology,

misinformation from the media and perceptions of evolution as a controversy (Burmeister & Smith, 2016).

Evolution is the process through which all life forms and their traits have developed. However, evolution is not only a historical framework for retrospective studies, but also has broad societal implications in various areas. These include emergence of new diseases, plant- and animal improvement, biodiversity management, response and adaptation to climate change as well as antibiotic resistance (Futuyma, 1995; Meagher, 2007). The most urgent area in which evolutionary reasoning could play a more significant role is medicine (Antonovics, 2016; Bull & Wichman, 2001). Antonovics (2016) suggests one reason for why the medical community occasionally fails to properly apply evolutionary reasoning to the problem of antibiotic resistance. She argues that medicine prioritizes the individual patient whereas evolutionary theory is largely dependent on a population-level approach (Antonovics, 2016). One strategy for overcoming this problem would be including lectures on the importance of evolution within medical education. This could help prospective doctors gain a deeper understanding of resistant bacteria, and, as a result, improve overall patient care (Hidaka et al., 2015). For example, evolutionary reasoning can be used to predict why different measures against antibiotic resistance are more effective than others (Gluckman et al., 2011). Hence, evolutionary explanations for antibiotic resistance would not only benefit physicians, but patients as well, because knowledge of causal mechanisms permits more flexibility in novel situations.

There are several ways that evolutionary reasoning could improve public knowledge of antibiotic resistance. One concerns the widespread misconception that people who abuse antibiotics will become resistant themselves (e.g. André et al., 2010). The evolutionary (and correct) explanation is that the use of antibiotics provides a selective advantage for already resistant bacteria, which are then allowed to rapidly increase in number and potentially spread to other people. Individuals infected by the same bacteria are at risk of experiencing an untreatable infection no matter how careful they have been with antibiotic use themselves (Bull & Wichman, 2001). Moreover, the possibility of an increased number of resistant bacteria is affected by circumstances regarding how the dose is delivered. Dosage and compliance with the treatment is mainly under our own control, and may impede the spread of resistance if performed correctly (Bull & Wichman, 2001). Also, as mutations leading to resistance occur randomly, the number of occurrences increases with population size. This is an important reason for why antibiotics should be used with caution and as selectively as possible, preferably only against the specific strain causing the

infection. Diagnosing the correct strain may take a few days, which will delay patient treatment. In this way, awareness of how resistance develops can help a patient understand the physician's decision. Another example of evolution's explanatory value on antibiotic resistance is situations in which selective pressure is not strong and/or only affects a population sporadically. These types of selective pressures may result in the evolution of phenotypes that do not currently exist in a population. Strong and immediate selection for such phenotypes would likely extinguish the current population. For this reason, antibiotics, when used, should be delivered in strong enough doses and used for the whole duration of treatment. Otherwise, partly resistant bacteria might survive and can later acquire full resistance through further mutations (Blondeau et al., 2001).

An apparent paradox exists in the public stance on antibiotics. On the one hand, antibiotics should be used as scarcely as possible in order to reduce the spread of resistance. However, on the other hand, once prescribed, patients are encouraged to use high doses well after the symptoms have declined (although the latter advice is currently being debated, see Llewelyn et al., 2017). Evolutionary reasoning is necessary to make sense of this conflicting advice. Otherwise, patients are solely dependent on the treatment instructions provided by physicians. In Sweden, trust in physicians is generally high, but problems can still arise. For example, Swedes that travel abroad may find antibiotics available over the counter in other countries.

Antonovics and colleagues (2007) studied how well the research community recognizes the evolutionary background of antibiotic resistance by investigating the extent to which the term evolution was used in research papers about antibiotic resistance. They found a large disparity between biomedical journals, in which the word "evolution" was mentioned in 2.7 % of the articles about antibiotic resistance, and journals in the fields of evolutionary biology or genetics, in which 65.8 % of antibiotic resistance articles used the term. They also found a high correlation between the use of the term evolution in popular scientific press and how often it was used in the original scientific paper that the article cited. Thus, they argue that biomedical researchers could help influence public perception of antibiotic resistance as an evolutionary process by using the term more explicitly in their primary literature (Antonovics et al., 2007). Singh and colleagues (2016) specifically investigated the usage of the word "evolve" in popular press articles relating to antibiotic resistance in the United States, United Kingdom, Canada, India and Australia. The results revealed that articles used the term "evolve" at an overall rate of 18 %, although there were large differences based on country and the scope of the newspaper. Although this study only focused on the use of the word evolve, and did not consider

explanations of evolutionary mechanisms, the authors nevertheless concluded that usage is low and may affect both public understanding and acceptance of evolution (Singh et al., 2016). Somewhat contrary to the studies mentioned above, a recent study showed that although a large majority of biology students and faculty agreed with the claim that antibiotic resistance is an example of evolution, misconceptions and intuitive reasoning are widespread among the student group. This implies that it is not enough to simply point out the association between antibiotic resistance and evolution, but that details on the workings need to be taught and effectively communicated (Richard, Coley and Tanner, 2017).

2.3.2 Evolution in light of antibiotic resistance

The previous section hints that the potential benefits of introducing evolutionary reasoning into the public discourse on antibiotic resistance should be further investigated. But what are the possible benefits of presenting these subjects in the opposite order – making evolutionary mechanisms more understandable by explaining them through an antibiotic resistance context? The potential advantages presented in this section include compressed spatial and temporal scales, an increased focus on random processes as well as being a non-controversial and socially relevant example for teaching evolution.

As discussed in Section 2.2.3, one of the notions surrounding evolution that is particularly difficult to grasp is that it takes multiple generations to see visible and discernible effects. For mammals, this usually translates into thousands, or even millions, of years depending on the generation time and properties of the effect. In other words, evolution cannot be “seen” in real-time but must be studied historically through time frames so large that they are almost impossible to conceptualize (e.g. Cheek, 2010). Luckily, these time frames can be substantially reduced by using bacteria as an example. Many bacterial strains (such as *Escherichia coli* or *Staphylococcus aureus*) typically divide every 20-30 minutes and thereby exhibit impressive biotic potential. Moreover, given the small size of an individual bacterium, very large populations fit into a test-tube or under a microscope. Thus, bacteria provide teachers with an opportunity to demonstrate evolutionary processes in large populations within a school laboratory in real time (Elena & Lenski, 2003; Smith et al., 2015). Researchers have found that these kinds of laboratory set-ups are associated with the successful teaching of evolution (Krist & Showsh, 2007; Delpech, 2009; Robson & Burns, 2011; Serafini & Matthews, 2009), although exact reasons for increased student scores when

learning about evolution through bacterial contexts still remain to be explained.

There is also reason to believe that the notion of randomness is more comprehensible when embedded in a bacterial context. Nehm and co-workers have worked with so-called *surface features* in evolution education (Nehm & Ha, 2011; Nehm & Ridgway, 2011; Opfer, Nehm & Ha, 2012). Their studies indicate that students tend to focus on aspects lying at the “surface” of problems without seeing the general mechanisms. In other words, evolution in a population of cheetahs or bacteria is seen as two distinct processes (Olson, 2012). Therefore, similar response items that concern different organisms tend to, quite counterintuitively, result in different types of answers and explanations, and also cause students to cling onto their initial misconceptions. These findings show the importance of teaching students the concept of evolution through a variety of contexts, for example, mammals and microbes. There is sporadic evidence that students are more prone to include randomness in their responses to questions dealing with evolution after working with an antibiotic-related exercise (Cloud-Hansen et al., 2008), and that antibiotic resistance seems to have surface feature effects that lead students towards thinking about randomness (Göransson, Fiedler, Orraryd & Tibell, unpublished data). Since an understanding of randomness and its relation to evolution have relevance for understanding of evolutionary mechanisms (Fiedler, Tröbst & Harms, 2017; Garvin-Doxas & Klymkowsky, 2008; Tibell & Harms, 2017), previous studies, at the very least, tell us that antibiotic resistance is a context that deserves increased interest within evolution education research.

Finally, teaching evolution through antibiotic resistance has a certain amount of affective value. Hillis (2007) stresses that evolution must be presented to students as a relevant and engaging subject, and antibiotic resistance has the potential for awaking interest in students through its societal relevance (e.g. Krist & Showsh, 2007; Wolf & Akkaraju, 2014). Focusing on antibiotic resistance also enables teaching of evolutionary mechanisms without an explicit focus on evolution. This could be useful when teaching evolution in contexts where the theory of evolution is questioned, such as in classrooms where a large proportion of pupils hold certain religious beliefs (DeSantis, 2009; Scharmann, 1994). The motivational value of antibiotic resistance is also high because the relevance of evolution is not always apparent. Bull and Wichman (2001) write that: *“‘Evolution’ is still a bad word to many people, not only because it is perceived as conflicting with some religious views, but also because it is widely viewed as an irrelevant science with no social value. Acceptance of evolutionary biology is far more likely when the public realizes that it holds*

the key to many social improvements... ...As evolutionary biologists, we need to use these examples of relevance when explaining evolution to our students and the public." One promising strategy for further increasing the affective value and making the content more understandable is using visualizations, which is the subject of the following section.

2.4 Visualizations as mediators of scientific knowledge

As most subject content within science is either too fast or slow, too large or small, or too complex or abstract to be directly perceived, physical and visual representations of science have a history that is almost equally as long as that of science itself. Ever since John Amos Comenius published his books *Didactica Magna* and *Orbis Sensualium Pictus* in the 17th century, there has been a steady increase in scientific imagery. Today, a never-ending amount of visual explanations to scientific phenomena are available through multiple channels including (but not limited to) science textbooks, popular magazines and various Internet sources. There is also an established research area within science education that focuses on the use of visual materials in teaching (e.g. Gilbert, 2005; Phillips et al., 2010). Today's visualizations are not limited to still pictures, but also include plenty of simulations as well as video streaming sites that provide science-related videos and animations to millions of daily viewers, many of whom are pupils and students (e.g. Brossard, 2013). However, although textbooks go through editorial control¹, user-driven web sites do not. This presents a potential problem in learning situations and has not received enough attention from the research community.

There are some definitional ambiguities with regard to visualizations and their relation to other concepts such as models and representations. Throughout this dissertation, visualizations will be used to mean a physical entity that exists outside of our minds and includes (but is not restrained to) graphical aspects. For example, a video typically contains both moving images and a recorded narrative that form two parts (modes) of the visualization. This is in contrast with other lines of thinking, for example, Gilbert (2008) defines visualization as a process in which one makes meaning of a representation that could be either external (physically available to others) or internal (mentally available to an individual person). Furthermore, even though the practical use of the term visualizations will be limited to the description of moving images with or without audio-elements

¹ Note that editorial control of textbooks does not ensure accuracy of the included content (e.g. Tshuma & Sanders, 2014).

(so-called dynamic visualizations) in this dissertation, the term could just as well be used to describe illustrations, instrumental outputs, physical models, simulations or photographs (cf. Kozma & Russell, 2005).

Over the years, a number of theories regarding how visual material can enhance learning and/or supplement verbal instructions have emerged. One of these is the dual-coding theory, the basis of which is that visual and verbal information is processed and stored separately and independently (Paivio, 1971). Another influential theory is the cognitive theory of multimedia learning, which describes the cognitive processes involved in learning through multiple modes. This theory suggests that a learner first extracts relevant information, both visual and verbal, from a stimulus and then later organizes this information into mental representations based on one's prior knowledge (Mayer, 2001). A third relevant theory concerning learning with visualizations is cognitive load theory (Sweller, 1999). This theory is based on limitations of human working memory, which is exposed to three types of load: intrinsic load, which is related to the inherent complexity of the task (and thus cannot be changed); extraneous load, which is related to the unnecessary processing of irrelevant information (and thus can be influenced); and germane load, which constitutes the mental effort put into understanding the problem at hand and construction of schemas. The main implication of cognitive load theory for instructional designers is that extraneous load should be reduced and learners' attention should be redirected towards schema construction (germane load).

In addition to providing coherent descriptions of how learning with visual imagery takes place, the aforementioned theories have also inspired the development of various practical design principles that are important to consider when designing or assessing visualizations (Plass, Homer & Hayward, 2009). These include the multimedia principle, which suggests that text and images presented together are easier understood than text alone (Mayer 2001; Fletcher & Tobias, 2005), as well as the signaling principle, which proposes that extraneous load can be reduced by directing the viewer's attention through visual signals and cues. Another noteworthy principle is the modality principle, which states that students learn better when information is presented auditory as speech rather than visually as text (Moreno & Mayer, 1999). Unnecessary extraneous load can also be avoided by abiding to the spatial- and temporal contiguity principles, which imply that printed words should be placed near corresponding graphics and that related words and graphics should be presented simultaneously (e.g. Moreno & Mayer, 1999; Mayer, 2011).

Do visualizations, and specifically dynamic visualizations such as videos or animations, aid learning? There is no straightforward answer to this

question. Even though one can argue that images are aesthetically appealing and attract attention (Tversky, Bauer Morrison & Betrancourt, 2002), the learning benefits that arise from visualizations are hard to state in general terms as they are typically context-specific. Studies have successfully shown a positive relationship between the use of animations and concept understanding in various subjects (e.g. Marbach-Ad, Rotbain & Stavy, 2008; Tasker & Dalton, 2006), while other research has revealed that animations may provide a deceptive clarity (e.g. Hoffler & Leutner, 2007). In general, learning scientific content is connected with the ability to mediate between physical phenomena and symbolic models; in this regard, visualizations are beneficial to teaching science (Kozma et al., 2000). In particular, visualizations help students perceptualize concepts of abstract character (Niebert & Gropengiesser, 2015), and specifically draw connections between different levels of organization (Gilbert & Treagust, 2009; Tibell & Harms, 2017). Mayer (2011) states that instructional methods, rather than instructional media, facilitate learning. Research in learning with visualizations should therefore focus more on scaffolding issues than direct comparisons of different media (Mayer, 2011). Hence, the answer to the previously posed question seems to be that animations have a strong potential to convey scientific concepts, in particular dynamic processes, complex relationships and connections between organizational levels. However, the ultimate learning effect depends on a number of factors, both inherent aspects in the animation and external matters ranging from viewers' prior knowledge to scaffolding issues (e.g. Ainsworth, 2008; Fletcher & Tobias, 2005; Rundgren & Tibell, 2010; Ryo & Linn, 2014).

With regard to evolution, there are several reasons to consider the visual medium. For example, natural selection consists of a network of processes that affect each other at different organizational levels (e.g. Jördens et al., 2016). As discussed in Section 2.2.3, the spatial spread of processes underlying natural selection can span from molecular events to migration over continents. This is not obvious when focusing on key concepts, but there are several ways that visualizations can make certain evolutionary mechanisms more accessible to the viewer (Tibell & Harms, 2017). Furthermore, the speed at which mutations arise in cells (happening on the scale of nanoseconds) and the time needed to discern adaptations over multiple generations, are both well outside the range of our normal perception (depending on the generation time of the respective organism). Visualizations, especially dynamic visualizations, offer many possibilities in this regard (O'Day, 2006; McElhaney, 2015). A literature review of technology-supported learning in biology found evolution to be among the less frequently studied topics in educational research focusing primarily on

visualizations. The authors of the study recommended that future research should investigate how learning abstract and complex biological concepts can be facilitated through dynamic visualizations (Lee & Tsai, 2013).

2.5 Scientific literacy

Scientific literacy concerns the type and amount of scientifically-rooted knowledge and abilities that citizens need to participate in a democratic society. The concept is thus closely related to questions concerning science education, in particular, curricular questions. Numerous initiatives have proclaimed the necessity of scientifically literate populations (e.g. AAAS, 1989). Laugksch (2000) lists suggested motivations for a high level of scientific literacy sorted under macro- and micro-perspectives (not to be confused with biological macro- and micro-scale), with the macro-view comprising arguments for the well-being of nations or larger communities (such as successful competition on international markets), and the micro-view focusing on individual benefits (such as confidence and competence to deal with science-related issues in their daily lives).

However, a plethora of scientific literacy definitions has been suggested over the years. Shen (1975) differentiates between three types of scientific literacy: practical (knowledge that can be used to help in practical problems); civic (awareness of science that enables participation in democratic processes); and cultural (appreciation of science knowledge as part of human achievement). These were later ordered into a hierarchical structure in which the levels are achieved chronologically by Shamos (1995). He named the levels cultural (where citizens share common references), functional (where citizens are able to converse, read and write in a scientifically coherent way) and true (where citizens know major conceptual schemes, can assess the relevance of these, and appreciate the role of experiments and analytical/deductive reasoning). According to his own analysis, Shamos notes that the 'true' level of scientific literacy is reached by only a small proportion of the population, in practice only the people working in science-related occupations, and thereby titles his work 'the myth of scientific literacy'.

Both DeBoer (2000) and Laugksch (2000) have provided conceptual overviews of scientific literacy and conclude that the term has a wide variety of meanings among scholars. Whether this calls for a more specific definition or better efforts to address all aspects is a difficult question, and DeBoer (2000) states that we should accept that scientific literacy is a broad concept and, as such, should be flexible so it can be adjusted to unique situations and contexts. He also concludes that public understanding of

science is open-ended and ever-changing. Therefore, it is futile to strictly define and assess its status. Nevertheless, he deduced nine distinct scientific literacy goals for science education from previous literature (Table 2.2).

Table 2.2. Scientific literacy goals as comprised by DeBoer (2000).

-
1. Teaching and learning about science as a cultural force in the modern world.
 2. Preparation for the world of work.
 3. Teaching and learning about science that has direct application to everyday living.
 4. Teaching students to be informed citizens.
 5. Learning about science as a particular way of examining the natural world.
 6. Understanding reports and discussions of science that appear in the popular media.
 7. Learning about science for its aesthetic appeal.
 8. Preparing citizens who are sympathetic to science.
 9. Understanding the nature and importance of technology and the relationship between technology and science.
-

This dissertation places specific weight on the fourth and sixth goal although relevance is also found in several of the others, for example number three. DeBoer mainly motivates the sixth goal by democratic principles in the sense that everyone should have a reasonable opportunity to stay informed and offer opinions on scientific issues of societal relevance. The ability to follow scientific media reports has also been linked to scientific literacy by several other authors (e.g. Laugksch, 2000; Maienschein, 1998; Norris & Phillips, 2003).

The concept of *literacy* can be defined as the ability to read and write on the one hand and being knowledgeable, learned and educated on the other. Norris and Phillips (2003) transfer this distinction to scientific literacy and label the two definitions *fundamental* and *derived* senses of scientific literacy, respectively. They argue that published research typically focuses on the derived sense while the fundamental notion is often omitted. They argue that ‘the ability to read and write’, which encompasses far more than just word recognition, is a prerequisite for the derived sense. Rather, interpreting a text correctly also requires the ability to integrate information that is not directly expressed in the words (so-called *extratextual* information) (Norris & Phillips, 2003).

But the scientific literacy framework that is most widely used today is that described by Roberts (2007). He presents a thorough review of the literature concerning scientific literacy and defines two parallel frameworks, or visions. Vision I looks inward at the products and processes of science itself, and is exemplified by the approach in Benchmarks for Science Literacy (AAAS, 1993). In contrast, Vision II concerns situations that students are likely to encounter as citizens (Roberts, 2007). Roberts also notes that we are currently in the midst of a gradual shift from Vision I towards Vision II: *“Vision I, rooted in the products and processes of science, has historically been the starting point for defining scientific literacy, which has then been exemplified by reaching out to situations or contexts in which science can be seen to have a role. Recently, however, an increasing number of voices have stressed the importance of starting with Vision II, that is, with situations, then reaching into science to find what is relevant.”* Thus, an important distinction between Vision I and Vision II is that the ethos of Vision II requires students to develop scientific literacy, or an understanding of scientific inquiry, that is appropriate to situations other than conducting scientific inquiry regardless of their career plans (Roberts, 2007). The scientific knowledge being taught is thereby anchored in a relevant context. Bybee questions the often unstated assumption that students who properly understand scientific concepts will automatically apply this knowledge in problems they encounter as citizens. Instead, he argues, school science programs should clearly and consistently incorporate Vision II into the teaching (Bybee, 2012). More recently, a third vision of scientific literacy has been suggested (Sjöström, Eilks & Zuin, 2016). Influenced by the German term *Bildung*, Vision III incorporates moral, philosophical, existential and political perspectives into science education (Sjöström, 2017).

The connection between evolution and scientific literacy is not new. Catley and Novick (2009) claim that: *“it is impossible to have a scientifically literate public without a widespread understanding of evolutionary principles that allow us to make sense of all facets of the natural world.”* Additionally, Smith (2010b) states that: *“...a working understanding of evolution is simply part of science literacy that is expected of the modern high school graduate.”* Fowler and Zeidler (2010) showed that evolutionary knowledge is crucial for informal reasoning about genetic engineering and also elaborated on how evolutionary misconceptions translate into faulty understanding of genetic engineering. A large-scale international survey concerning acceptance of evolution identified relatively large national differences. Sweden was among the countries with the highest acceptance scores while the United States showed one of the lowest

acceptance rates of evolution. The same study also found that the level of genetic literacy is a powerful predictor of an individual's view on evolution. The authors recommended that evolutionary concepts should be taught from middle school until the end of mandatory education. They also concluded that biomedical advances will be made throughout citizens' lives well after formal education and that the relevance of these advances therefore need to be learned through informal learning settings. However, accomplishing this would be troublesome without a firm evolutionary knowledge basis (Miller, Scott & Okamoto, 2006). The Parliamentary Assembly of the Council of Europe (PACE) adopted a resolution on the importance of evolution education and the dangers of creationism in 2007. Several passages of the resolution emphasize the wide implications of a basic understanding of evolution: *"The teaching of all phenomena concerning evolution as a fundamental scientific theory is therefore crucial to the future of our societies and our democracies. For that reason, it must occupy a central position in the curriculums, and especially in the science syllabuses, as long as, like any other theory, it is able to stand up to thorough scientific scrutiny. Evolution is present everywhere, from medical overprescription of antibiotics that encourages the emergence of resistant bacteria to agricultural overuse of pesticides that causes insect mutations on which pesticides no longer have any effect."* (PACE, 2007).

3. Aims and research questions

The aim of this dissertation is to study the nature of information regarding both antibiotic resistance and natural selection that is conveyed to members of society. The underlying research considered two main matters: the type of communication that has a wide reach in the public realm and what educational standards that must have been accomplished to understand the disseminated information. For this purpose, the results from these studies are interpreted and discussed through certain meanings of scientific literacy. Furthermore, special focus is given to visual modes in explanations, as well as the role and inclusion of threshold concepts. A final aim is to determine the potential benefits of teaching natural selection through visual accounts of antibiotic resistance. This dissertation presents four different studies that answer the following research questions²:

Overall research questions

1. What type of information regarding antibiotic resistance is the Swedish public exposed to through newspapers (Paper I)?
2. To what extent are evolutionary explanations used when antibiotic resistance is communicated through (i) newspapers, (ii) online websites and (iii) biology textbooks (Paper II)?
3. What content with regard to (i) key concepts, (ii) threshold concepts, (iii) misconceptions and (iv) organismal context is conveyed through videos explaining evolution that are accessible through the Internet (Paper III)?
4. Which obstacles and/or opportunities can be discerned in using antibiotic resistance as a context for learning natural selection through animations? (Paper IV)?

² Each research question is divided into subquestions within the appended papers, and these subquestions are presented within respective sections of Chapter 5.

4. Methodology

The four studies underlying this dissertation applied somewhat different methodological strategies. This chapter aims to discuss the choices behind these strategies in light of their advantages and drawbacks. First, the included studies are briefly introduced in order to provide context for the discussion of methodological choices. Content analysis is presented next, and the section includes a description of how the method was modified according to the data sources of the different studies. I then discuss how the group discussions were arranged, transformed into data, and analyzed, which is followed by a description of how the pre-post tests were used in Paper IV. Thereafter, the interactive animation used in Paper IV will be presented, and the chapter concludes with a discussion of the validity and reliability of the chosen methods. For a more detailed account of any particular study, please visit the individual paper.

4.1 Brief presentation of the included studies

In *Paper I*, we sought to characterize the reporting of antibiotic resistance in Swedish newspapers. We were interested in both the total amount of reporting on the subject and how antibiotic resistance was presented with regard to magnitude, causes and risk-reduction measures. Finally, we sought to characterize whether suggested risk-reduction measures are aimed at societal institutions or individual readers (members of the public). A code sheet was developed to analyze reporting in the seven largest daily Swedish newspapers over a three-year period.

Paper II focused specifically on the inclusion of evolutionary explanations in accounts of antibiotic resistance in newspaper reports, online websites and biology textbooks. We used a deductive content analysis to study the extent to which evolutionary explanations were used, what aspects of evolution that were included, as well as the extent of visual support in reports covering antibiotic resistance and compared the results across the aforementioned media.

Paper III concentrated on natural selection rather than antibiotic resistance. A framework based on key concepts and threshold concepts was used to develop a criteria catalogue that was applied as a grid in the content analysis of videos accessible through online streaming sites. The videos were analyzed based on their inclusion of key concepts, threshold concepts, possible misconceptions as well as with regard to what organism(s) that were used as contexts for natural selection. We also noted the length and

explicitly mentioned audiences for the videos. Further analyses sought to identify clusters of variables and videos, respectively, based on the co-occurrence of variables.

In *Paper IV*, we empirically studied the possibility of using antibiotic resistance as a context to teach natural selection to novices. 32 pupils aged 13-14 years were shown a series of animations while they discussed questions in groups. The study was designed to shed light on novice pupils' understanding of the origin of resistance and how this comprehension was influenced by the animations, as well as identify any obstacles and opportunities associated with learning natural selection through animations of antibiotic resistance. Data were collected on both the individual (pre-post tests) and group level (video-taped and transcribed discussions as well as written group assignments).

4.2 Content analysis

The primary method employed in papers I, II and III was quantitative content analysis. This method can be described as *“the systematic, objective, quantitative analysis of message characteristics”* (Neuendorff, 2002) and is therefore well suited for pre-existing and non-modifiable data sources. It is systematic in the sense that it follows a defined procedure, i.e. definition of the unit of analysis, formation of coding scheme and operationalization of variables, deductive application of coding, among others. It is objective in the sense that it should be carefully executed, and replicability is ensured through the use of multiple coders with pre-defined inter-rater reliability coefficients (Krippendorff, 2013). Although this method is most often performed using a quantitative approach, it is also applied in purely qualitative research (Elo & Kyngäs, 2008). Krippendorff (2013) actually questions the distinction between quantitative and qualitative content analysis because *“ultimately, all reading of texts is qualitative, even when certain characteristics of a text are later converted into numbers.”* Furthermore, this method can be applied to all sorts of pre-existing material such as texts, television programs, and sound recordings. Although content analysis was utilized in three of the included papers, the methodology was modified in each study based on the nature of the analyzed material along with the theoretical starting points. (Table 4.1). The following sections will provide an account of how these different approaches were arranged, including sampling procedures, variable-generation and operationalization, the actual coding procedure, data analysis and processing.

Table 4.1. An overview of differences in the content analysis approaches applied in papers I, II and III.

Paper no.	Variable generation	Type of media	Unit of analysis	No. of variables
Paper I	Inductive/ deductive	Text	News articles	15
Paper II	Deductive	Text/Images	News articles, textbooks, websites	6
Paper III	Deductive	Moving images / narration	Videos	38

4.2.1 Samples and contexts

This section will describe the various sampling procedures used for papers I, II and III. The different types of media that were included in the studies are shown in Table 4.2.

Table 4.2. The different types of media and number of units used in the content analyses.

Type of media	Number of units	Used in paper
Newspaper articles	221	Paper I/Paper II
Websites	19	Paper II
Biology textbooks	6	Paper II
Online videos	60	Paper III

We applied newspaper sampling to gain a broad view of the type of information that is being provided to general news consumers without a specific interest in antibiotic resistance. To accomplish this, we focused on the seven largest newspapers in Sweden, which boast a combined circulation of about 1.5 million copies/day. We used the database *Mediearkivet* to identify relevant articles from these newspapers during a three-year period (1 June 2008 – 1 June 2011). We used three keywords to access relevant articles: “antibiotikaresistens” (antibiotic resistance); “resistent bakterier” (resistant bacteria); and MRSA (acronym for methicillin-resistant *Staphylococcus aureus*). This resulted in 335 articles that were then refined according to the following criteria: (1) identical copies were removed; (2) news stories shorter than 35 words were removed; (3) articles in which the story was unrelated to the topic of interest, and only mentioned the keywords in passing, were removed; and (4) cases in which subsections of articles are stored separately were combined into single articles. A subset of

the results from the refinement process was reviewed by the second author to ensure that no relevant articles were excluded by mistake. In the end, the refinement process resulted in a list of 221 articles that were used in the analysis.

The screening of websites was intended to include information that is readily available to both citizens and students. It is important to note that, in the case of online resources, the user always has some degree of motivation as they must actively search for specific content. This distinguishes online media from newspapers, in which news about antibiotic resistance are presented together with various other articles. We used a popular online search engine (www.google.se) and conducted one search for each of the keywords that were used during newspaper sampling. For each keyword, the results on the first page (retrieved 23 Jan 2014) were retained for further analysis. A refinement step, in which non-Swedish results and duplicates were removed, resulted in 19 websites that were then used in the subsequent analysis (cf. Mager, 2012).

Biology textbooks were sampled based on the following characteristics. The only mandatory biology course that includes antibiotic resistance is that in years 7-9 (see Section 2.1.2). In addition, evolution is one of the primary objectives in this course. Although news articles have a wide distribution in society but are only highly accessible for a short amount of time, they will not always reach a large audience. Textbooks, on the other hand, concern a very specific age group and are likely to reach a large portion of this group. For the analysis, we used six textbooks produced by the largest publishers of educational material. These were published in 2011-2012 and designed to match the content of the most recent Swedish curriculum, Lgr11 (The Swedish National Agency For Education, 2011).

The video analyses in Paper III focused strictly on evolution. We were interested in exploring what kind of messages that are conveyed to individuals who use video streaming sites to access explanations of biological evolution. In the sampling of videos, we therefore utilized video streaming sites that were open to the public (Google VideoTM and YouTubeTM). Where search results led to other educational platforms (e.g. Khan Academy), subsequent searches were made on these resulting websites (cf. Ortiz-Cordova et al., 2015). In cases in which the streaming site included a function of “related/suggested videos”, these were also considered for inclusion (Lei et al., 2015). Additional targeted searches were executed on selected platforms (ed.ted.com, evolutionfilmfestival.org, Cassiopeia Project, HHMI Biointeractive, Annenberg Learner and Encyclopedia Britannica) that did not emerge through the main procedure. The flexible search strategy is also reflected in the search strings that were

used, which consisted of “evolution” and/or “natural selection” alone or together with terms such as “animation”, “visualization” and “explanation”. The resulting videos were considered for inclusion if they adhered to the following inclusion criteria: (1) the video presents biological evolution (and does not, for example, show the evolution of transistors); (2) the video does not explicitly promote a creationist agenda; and (3) the video adopts an explanatory approach towards evolution. This third criterion was applied generously, and, as such, the analysis included not only videos with titles such as “how evolution works” or “evolution explained”, but also videos with more neutral titles that used narration or images to convey information about evolutionary mechanisms. The final video sample included 60 videos.

4.2.2 Variable generation

The variables used in papers II and III were mostly deduced from literature whereas the variables applied in Paper I were obtained through a combination of inductive and deductive approaches. In all of the studies, the variables were operationalized in a dichotomous manner (present/non-present), although the design did not allow for registering multiple occurrences of an individual variable within one unit of analysis. All of the variables utilized in the individual papers are displayed in Table 4.3.

The variables used in Papers II and III were deduced from the rich body of literature regarding conceptual elements in evolution education (e.g. Gregory, 2009; Smith, 2010b). For Paper II, the variables were restricted to only those that are most relevant to bacterial evolution of antibiotic resistance. In contrast to Paper II, which focused on evolutionary explanations to antibiotic resistance, Paper III sought to provide a broader picture of evolutionary explanations. Thus, this paper also extended into fields such as threshold concepts, while still focusing on natural selection (Meyer & Land, 2005; Ross et al., 2010b). As a result, the selection of variables for this study was a rigorous process that involved a group of senior researchers from varying fields, such as science education, linguistics and biochemistry. The resulting compilation of variables was strongly related to the work of Tibell and Harms (2017). Several rounds of variable selection from literature sources were performed until the group of researchers unanimously agreed on a suitable compilation.

In Paper I, we wanted to explore communication about antibiotic resistance, an area that has not been granted as much research as communication about evolution. There is one previous media study on antibiotic resistance that is based on magnitude, causes and risk-reduction measures (Desilva, Muskavitch & Roche, 2004). This study, along with

related studies concerning other infectious diseases (Dudo, 2007; Roche, 2003; Evensen, 2012), helped us construct a number of variables. However, in order to ensure that we captured valuable information that was possibly missed by the related studies on other diseases, we performed an inductive coding procedure on all articles published in the five months preceding June 2011. Every mention of causes and risk-reduction measures in these studies were noted in an open coding step (cf. Elo & Kyngäs, 2008) and later structured into defined variables that were applied to the whole dataset. In addition, we created a generic variable under each category (e.g. “other causes”) in order to capture less frequently appearing alternatives.

Table 4.3. Labels of all the variables included in papers I, II and III. For details and operationalization of the variables, please visit the individual papers.

Paper I	Paper II	Paper III	
<i>Magnitude</i>	1 Biotic potential	1 Origin of variation	20 Shorter than seconds
1 Non-numerical descriptions	2 Differential survival	2 Individual variation	21 Seconds
2 Number of infections	3 Individual variation	3 Differential fitness	22 Minutes/hours
3 Number of deaths	4 Origin of variation	4 Inherited variation	23 Days
<i>Causes</i>	5 Inherited variation	5 Limited resources	24 Years
4 Unnecessary prescription	6 Change in population	6 Limited survival	25 Generations
5 Impaired health care hygiene/logistics		7 Change in population	26 Randomness
6 Tourism		8 Speciation	27 Probability
7 Livestock/agriculture		9 Number of traits	28 Need

8 Transport/ groceries	10 Negative mutations	29 Anthropomorphism
9 Other causes	11 Extinction	30 Only good traits are inherited
<i>Societal measures</i>	12 Molecule	31 Natural selection as an event
10 Lower prescription rate	13 Genome	32 Acquired traits are inherited
11 Improved health care hygiene/ logistics	14 Individual	33 Essentialism
12 New antibiotics	15 Population	34 Bacterial evolution
13 Other societal measures	16 Species	35 Animal evolution
<i>Individual measures</i>	17 Gene-protein	36 Human evolution
14 Rational expectations on receiving antibiotics	18 Protein-cellular function	37 Plant evolution
15 Other individual measures	19 Cellular function- individual characteristics	38 Symbolic evolution

4.2.3 Coding and analysis

The coding procedure differed between the various studies and source materials. For the newspaper analysis in Paper I, the first author coded all of the articles according to our determined variables. The second author then coded 16 % of the total material, which was used to calculate reliability (cf. Evensen & Clarke, 2012). For the newspaper analysis in Paper II, the first author coded all articles followed by the second author initially coding all of the articles found to include any evolutionary explanations and an additional 10 % of the total sample. The complete sample of textbooks and websites were coded by both authors of Paper II.

In Paper III, a total of 60 videos were coded. The first and second authors each analyzed a subset of the videos that included an overlapping sample of 33 videos (used to calculate reliability). Thus, neither author coded the whole video sample. Since the videos are multimodal (containing both text and images), both of these modes were taken into account in the coding procedure. A variable was coded as present if it was represented either visually or orally (or both). Only explicit information was considered, but given that the operationalization of the variables was formulated in words, there was room for a certain amount of subjectivity when judging the purely visual material.

Coding discrepancies were also handled slightly differently in each of the studies. In Papers I and II, discrepancies were discussed and consensus decisions were reached. In contrast, the more subjective nature of the visual data in Paper III sometimes made exact rulings impossible. Therefore discrepancies in these data (one judges a variable to be present while the other considers it absent) were counted as if the variable was present. Thus, it is important to note that a degree of overestimation in the frequency of some variables is possible.

The data underlying all of the content analyses were analyzed for patterns and frequency distributions using descriptive statistics in SPSS® statistical software (version 19.0 for Papers I and II and version 24 for Paper III, IBM Corporation, Armonk, NY). The results were then interpreted in light of the respective underlying theoretical assumptions. To illustrate the found patterns, we also reported qualitative excerpts from the texts in Paper I and Paper II.

The results in Paper III were further analyzed using explorative cluster analysis (Everitt et al., 2011). This method identifies groups/clusters of objects or variables based on their similarities (with respect to a specific similarity matrix). We employed a hierarchical agglomerative clustering approach, meaning that the variables were ordered into clusters during a process of successive fusions based on a chosen similarity measure (Everitt et al., 2011). With individual variables as the starting point, clusters were formed sequentially during the analysis, as shown in Fig. 4.1. The fusion process is based on an algorithm that iteratively combines clusters based on the similarity measure until there is only one cluster. Two consecutive analyses were performed based on: (i) variables and (ii) videos (cf. Islam et al., 2014).

Initial screening and selection of variables is a crucial step in cluster analysis. This is because variables that provide little or no information to the dataset might add noise that masks underlying patterns (Hamid et al., 2015). In our case, 16 variables for which 90 % of the data were identical (i.e. the

relative presence of these variables was 10 % or lower, resp. 90 % or higher) were removed prior to the analyses (cf. Hamid et al., 2015).

The most commonly used similarity measure in cluster analyses is Euclidian distance. However, this measure is not appropriate for binary variables (Hamid et al., 2015). Therefore, in Paper III, two different similarity measures were used for the variables and videos, respectively. For the variables, we used Yule’s Q as a measure of association because it considers both positive and negative matches informative, as opposed to, for example, the Jaccard coefficient (Islam et al., 2014). We used the simple matching coefficient (SMC) for the clustering of videos as both the presence and absence of conveyed features can be considered informative in this approach (Everitt et al., 2011).

Fig. 4.1. A dendrogram that illustrates the fusion of clusters during the hierarchical agglomerative clustering procedure. The horizontal axis indicates the distances at which clusters were combined. The four resulting variable clusters are shown by rectangles.

4.3 Group discussions

In Paper IV, we used a series of animations (detailed in Section 4.5) to introduce novice pupils to the subject of evolution with bacterial resistance to antibiotics as a context. We wanted to explore whether it is possible to introduce evolutionary thinking within the timeframe of a few hours as well as investigate which qualities (both potential benefits and obstacles) could be discerned from using bacteria as a context for understanding natural selection. Given the exploratory approach of the study, we chose to let the pupils work together with the animation in groups of 3-5 (total $n=32$) while engaging with group questions. The whole sequence was recorded, videotaped and later transcribed (verbatim).

The questions that were discussed in the groups were divided so that three items concerned the ability to make evolutionary predictions concerning bacterial resistance to antibiotics, two items concerned explanations of the origin of resistance and one item concerned evaluation of the animations. The questions were handed to the pupils on separate sheets one after another. Thus, they did not have access to the upcoming question before responding to, and handing in, the previous one. The role of the researchers was to administer the questions and clarify any ambiguities that arose. The time that it took the groups to complete the interaction ranged from 47 to 72 minutes, and provided a total video footage of 7 hours and 9 minutes that was transcribed and analyzed.

4.3.1 Transcription

A total of eight groups, each consisting of 3-5 pupils, participated in the fourth study. One group consisted of pupils who did not want to be videotaped or recorded; thus, only the written collective answers and the pre-post tests were gathered for this group. The discussions of the remaining seven groups were transcribed from the videos using Aegisub software (<http://www.aegisub.org>). The transcription of group discussions involves movement between two forms of medium, oral and written, and will therefore inevitably entail some degree of interpretation. As this may affect accuracy, we transcribed the videotaped discussions in their entirety to ensure that nothing was left out. Furthermore, the resulting transcripts were continuously checked against the video recordings to ensure accuracy (Gibbs, 2007). The software allowed the resulting transcripts to be inserted as subtitles to the videos, which facilitated the accuracy check, as well as exported into text documents that were used in the subsequent analysis.

4.3.2 Analysis of transcripts

Qualitative text analysis generally involves several tasks, such as the discovery/construction of codes and themes, the winnowing of these themes to a manageable number, as well as the linking of the identified themes to theoretical models (Ryan & Bernard, 2003). The transcripts from the video-recordings were subsequently transferred into MaxQDA[®] software (Verbi Software, Berlin, Germany) after which they were independently analyzed in several steps. First, all of the authors read the complete transcripts in an attempt to get a sense for the material. This step (called pawing) involves the initial identification of key components and patterns (Ryan & Bernard, 2003). Three of the authors then independently conducted an inductive coding procedure focusing on pupils' statements regarding the subject matter (antibiotic resistance and/or evolution) and how they referred to the animation (Graneheim & Lundman, 2004; Robson, 2011). During this step, codes were inductively created and labeled with a memo. These codes were then compared to one another to identify similarities and differences for subsequent sorting into sub-categories. The coding results from the three authors were later merged, including several rounds of further processing and categorization based on the research questions, until an acceptable categorization scheme had been established (Robson, 2011).

4.4 Pre-post tests

In addition to the group discussions, we also used pre-post tests in the research presented in Paper IV. Pre-post tests are usually used in social- and behavioral sciences to measure the effect of a treatment or intervention (Robson, 2011). The pupils in our study were novices to evolution and could hardly be expected to develop a mature understanding of the subject as a whole (e.g. Andrews et al., 2011). But as we were interested in the feasibility of introducing evolutionary content in a bacterial context, the pre-post test could provide information on the direction of a group's progress as well as match individual achievements to their respective group.

The test design was considerably smaller in comparison to commonly used pre-post tests. The pretest consisted of a single multiple-choice item that was provided to all pupils after a common introduction. The item reflected the question that was included in the 2014 national test (discussed in Section 2.1.1) (Lind Pantzare et al. 2014). Two of the response options corresponded to two common misunderstandings of how resistance develops: that bacteria actively develop resistance due to need; and that resistance occurs in humans rather than in bacteria (Table 4.4). After the intervention and group discussions, the pupils received the same question in

return and had the option to change their initial response. They were also asked to provide motivation for their decision regardless of whether they changed or maintained the response. A McNemar test was conducted to determine whether the potential increase in the proportion of correct responses between the pre- and post-tests was statistically significant. After this, the pupils were also asked to respond to an open-response item that had been designed to explore the possible transfer of knowledge from a bacterial to a mammalian context. This question was included to determine which evolutionary mechanisms the pupils choose to include when moving from a bacterial to a mammalian context. The responses to this question were imported into MaxQDA software and coded based on their adherence to origin of variation, inheritance of traits and selection of individuals with beneficial traits (Godfrey-Smith, 2007; Tibell & Harms, 2017).

Table 4.4. The questions included in the pre-post test in Paper IV.

Pre- (and post-*) exercise (individual, closed-response)	Which of the following best describes how bacteria develop resistance to antibiotics? A. Bacteria always try to develop resistance when they are exposed to antibiotics. So, those that succeed will be protected the next time. B. Bacteria can become resistant if they infect a person who is already resistant because he or she has used too much antibiotics previously. C. Bacteria that have become resistant through random mutations can survive and spread when antibiotics kill non-resistant bacteria (correct option). D. Bacteria that have made a person ill will develop resistance if the person does not finish his or her course of treatment.
Post-exercise (individual, open-response)	Earlier generations of giraffes did not have as long necks as those found today. Try to describe similarities and differences between the neck-development of giraffes and bacterial development of antibiotic resistance.

*This item was presented to the pupils again after the exercise, and then they were asked to justify their decision to change/not change their initial response.

4.5 Interactive animation

The interactive animation used in Paper IV was, technically, a series of seven linked animations (termed A-G, see Fig. 4.2) that the pupils navigated through. After part C, the pupils were able to choose if they wanted to access part D or E first before continuing to part F. The animation depicted a

laboratory environment in which the pupils cultivated virtual bacteria on agar plates with different types of antibiotic coating. During the course of the animations, pupils were given the opportunity to learn about generation times, sizes and the chance of mutations occurring in bacterial cells. A predict-observe-explain sequence was also incorporated into the animations. The animation was created for the purpose of this study and subject content that was novel to the pupils (such as DNA, mutations etc.) was carefully introduced in the animations.

Fig. 4.2. Overall structure of the animations utilized in Paper IV.

Screenshots from the animations are shown in Figs. 4.3, 4.4, 4.5 and 4.6. The assay in part G involves three agar plates. One agar plate contains no antibiotic and the remaining two agar plates both contain a unique antibiotic. Bacterial growth on the three plates after incubation is shown in Fig. 4.6.

Fig. 4.3. Screenshot of the laboratory context (part A).

Fig. 4.4. Screenshot of a schematic bacterium (part C), with options to proceed to either part D or E.

Fig. 4.5. Screenshot of a test tube and the three experimental agar plates (part G).

Fig. 4.6. Screenshot of bacterial colonies growing on three plates after incubation (part G).

Throughout the animations, narration was provided either through audio or textual cues, but these two did not overlap since this has been found to cause higher cognitive load due to the modality principle (e.g. Moreno & Mayer, 1999). We also adhered to the spatial and temporal contiguity principles by mentioning visual content in order of appearance and placing labels and printed words near the corresponding graphics (Mayer, 2011).

4.6 Validity and reliability

The concepts of validity and reliability are a crucial part of any research endeavor. Validity refers to how well a test or study measures what it is supposed to measure, whereas reliability refers to the extent to which a test produces stable and consistent results (Robson, 2011). On a general note, members of the research community have scrutinized all of the papers included in this dissertation during the peer-review process and iterative revisions have been performed to strengthen the validity and trustworthiness of the findings. However, several additional detailed aspects of validity and reliability are discussed in this section.

In terms of content analysis, one of the most important aspects of reliability is inter-rater reliability. This is calculated to make sure that every rater interprets the variables in the same way and provides consistent results. A number of coefficients are available for calculating inter-rater reliability, for example, Scott's Pi, Cohen's Kappa, Fleiss's K and Krippendorff's Alpha (Neuendorf, 2002). We used Krippendorff's alpha in all of the included studies so that inter-rater reliability could be presented consistently regardless of number of observers, level(s) of measurement, sample size and the presence of missing data (Hayes & Krippendorff, 2007). The calculations were performed using the KALPHA macro, which is designed for SPSS® software (downloaded from <http://www.afhayes.com/spss-sas-and-mplus-macros-and-code.html>). We chose to set the reliability standard to 0.7 in all of our studies because this is the level that is normally used in exploratory research.

The results of the reliability calculations demonstrate that all of the variables in Paper II adhere to our pre-set reliability standard. In Paper I, two variables initially fell slightly below our preset cut-off value. Following a discussion of the discrepancies, we decided to extend the sample and analyze more articles to ensure reliability for these variables as well. In Paper III, a majority of the variables reached the reliability threshold, but several still fell below this cut-off. This implicates that findings regarding these variables need to be interpreted with more caution than those relating to variables with higher reliability values. However, there may be several reasons that certain variables in this specific paper showed lower alpha

values. As the analysis concerned visual material, the communication of certain abstract constructs is not as obvious as when it is performed with words. For example, when determining if randomness is conveyed in words, researchers essentially only listen for any mention of this word. However, it is more difficult to determine if randomness has been conveyed by visual means, and any analysis inevitably demands a certain degree of subjective interpretation. These issues were discussed prior to the analysis, but they may nevertheless still pose problems. Potentially, a lower threshold value should have been set in this case. Furthermore, variables that are either present in the absolute majority or only sporadically in the material (thus exhibiting low variation) require more agreement in order to be approved by Krippendorff's alpha. This is well illustrated by looking at the percentage agreement between the coders. For example, one coder registered that one video (out of the total 60) represented time in days. This was not noticed by the other coder, and led to a single disagreement in the reliability sample (from a total of 66 decisions) and a percentage agreement of 97 % regarding this variable. However, the Krippendorff's alpha value for this variable is zero. The same was noticed for the majority of low-reliability variables (see exact numbers in Paper III). We did not exclude these variables from subsequent analyses based on this value alone, as other researchers have suggested that additional measures, such as the magnitude and relative proportion of the disagreements, should be considered to establish a meaningful level of reliability (Milne & Adler, 1999).

An important validity measure in content analyses is the construct of the coding schemes (Krippendorff, 2013, Potter, 1999), which can be constructed in two different ways: deductively or theory-driven, as was the case in papers II and III and partly in Paper I; or inductively or theory-generating, which characterizes some of the variables in Paper I. Under a deductive approach, variables are deduced from existing theory, thereby raising the validity of the construct. The variables in Paper III were compiled in a process that involved experts from diverse areas - biology, biology education, molecular biology, biomedicine, pedagogy and linguistics - to further ensure the validity of these variables. In contrast, Paper I applied an inductive approach, i.e. the creation of new theories based on patterns that are identified from the underlying data, by screening newspapers for any mention of the causes and risk-reduction measures for antibiotic resistance over a five-month period to ensure that the variables were well suited for the Swedish context. (cf. Elo & Kyngäs, 2008). These were later categorized and operationalized into variables that were used in the main analysis. To further ensure that the instrument captured the full range of possible explanations, generic variables were generated for each

category (e.g. “other causes” or “other societal measures”). This approach allowed us to capture any rare and/or unforeseeable mentions of antibiotic resistance during the study.

Several considerations should be highlighted with regard to the study presented in Paper IV, which had a more flexible and qualitative approach than the other papers forming part of this dissertation. The standard definitions of validity and reliability may be hard to apply directly to qualitative research, which is generally performed on a smaller scale. Thus, a more pragmatic term could be the assessment of trustworthiness (Robson, 2002). A way to ensure trustworthiness is to strive for transparency. For this reason, we included excerpts from transcripts as well as descriptions of the contexts, participants, data collection process and analyses to support our observations (Graneheim & Lundman, 2004). During the transcript analysis, we constructed memos to avoid code drifting and to keep the code definitions constant (Gibbs, 2007). To minimize single-researcher bias, we performed the initial analyses in parallel while all authors agreed with the merging and categorizing of the codes and themes. Furthermore, the collection of several different kinds of data (discussion transcripts, written group responses and individual responses) is a form of triangulation that increases the validity of findings. Although the proportion of correct answers to the closed-response item significantly increased after the educational exercise, this should not be interpreted as clear evidence that learning had occurred given the relatively small sample of participants as well as the absence of complementary questions. However, it shows a clear tendency and is encouraging from the previously mentioned triangulation standpoint.

Due to the almost exponential increase in online media, the concerns associated with studying print newspapers (Paper I and parts of Paper II) seem to rise with every passing year (e.g. Schäfer, 2012). At the time when the studies presented in Papers I and II were performed (years 2008-2011), the use of newspapers as a study object was justified for three main reasons. First, print newspapers, as compared to media found online, provide a permanent and accessible data source. Second, it was possible to compare results with several studies that focused on newspapers in other countries or contexts (e.g. Desilva, Muskavitch & Roche, 2004; Evensen & Clarke, 2012). Third, according to a nation-wide survey performed in 2011, Swedes ranked newspapers as being more credible than Internet news. Furthermore, 61 % of the Swedish population read print newspapers at least five days a week in comparison to 12 % who read newspapers online (Weibull, Oscarsson & Bergström, 2012). We can expect these percentages to be different today, and, as such, it is harder to justify using newspapers as a

source with every passing year. Therefore, print newspapers will be an increasing potential limitation in future studies that aim to measure aspects of public communication.

5. Results

The following chapter presents the results from the individual papers included in this dissertation. The chapter concludes with a summary of the results in light of the posed research questions. For a full report of the results, please visit the individual papers.

5.1 Paper I

'Is it my responsibility or theirs? Risk communication about antibiotic resistance in the Swedish daily press.'

In this study, we wanted to characterize the Swedish news reporting of antibiotic resistance and relate the reporting to different risk communication models. More specifically, we pursued three research questions:

1. To what degree is bacterial resistance to antibiotics reported in Swedish newspapers?
2. To what extent and through which examples is antibiotic resistance presented in light of its (a) magnitude, (b) causes and (c) risk-reduction measures?
3. Are suggested risk-reduction measures aimed at societal institutions or individuals?

The results are based on 221 news articles, which is the total number of unique articles that cover antibiotic resistance published in the seven largest Swedish newspapers during a three-year period (2008-2011). Fig 5.1 shows the frequencies at which articles contained information on each of the four main categories. The majority of the articles provided some description or explanation related to magnitude, cause and/or societal efficacy measures, yet less than a quarter of the articles reported personal efficacy measures.

Fig. 5.1. Frequency of news articles reporting magnitude, causes and risk-reduction measures (societal and individual) both in the sample used in code sheet development (n=27) and the complete dataset (n=221).

Magnitude, or the size/extent of the risk posed by antibiotic resistance, was mainly reported through qualitative statements (such as ‘a rising problem’) rather than quantitative estimates. This provides lower contextual precision and, unlike numerical information, allows each reader to make their own interpretation. The most frequently reported cause for antibiotic resistance was unnecessary prescription, which was followed by impaired healthcare hygiene. These reflect two unique causes, as a high prescription rate drives natural selection and thus creates more resistant bacteria, whereas impaired hygiene or logistics in healthcare provide a way for these bacteria to spread outside of their host. Sound reporting of causes not only forms the basis for relevant counter-measures, but also affects risk perception. For example, self-explanatory risks are perceived as smaller than those that are poorly understood (Covello et al., 2001).

Regarding counter-measures, the reporting demonstrated a clear tendency of focusing on the responsibility of societal institutions, such as the interplay between politicians, non-governmental organizations and medical practitioners, in reducing the prescription rate. Other commonly reported societal measures included improved healthcare hygiene/logistics (such as staff hygiene routines or the ability to isolate infected patients) and the invention of new antibiotics. The only repeated individual measure was rational expectations for receiving antibiotics when visiting the physician. The importance of completing a round of treatment after prescription was

only reported in a single article, a surprisingly low result in comparison to North American newspapers, which mention this in 10 % of the news stories (Desilva, Muskavitch & Roche, 2004). Moreover, important facts such as antibiotics being ineffective against viruses are rarely mentioned in Swedish print newspapers, which is again in contrast with reporting in North America.

Taken together, the reporting of antibiotic resistance in Sweden is characterized by several underrepresented topics. Among these are facts that could help the public fathom the risk of antibiotic resistance and advice for useful individual counter-measures. For example, the two most important facts about antibiotic resistance for the public, namely, that antibiotics are useless against viral infections and that it is crucial to complete the entire course of treatment, were both mentioned in Swedish daily newspapers to a considerably lower extent than in comparable data from other countries. Based on theories of risk perception, we suggest that Swedish newspapers should also provide more information on the evolutionary background of antibiotic resistance. This could have both explanatory and motivational functions in helping the public understand how resistant bacteria develop and spread.

5.2 Paper II

'Evolutionary Explanations for Antibiotic Resistance in Daily Press, Online Websites and Biology Textbooks in Sweden.'

In this study, we wanted to assess whether evolutionary explanations were being used in the communication of antibiotic resistance in different media. Three different media were chosen to provide an extensive view of what information the Swedish public may encounter. The analysis was based on biology textbooks (n=6), newspaper articles (n=221), and websites reached through a common search engine (n=19). The research questions addressed in this study were:

1. To what extent are evolutionary explanations for antibiotic resistance reported in Swedish daily newspapers, biology textbooks and online websites?
2. What evolutionary aspects are used/not used to explain antibiotic resistance in Swedish daily newspapers, biology textbooks and online websites?
3. To what extent is there visual support for evolutionary explanations of antibiotic resistance in Swedish daily newspapers, biology textbooks and online websites?

4. Is there a difference in how Swedish daily newspapers, biology textbooks and online websites use evolutionary concepts to explain antibiotic resistance?

We scrutinized prior evolution education research with a focus on bacterial resistance to antibiotics to compile a coding scheme comprising six variables that capture the principles of how antibiotic resistance evolves. The overall results from the analysis are summarized in Table 5.1.

Table 5.1. Evolutionary concepts reported in newspaper articles, textbooks and online websites. The first number indicates the total number of mentions, and the percentage of mentions within the dataset is given in parentheses.

	Biotic potential	Differential survival	Individual variation	Origin of variation	Inherited variation	Change in population
News-papers (<i>n</i> =221)	5 (2.3 %)	11 (5.0 %)	7 (3.2 %)	6 (2.7 %)	8 (3.6 %)	2 (0.9 %)
Textbooks (<i>n</i> =6)	1 (17 %)	3 (50 %)	2 (33 %)	2 (33 %)	3 (50 %)	1 (17 %)
Websites (<i>n</i> =19)	0 (0 %)	2 (11 %)	2 (11 %)	2 (11 %)	5 (26 %)	3 (16 %)
<i>Reliability^a</i>	<i>0.84</i>	<i>0.92</i>	<i>0.94</i>	<i>0.94</i>	<i>0.85</i>	<i>0.90</i>

a. The presented reliability scores are Krippendorff's alpha coefficients

As seen in the table, evolutionary accounts were rarely presented in any of the three data sources, particularly in newspapers. All of the concepts were scarcely reported and there were no newspaper articles that included all six concepts. The biology textbooks are based on a curriculum that includes both evolution and antibiotic resistance, and this would suggest that they cover the subject more extensively. Surprisingly, only one of the commonly used textbooks covered all of the concepts and one did not mention any of them. For the websites, 13 out of 19 did not contain any evolutionary aspects of antibiotic resistance. Two pages, one belonging to a company in

the healthcare industry and one belonging to Wikipedia, covered all of the concepts except biotic potential.

Notably, no visual references to the evolution of bacterial resistance were found in either the textbooks or the websites. Two unique images were found in the sample of news articles collected over three years. Both of these depicted a step-like process with a bacterial population before, during and after exposure to antibiotics. One of these images included all of the concepts except origin of variation while the other included inherited variation and differential survival.

In conclusion, the results from this study indicate that three of the most significant public communication channels, including educational material, do not support an understanding of the factors that underlie antibiotic resistance and form the basis for recommended counter-measures. This could well impact both citizens' acceptance of, and adherence to, recommendations working to reduce the spread of antibiotic resistance.

5.3 Paper III

'A conceptual characterization of online videos explaining natural selection.'

In resemblance to Paper I, this study also employed an exploratory approach, but focused on natural selection rather than antibiotic resistance. Another difference is that videos, rather than news articles, were studied. We used a framework based on evolutionary key concepts and threshold concepts to assert how natural selection was being conveyed through online video streaming sites. The following research questions were pursued:

1. What content with regard to specified (a) key concepts, (b) threshold concepts and (c) misconceptions associated with natural selection is conveyed by videos on the Internet purporting to explain evolution?
2. What organismal contexts are used to illustrate natural selection in videos on the Internet?
3. What patterns with regard to co-occurrence of the identified content can be distinguished in the sampled videos?

The analyzed sample was collected through online video-streaming sites and consisted of 60 videos purporting to explain evolution. A criteria catalogue consisting of 38 variables was used as a grid in the content analysis (Table 5.2). A general view of the findings is presented in Fig. 5.2, with the relative presence of each variable marked as a percentage of the total. For a full list

of frequencies, reliability scores and operationalization of each variable, see the appended paper.

Table 5.2. Variables included in the criteria catalogue used in Paper III.

KEY CONCEPTS	THRESHOLD CONCEPTS	MISCONCEPTIONS
Variation	Spatial scale	28 Need
1 Origin of variation	12 Molecule	29 Anthropomorphism
2 Individual variation	13 Genome	30 Only good traits are inherited
3 Differential fitness	14 Individual	31 Natural selection as an event
	15 Population	32 Acquired traits are inherited
Inheritance	16 Species	33 Essentialism
4 Inherited variation		
	Transition between organizational levels	ORGANISMAL CONTEXT
Selection	17 Gene-protein	34 Bacterial evolution
5 Limited resources	18 Protein-cellular function	35 Animal evolution
6 Limited survival	19 Cellular function-individual characteristics	36 Human evolution
7 Change in population		37 Plant evolution
8 Speciation		38 Symbolic evolution
	Temporal scale	
Additional variables	20 Shorter than seconds	
9 Number of traits	21 Seconds	
10 Negative mutations	22 Minutes/hours	
11 Extinction	23 Days	
	24 Years	
	25 Generations	
	Randomness	
	26 Randomness	
	Probability	
	27 Probability

Fig. 5.2. Relative frequency of the 38 variables (see Table 5.2) in the videos (n=60).

In addition to the analysis of relative frequencies, we noted the length and explicitly mentioned intended audiences of each video. Moreover, a cluster analysis consisting of two parts was performed to assess the co-occurrence patterns of the variables. The first of these explored relations between the variables and the second explored groups of videos. Both analyses yielded four-cluster solutions as the most feasible. These are presented in Tables 5.3 and 5.4.

Table 5.3. Results from the variable-based clustering in Paper III.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
<i>Key concepts</i>	- Individual variation - Inherited variation - Differential fitness - Limited survival - Change in population - Speciation	- Origin of variation	- Limited resources - Extinction	
<i>Level(s) of organization (space)</i>	- Individual - Population	- Molecule - Genome - Cell to individual	- Species	
<i>Level(s) of organization (time)</i>	- Generations	- Years		
<i>Randomness/Probability</i>	- Probability	-Randomness		
<i>Organismal context</i>		- Humans	- Animals	- Bacteria

Table 5.4. Results from the video-based clustering in Paper III, showing variables that appear in 50 % or more of the included videos.

	Cluster 1 (n=35)	Cluster 2 (n=20)	Cluster 3 (n=4)	Cluster 4 (n=1)
<i>Key concepts</i>			- Origin of variation	- Origin of variation
		- Individual variation	- Individual variation	- Individual variation
		- Inherited variation	- Inherited variation	
		- Differential fitness	- Differential fitness	
		- Limited survival	- Limited survival	- Change in population
		- Change in population	- Change in population	
			- Speciation	
<i>Level(s) of organization (space)</i>			- Molecule	- Molecule
			- Genome	- Genome
			- Cell to individual	- Gene to protein
	- Individual	- Individual	- Individual	- Cell to individual
		- Population	- Population	- Individual
			- Species	- Days
<i>Level(s) of organization (time)</i>				- Years
		- Years	- Years	
		- Generations	- Generations	
<i>Randomness/Probability</i>			- Randomness	- Randomness
		- Probability		- Probability
<i>Organismal context</i>	- Animals	- Animals	- Animals	
			- Humans	
				- Bacteria

The cluster tables and Fig. 5.2 demonstrate both that only a few of the sampled videos presented many of the included variables and that there was large variation with regard to how often the variables are presented across the videos. In the variable-based clustering, a group of key concepts comprising *individual variation*, *inherited variation*, *differential fitness*, *limited survival*, *change in population* and *speciation* were found together. The same cluster included the threshold concept *probability* and organizational levels of *generations* or *individual/populations*. However, *origin of variation* was found in a separate cluster together with *randomness*

and smaller spatial scales (such as *genomic* level). The four clusters resulting from the video-based clustering were unevenly distributed with the largest two clusters comprising 55 of the 60 videos in total. While the second largest video-cluster contained most of the key concepts grouped above as well as probability - origin of variation and randomness were only prevalent in the smaller clusters. A fifth (20 %) of the included videos did not convey any of the most important key concepts (variables 1-8). In summary, underrepresented variables across categories seem to be related. Thus, small temporal and spatial scales, origin of variation and randomness generally co-occurred although they were expressed less frequently than probabilistic reasoning on, for example, differential fitness manifesting on the individual or population level.

The variables associated with threshold concepts were conveyed to very different extent across the videos. This was especially noticeable for levels of organization in space and time. Spatially, most videos showed phenomena at both the individual and population levels, yet events occurring on the genomic or molecular levels were rarely shown. The same pattern was even stronger for temporal scales, as phenomena were almost exclusively conveyed in years or generations and hardly ever in smaller units (*days* and *shorter than seconds* in one respectively). Probability and randomness were explicitly conveyed in 32 % and 23 % of the videos, respectively, and both were more often represented in text or through narration rather than with visual modes.

Misconceptions were included in 20 % of the sampled videos, with the most common incorrect explanation being that variation occurs in response to need. The second most common misconception was that only beneficial traits are inherited. As a result, individual misconceptions were conveyed relatively rarely (>10 %), and were not part of the cluster analyses. However, a post-analysis check showed that the vast majority of misconceptions were included in video cluster 1 (see Table 5.4), whereas none were included in clusters 3 or 4. With regard to organismal context, the majority (70 %) of the videos showed natural selection happening in animals (excluding humans), followed by humans (25 %), bacteria (18 %), symbolic organisms (10 %) and plants (8 %).

5.4 Paper IV

'Insights from introducing natural selection to novices using animations of antibiotic resistance.'

The fourth study included in this dissertation aimed to move beyond a theoretical account of the potential benefits of conjoining evolution with antibiotic resistance by performing tests in a classroom environment. Another aim was to partly reverse the order of the two topics. Instead of enabling an understanding of antibiotic resistance through evolutionary explanations, we sought to explore the benefits of using antibiotic resistance as a context in which to learn evolution, specifically natural selection. We wanted to explore the possibilities of using antibiotic resistance, presented through a series of animations, in the very beginning of evolution education. Three research questions were pursued:

1. What characterizes novice pupils' understanding of the origin of resistance, and how is their understanding affected by an interactive animation and accompanying exercise?
2. What obstacles and/or opportunities can be discerned for teaching the evolution of antibiotic resistance to novice pupils through a series of interactive animations in terms of (a) the origin of resistance, and (b) the ability to make predictions?
3. What evolutionary aspects do the pupils choose to include when asked to transfer reasoning from a bacterial to a mammalian context?

We recruited 32 pupils between the ages of 13-14 years and who had no previous education in evolution for this study. The general design of the study is shown in Fig. 5.3.

Fig. 5.3. Overview of the study design in Paper IV.

After a common introduction, all of the pupils replied to a closed-response item. Following this, they interacted with animations (detailed in Section 4.5) that were divided into seven parts (termed A-G). They were given the

first group question before part G, and after responding they could progress to the final animation. After finishing the animations, they were handed the remaining group questions sequentially (i.e. they could not see the next question before handing in the response to the previous one). During these questions, the pupils had the opportunity to go back and revisit any part of the animations. After the group exercise finished, all of the pupils were asked to reconsider the initial closed item and were allowed to either revise or retain their response. They were asked to justify their decision in writing regardless of whether they decided to revise or retain their initial answer. To finalize the study process, all of the pupils were asked to respond to an individual open-response item, which asked them to compare the similarities and differences between the development of bacterial resistance to antibiotics and giraffes' development of longer necks. An overview of all of the posed questions is displayed in Table 5.5.

Table 5.5. The questions included in Paper IV.

Pre- (and post-*) exercise (individual, closed- response)	<p>Which of the following best describes how bacteria develop resistance to antibiotics?</p> <ul style="list-style-type: none"> A. Bacteria always try to develop resistance when they are exposed to antibiotics. So, those that succeed will be protected the next time. B. Bacteria can become resistant if they infect a person who is already resistant because he or she has used too much antibiotics previously. C. Bacteria that have become resistant through random mutations can survive and spread when antibiotics kill non-resistant bacteria (<i>correct option</i>). D. Bacteria that have made a person ill will develop resistance if the person does not finish his or her course of treatment.
Group questions (open-response)	<p><i>After streaking bacteria on three plates (one neutral and two containing different types of antibiotics):</i></p> <ul style="list-style-type: none"> 1. What do you think the plates will look like after incubation? Provide as much detail as possible. <p><i>After retrieval of the plates from the incubator:</i></p> <ul style="list-style-type: none"> 2. Were the results consistent with your expectations? Try to explain what has happened and why the plates look as they do. 3. Now imagine that you isolate and grow bacteria from the AB2 plate, then streak them out on three new plates like the first set. How would these plates look after incubation? Explain why. 4. When and how does the resistance arise in the bacteria shown in the animations? 5. Mutations occur randomly and very rarely. Explain how the establishment and growth of resistant strains can still happen so quickly in the presence of antibiotics on the plates.
Post-exercise (individual, open-response)	<p>Earlier generations of giraffes did not have as long necks as those found today. Try to describe similarities and differences between the neck-development of giraffes and bacterial development of antibiotic resistance.</p>

*This item was presented to the pupils again after the exercise, and they were asked to justify their decision to change, or not change, their initial response.

The number of correct responses to the closed item increased from 6 (before) to 17 (after) during the educational exercise. The increase in the proportion of correct answers was found to be statistically significant ($p=0.007$) according to a McNemar test. Furthermore, we observed a tendency to move from needs-based reasoning (option A) towards a correct explanation based on selection of already resistance bacteria (option C) (Fig. 5.4). Due to the qualitative nature of the transcript analyses, the results are partly composed of excerpts that require considerable space. Therefore, only a summary of the results is presented in this section, and a more elaborated account is provided in the appended paper.

Fig. 5.4. Distributions of responses to the closed-response item in Paper IV (see Table 5.5). The increase in the proportion of correct responses (option C) was statistically significant ($p=0.007$).

Several characteristics related to the bacterial context were identified through the transcript analyses. The relatively short generation time of bacteria, along with the possibility of cultivating large bacterial populations on small surfaces, seemed to facilitate the acceptance of the origin and spread of rare point-mutations. These results are interesting in light of previous evidence that pupils have problems inferring processes over long time periods. In this way, the comparison of relative and absolute time-scales between bacteria and animals might be a promising strategy for countering the conceptual problems associated with deep time. The results also provide strong support for using animations to convey both temporal relationships and the subcellular processes involved in mutations.

Another finding indicates that pupils perceive the fitness associated with resistance differently from the fitness that is associated with other organisms, for example, mammals. In the latter case, differences in fitness usually entail subtle variations in already existing differences such as running speed, neck length, among others. In contrast, antibiotic resistance is perceived as a discontinuous trait (i.e. either you have the trait or you don't). This observation might be useful for the teaching of evolution and natural selection, as continuous traits are more prone to Lamarckian explanations of evolution. Furthermore, the definitive character of the trait (resistant or not resistant) is easier associated with changes in the genome. However, the use of antibiotic resistance as a context for natural selection does not eliminate the need to be cautious for pupils providing teleological explanations, as such were noticed in the data with regard to both nucleotide mismatches and the adaptation of organisms and species. In conclusion, the paper provides support for using antibiotic resistance during the teaching of evolution and highlights empirical examples of situations where this might be useful. However, the paper does not advocate teachers to restrict explanations of evolution to the bacterial context. Preferably, various organismal contexts should be used to create a complete picture of evolution.

5.5 Summary of results

This section will summarize the most important results from the included studies with regard to the research questions posed in Chapter 3.

R.Q. 1: What type of information regarding antibiotic resistance is the Swedish public exposed to through newspapers?

The results in Paper I show that information about antibiotic resistance was primarily directed towards societal institutions rather than individual readers. There is clear room for Swedish newspapers to increase the reporting of facts and advice so that citizens can act more responsibly and develop a nuanced risk perception of antibiotic resistance. One strategy suggested in Paper I was to include evolutionary explanations in the reporting. However, Paper II found that evolutionary accounts were very scarcely reported when news media covered the topic of antibiotic resistance.

R.Q. 2: To what extent are evolutionary explanations used when antibiotic resistance is communicated through (i) newspapers, (ii) online websites and (iii) biology textbooks?

The results from Paper II showed that evolutionary explanations are rare in all three of these media types. This finding is especially remarkable for the textbooks, which have a clear educational responsibility with regard to both antibiotic resistance and evolution. Evolutionary explanations were least common in newspapers, as not a single article that covered six relevant concepts of natural selection was found during a three-year period. For the websites, 13 out of 19 did not contain any evolutionary aspects of antibiotic resistance while only two webpages covered five out of six aspects. Even though biology textbooks are written based on a curriculum that includes both evolution and antibiotic resistance, only one of the commonly used textbooks in Sweden provided a complete account. In conclusion, the results from Paper II indicate that three of the most significant public communication channels, including educational material, do not support a complete understanding of the factors that underlie antibiotic resistance and are at the heart of developing viable counter-measures.

R.Q. 3: What content with regard to (i) key concepts, (ii) threshold concepts, (iii) misconceptions and (iv) organismal context is conveyed through videos explaining evolution that are accessible through the Internet?

The videos analyzed in Paper III conveyed evolutionary concepts to very different degrees. A fifth of the videos did not include any of the commonly acknowledged key concepts. Among the video-clusters that contained several key concepts, the largest cluster included individual variation, inherited variation, differential fitness, limited survival and change in population. These videos also typically conveyed the concept of probability and time scales of generations and/or years. Missing from this cluster and only appearing in the smaller video-clusters were origin of variation, randomness and smaller spatial and temporal scales. An unfortunate discovery was that common misconceptions were promoted in about 20 % of all included videos, of which the most prevalent was that variation appears as a response to the needs of an organism. The majority of videos (70 %) used animals (excluding humans) as a context for natural selection, followed by humans (25 %) and bacteria (18 %). The least common organism type used as context was plants, which were present in 8 % of the videos.

R.Q. 4: Which obstacles and/or opportunities can be discerned in using antibiotic resistance as a context for learning natural selection through animations?

We found a number of benefits for teaching natural selection in a bacterial context within Paper IV. The short generation times and ability to cultivate large populations of bacteria in a small space facilitate acceptance of origin and spread of rare point-mutations within populations. This was further facilitated by the visual medium, which helped pupils realize the random and molecular basis of mutations. Furthermore, fitness associated with resistance was perceived as a discontinuous trait as opposed to usual perceptions of more subtle differences in fitness that are often associated with Lamarckian explanations. This finding might explain previous sporadic evidence of how students are more prone to include molecular mechanisms in descriptions of bacterial evolution than those of evolution in animals (Göransson, Fiedler, Orraryd & Tibell, unpublished data). However, teachers should pay particular attention to pupils developing teleological explanations of how resistance develops. On a general level, a relatively short intervention succeeded in helping a majority of the pupils apply basic evolutionary reasoning to predictions of bacterial resistance to antibiotics. Thus, we conclude that antibiotic resistance, which is often used to justify the teaching of evolution, is also a promising context in which pupils can learn about evolution.

6. Discussion

Before discussing the results, I want to emphasize that it is not possible to fully separate antibiotic resistance and evolution. As stated previously, natural selection is a set of general principles that can be applied to all living entities. In the case of bacterial resistance to antibiotics, these principles have a particularly strong impact. Following this logic, the development of antibiotic resistance *is* evolution and could not be properly understood without first understanding how natural selection operates. Evolution, on the other hand, could be sufficiently well explained without mentioning bacteria or antibiotic drugs, although there seems to be justifiable reasons to do so. This being said, parts of this chapter seemingly separate these two topics. However, the goal of this separation is to clarify the order in which we consider them, i.e. antibiotic resistance in light of evolution or evolution in light of antibiotic resistance. In the first case, the focus is on understanding antibiotic resistance, both in the public realm as well as in an educational context. The second case revolves around how the bacterial context can influence the teaching of evolution.

In Section 6.1 of the discussion, I will revisit some of the ideas regarding scientific literacy (Section 2.5) and introduce a discussion about how this concept is relevant for knowledge about natural selection and evolution. The perspective of scientific literacy is further used to elaborate on selected results in subsequent sections. Section 6.2 is devoted to the content regarding antibiotic resistance and/or natural selection that is conveyed through communication channels with broad audiences, specifically, newspapers, websites suggested by search engines, streamed videos and biology textbooks. Thus, aspects that are rarely included in these sources but are nevertheless important for understanding antibiotic resistance are discussed, and then in Section 6.3, extended to implications and suggestions for how to develop the teaching of evolution and influence the national biology curriculum. The chapter ends with a concluding section and a paragraph on possible directions for future research.

6.1 Evolution as part of scientific literacy

It would be hard to argue that evolution or natural selection are not vital components of scientific literacy given their wide implications when only considering the field of biology. That is, if knowledge of biology is considered to be part of scientific literacy, then understanding evolution is also crucial. However, the importance of natural selection as an element of

scientific literacy needs further specification if it is to be thoroughly discussed. Foremost, what definition of scientific literacy are we talking about? Does it concern the education of future scientists or the abilities of the general public? Is it directly coupled to responsible actions, opinions or the ability to consume news reports concerning antibiotic resistance? Further, do we aim for Shen's (1975) cultural, functional or true levels of literacy?

As was previously expressed in the background chapter, plenty of societal issues that concern large portions of the public could *potentially* be dealt with more responsibly if there was higher public awareness of evolutionary theory. Public awareness can also fall into different categories, for example, the public may require better evolutionary reasoning skills or, on the other hand, it may be an issue of public acceptance/belief of evolution (see e.g. Smith & Siegel, 2016). Another crucial question, which remains largely unanswered, is whether increased public understanding and acceptance of evolution would actually influence public behavior on issues such as antibiotic resistance (or genetically modified crops, biodiversity management etc.). As noted by Smith and Siegel (2016), this claim has not been tested empirically.

Although no definition of scientific literacy requires strict empirical support for a strong link between knowledge and action, there are nevertheless a number of other values to consider. Smith (2010b) argues that evolution should be part of our basic education on economic, utilitarian, democratic and cultural grounds, concluding that: *“omitting evolution from the basic instruction of our citizenry would constitute the equivalent of educational malpractice.”*

In terms of Roberts's two visions of scientific literacy, the education of future engineers, scientists and medical practitioners (Vision I) requires a thorough understanding of evolution that can be applied to bacterial resistance (e.g. Gluckman et al., 2011), whereas an educated and literate public, capable of participating in the public debate as well as complying with prescriptions, would conform to Vision II (Roberts, 2007). The Swedish curriculum for biology during school years 7-9 has an observed emphasis on Vision II. Thereby, this dissertation may provide possible teaching strategies that can be used to fulfill these curricular goals. The included studies may also serve as an example of Roberts's (2007) descriptions regarding how a societal issue (increasing levels of antibiotic resistance) can be used to explore what kinds of scientific knowledge (especially in terms of evolution) citizens would need to cope with this problem. Through these examples, this dissertation may have both curricula-developing and curricula-fulfilling implications.

6.2 Information conveyed through public channels

The following sections will discuss the characteristics of conveyed information regarding antibiotic resistance and natural selection. With regard to news-reporting, an implied message seems to be that antibiotic resistance is not crucial for the general public to understand, as practical advice are mostly directed towards medical professionals and public policy decision-makers. However, as discussed mainly in Section 2.1.1, there are plenty of reasons to raise awareness of antibiotic resistance, along with the underlying natural selection mechanisms, among the general public (e.g. McNulty et al., 2007; O'Neill, 2016; WHO, 2011). In populations with higher awareness, both the prescription levels (Davey, Pagliari & Hayes, 2002) and the prevalence of resistant strains in society (Grigoryan et al., 2007) tend to be lower than in comparable populations with lower degrees of awareness.

Most definitional levels of scientific literacy require citizens to apply scientific knowledge in practical situations. This would conform to both Shen's (1975) practical level, Shamos's (1995) functional level and Roberts's (2007) second vision. Furthermore, the practical ability to read and make sense of media reports is a common goal for scientific literacy (e.g. DeBoer, 2000; Bybee, 2012; Maienschein, 1998). It is important to note that this goes beyond word recognition and should also include the ability to integrate information that is *not* present in the text (or video) (Norris & Phillips, 2003).

The relationship between understanding, attitudes and behavior is very complex, and probably a psychological question at its core. As such, it is hard to make general assumptions as to what behavioral impact certain communication- or education strategies might have (see e.g. Pardo & Calvo, 2002). The outdated deficit model implies that increased public knowledge about science will also translate to higher support and agreement with scientific matters (Brossard & Lewenstein, 2009). However, public attitudes appear to be formed by values, emotions, ideology, social identity and trust in scientific institutions rather than through an understanding of scientific facts (Baram-Tsabari & Osborne, 2015). Nevertheless, an understanding of the underlying biology provides an important basis for making informed decisions. In the case of antibiotic resistance, this would translate into evolutionary explanations through natural selection. Therefore, the extent to which these are conveyed to the general public is critical in determining whether the facts required to build a solid theoretical basis are available.

6.2.1 Evolutionary explanations for antibiotic resistance

Both Papers I and II focused on the reporting of antibiotic resistance in the Swedish daily press. A number of patterns emerged from these data. Paper I demonstrated that facts and advice that would be helpful to individual patients and members of the public are scarce in relation to measures directed toward politicians, non-governmental organizations and prescribing doctors. This observed focus on societal rather than individual responsibility is consistent with other reports (e.g. Evensen & Clarke, 2012; Collins, Jaspal & Nerlich, 2017). Certain facts that would be important for all citizens to know, such as the inefficiency of antibiotics toward viruses or the importance of completing a course of treatment as prescribed by the physician, were reported to a very low extent.

Moreover, knowledge of the evolutionary mechanisms that mediate the development of resistance provides an explanatory framework for why, rather than if, different actions have different consequences (e.g. Gluckman et al., 2011). In this way, the results from Paper II further inform the discussion held in Paper I regarding the impact on readers' perception of risk based on factors such as controllability, understanding and uncertainty. In Paper I, we speculate that evolutionary explanations could compensate for the lack of specific advice offered to readers. In addition to its explanatory power for different aspects of antibiotic resistance, increased evolutionary awareness may also affect public perception of the risks imposed by resistance. For example, the risk perception model includes several theoretical implications for how our perception of antibiotic resistance may be more nuanced through evolutionary reasoning. One line of thinking is that an understanding of evolution makes the mechanisms of antibiotic resistances easier to understand, knowledge that can then be extended to realizations that the consequences of resistant bacteria are partially predictable and partially influenced by one's actions (cf. Covello et al., 2001; Slovic, 1987).

However, the results from Paper II clearly show that this explanatory framework is not being provided through news sources, as merely one article from seven newspapers over a three-year period provided a cluster of four important concepts. This observation points further to the relevance of conveying this knowledge already in formal education. The results from Paper II could also be considered in light of the study by Singh and colleagues (2016), which found that, on average, 18 % of popular news articles about antibiotic resistance include the term "evolve". Even though this percentage only reflects usage of the term and does not gauge possible explanations, it was still drastically higher than the percentage of evolutionary explanations found in Paper II and considered to be very low

by the authors (Singh et al., 2016). However, note that accepting that antibiotic resistance is an example of evolution does not imply understanding of the mechanisms (Richard, Coley & Tanner, 2017). Similar results were found for online websites that were among the top results for searches on Google. Surprisingly, even official health information websites concerning antibiotic resistance lacked sufficient explanations of evolutionary mechanisms.

The ability to read and understand a scientific report in a daily newspaper is part of a common definition of scientific literacy adopted by, for example, DeBoer (2000) and Rughinis (2011). This ability represents a “minimal threshold level” of understanding that is necessary for citizens to act responsibly (and safely) in modern industrial societies. The results from Paper II, as well as the study by Singh and colleagues (2016), showed that evolutionary knowledge seems to be implicit in news reports on antibiotic resistance. These findings, when considered from a scientific literacy perspective, suggest that biology education should include both basic knowledge of natural selection *as well as* the role that evolutionary mechanisms play in the development of antibiotic resistance. The ability to acknowledge and apply the mechanisms of natural selection in the context of news reports on antibiotic resistance could also be considered in light of fundamental and derived scientific literacy (Norris & Phillips, 2003). The ability to integrate *extratextual* information facilitates the extraction of meaning from news stories and encompasses, in this case, the explanation of natural selection. This ability is thereby argued to be a crucial part of fundamental literacy and thus deserves recognition in science teaching (Norris & Phillips, 2003).

Even though newspaper reporting adheres to journalistic rather than educational norms, the pattern seen in the reporting of antibiotic resistance raises two interesting questions. First, could this pattern somehow explain the survey results that show the Swedish population to possess, relative to other European countries, similar background knowledge but more favorable attitudes toward antibiotic resistance? And second, in light of the actually conveyed information, what background knowledge do these reports implicitly presume the readers to possess? The answer to the latter question could be used to inform outreach programs and educational goals conforming to Roberts’s Vision II. The data underlying the included papers lend some support for a low, even in international comparison (cf. Desilva, Muskavitch & Roche, 2004; Singh et al., 2016), level of reporting important facts in favor of presenting information appealing to attitudes by Swedish media. These data do not, however, enable us to make qualified statements about the extent to which this pattern affects public perception but could be

further pursued by future research. Regarding implicit background knowledge, data from Paper II strongly suggest that newspaper readers (and people searching for information about antibiotic resistance on Google) need to understand the mechanisms of natural selection, as well as that resistance originates through a random process, in order to fully comprehend what they are reading. The relevance of understanding the random genetic mechanisms for solid evolutionary knowledge is further developed in succeeding sections and has previously been emphasized by several authors (e.g. Garvin-Doxas & Klymkowsky, 2008; Kalinowski, Leonard & Andrews, 2010; Robson & Burns, 2011; Tibell & Harms, 2017).

In light of the scarce reporting of evolutionary mechanisms behind bacterial resistance, it was surprising that a similar pattern also existed in biology textbooks, which should be committed to a comprehensive presentation of both subjects. Of course, the disposition of a textbook is not synonymous with how the teaching is actually performed and teachers have all possibility to present the connections between evolution and bacterial resistance in their classrooms. However, the textbook is very influential in how the teaching is implemented (e.g. Lianghuo, 2000). Also, it can hardly be expected that the country's vast number of biology teachers would all consider clarifying the evolutionary background when a majority of the textbook publishers do not. The lack of student success on items concerning antibiotic resistance in the national tests (Lind Pantzare et al., 2014; 2015) further substantiates claims that there is room for improvement.

In summary, accounts of antibiotic resistance found in newspapers or through online search engines are very unlikely to include aspects pertaining to the evolutionary background explaining this phenomenon. It is also evident that biology textbook authors are, to a large extent, neglecting to address this topic. The few cases of evolutionary explanations were seldom (in two news articles and in no websites or textbooks) supported by visual graphics. This is a notable finding given the abundance of images and illustrations generally accompanying scientific news stories.

6.2.2 Explanatory videos of evolution

There are several previous studies that have studied the account of evolutionary content in textbooks and other written material (e.g. Nehm et al., 2009; Skoog, 2005; Swarts, Anderson & Swetz, 1994), but there is a lack of studies that focus on visual accounts of evolution. However, partly due to reasons discussed below and in Section 2.4, Lee and Tsai (2013) suggested that research should study the unexamined potential of learning

abstract and complex biological concepts through visualizations, particularly dynamic visualizations such as animations or simulations.

Visual accounts of evolution are of interest for several reasons. One of these reasons concerns the imperceptible nature of evolution (Niebert & Gropengiesser, 2015), as it involves processes that go far beyond our ability to grasp both space and time. Furthermore, evolution is a complex process in which multiple concepts and processes that occur on different organizational levels need to be integrated to provide meaning. Another reason is practical: we live in a digital world where images, simulations and videos are abundant and where students (as well as teachers and the general public) frequently reach out to online platforms such as YouTube™ to gather information (e.g. Welbourne & Grant, 2016). For the education community, knowing what is actually conveyed through these sources can provide rich information that could be utilized in multiple settings. From a literacy perspective, it has been suggested that visual scientific literacy, in contrast to “traditional” scientific literacy, does not depend as much on socio-demographic features. Visual scientific accounts can thereby function as a hook, attracting the attention of people who would otherwise not be interested in the subject (Bucchi & Saracino, 2016).

The results from Paper III showed that there was great divergence regarding which features of natural selection that were depicted in online videos. It is worth mentioning that a fifth of the analyzed videos did not mention any of the key concepts included in the criteria catalogue. Among those that did, individual variation, differential fitness, limited survival and change in population were the most prominent. Taken together, these ideas are capable of explaining that the presence of individual differences (that hold differences in fitness) and the fact that not all individuals live to reproduce will eventually lead to a relative change in the distribution of traits within a population and therefore provide an adequate representation of natural selection. However, these should be coupled with the genetic basis of variation, which explains the origin of mutations and how traits are inherited from parent to progeny, to make the ideas consistent (cf. Anderson et al., 2002; Smith, 2010b).

It has been suggested that certain threshold concepts are necessary for joining the key concepts together and gaining a full understanding of natural selection (Ross et al., 2010a; Tibell & Harms, 2017). We explored the extent to which randomness, probability, spatial scale and temporal scale were included in the videos and presented in relation to the key concepts. The findings revealed that randomness was less frequently addressed than probability, and clustered together with origin of variation and smaller levels of organization. Genetic mutations are subcellular processes that form the

basis for variation, a central component of evolution. Misunderstandings of how randomness is involved in evolutionary processes are tightly connected to a number of misconceptions and erroneous ideas (Gregory, 2009; Mead & Scott, 2010; Robson & Burns, 2011; Ross et al., 2010b). Therefore, a tendency to leave out randomness from explanations is worrying. Moreover, about 10 % of the examined videos (with or without intention) promoted the view that evolution is driven by the needs of an organism, a misconception that is strongly associated with an incorrect understanding of the concept of randomness (Burmeister & Smith, 2016; Gregory, 2009).

It is important to note that the visual medium has a unique advantage over textual accounts in that it can effectively convey genetic processes and relate these to perceptual scales. This makes the sparse presentation of origin of variation and random mutations even more worrying. Furthermore, the genetic mechanisms occurring over small spatial scales, i.e. subcellular processes, are very similar for most organisms. An increased focus on this idea could possibly help people who are learning about evolution understand that natural selection mechanisms can be generalized across taxa. The unifying character of natural selection is further obscured by the major dominance of animals as contexts for evolution in the videos. Although the familiarity of animals might function as a positive affective aspect for novice learners, a constant exposure to an animal context might hinder transfer across other organisms. Incentives for extending the focus to taxa such as bacteria or plants can be found in studies reporting selective understanding of natural selection in students based on the organismal context (e.g. Ha, Lee & Cha, 2006; Nehm & Ridgway, 2011). Moreover, the finding that time was usually conveyed in absolute time-scales (particularly in years) rather than in generations further impedes generalization across organisms since generation times can vary from minutes to many years. Presenting time in generations therefore provide more useful information to learners (Catley & Novick, 2009).

6.3 Implications for teaching

As mentioned previously in this dissertation and elsewhere (e.g. Carroll et al., 2014; Dobzhansky, 1973; Futuyma, 1995), biological evolution is the framework from which the majority of all biology and medicine can be derived and clarified. Thereby, the importance of successfully teaching evolution cannot be overstated. However, one might consider the situations in which evolutionary knowledge is of actual importance for non-biologists. Suggested motives for a scientifically knowledgeable citizenry include cultural reasons, such as an appreciation for nature and an understanding of our place in it; practical reasons, such as the ability to cope with issues such

as antibiotic resistance; and political reasons, such as a democratic opportunity for citizens to stay informed and offer opinions on scientific issues (DeBoer, 2000).

The following sections will elaborate on implications of public and student knowledge of evolution in light of the results from the included studies. Strategies for teaching antibiotic resistance are discussed first, followed by the potential benefits and/or obstacles of using a bacterial context when teaching natural selection.

6.3.1 Teaching evolutionary explanations of antibiotic resistance

Bacterial resistance to antibiotics is specifically mentioned as one of the learning goals in the Swedish biology curriculum for school years 7-9 (The Swedish National Agency For Education, 2011). Thereby, it is considered as something that all pupils (and future citizens) should have a basic understanding of. This is logical in light of both the need to develop solutions to growing antibiotic resistance and to have a well-educated public. Given that this is the last compulsory biology course in Sweden, it is highly relevant in the context of Vision II of scientific literacy, which concerns the broader public rather than a future scientific workforce. Against this background, it is troubling that antibiotic resistance seems to be one of the more difficult topics in this course, shown by needs-based reasoning as well as confusion about who actually becomes resistant (Lind Pantzare et al., 2014; 2015; Richard, Coley & Tanner, 2017).

Several important notions related to antibiotic resistance are not solely associated with evolutionary mechanisms, but rather linked to other biological disciplines. For example, understanding why antibiotics have no effect on viruses or why humans do not become resistant is foremost a microbiological question. Nevertheless, these are two very common misunderstandings found among pupils (Lind Pantzare et al., 2015), biology students (Richard, Coley & Tanner, 2017) as well as adults (e.g. André et al., 2010). Furthermore, the findings in Paper I indicate that the lack of antibiotic effect on viral infections is reported to a very low extent in newspapers. As such, it is critical that the biology course leaves no doubt with regard to these misunderstandings. Preferably, especially for pupils planning future studies within microbiology, erroneous conceptions of resistance as a physical coat or that antibiotics only affect pathogenic bacteria should also be addressed (Stevens et al., 2017). Burmeister and Smith (2016) provide further guidance by stressing the need to clarify language ambiguities related to evolution of microbial organisms.

In Paper IV, we demonstrated that novice pupils lacking previous education in both evolution and antibiotic resistance managed to drastically improve their results on a question similar to the closed-response item used in the national test after a relatively short educational exercise. A majority of the pupils shifted from needs-based reasoning to a more correct explanation in evolutionary terms after the included exercise. Moreover, many pupils succeeded in applying partial evolutionary reasoning to make predictions of resistance development. This provides direct evidence that the evolutionary background to antibiotic resistance should be acknowledged in education, and implies that evolutionary mechanisms deserve more attention by textbook authors and teachers to both improve pupils' results on national tests and prepare them for their role as future citizens.

Furthermore, understanding both bacterial and animal genetics requires reasoning on a spatial level that our minds, and senses, are not accustomed to. Visual tools such as animations can facilitate the understanding of important subcellular processes such as replication, which was included in our animations (e.g. Marbach-Ad, Rotbain & Stavy, 2008). Specifically, animations can help pupils navigate across organizational levels in both space and time, which is paramount to grasping the complexity of biological systems (e.g. Jördens et al. 2016). Several of the pupils included in the study explicitly mentioned that the animations had caused them to adjust their initial responses while a few specifically mentioned that the animations showed how random mutations cause resistance in bacteria.

6.3.2 Potential of using a bacterial context in evolution teaching

Our natural world is characterized by enormous diversity. Consider, for example, the vastly different appearances of bats, oak trees, salmon, elephants, mushrooms or *E. coli* bacteria. Nevertheless, evolution and natural selection work through general mechanisms that transcend organismal contexts (see e.g. Mayr's explication in Section 2.2.1). Moreover, all living species share common characteristics on the molecular level, with DNA as the hereditary material that is transcribed and translated into proteins through similar mechanisms across all taxa. This tenet provides an important foundation for understanding evolution (Kalinowski, Leonard & Andrews, 2010).

Nevertheless, there is evidence that learners consistently have problems when moving across organisms and that they tend to focus on features lying at the "surface" without seeing the underlying generality in the mechanisms (Nehm & Ha, 2011; Nehm & Ridgway, 2011; Opfer, Nehm & Ha, 2012). As a result, students commonly use different response strategies for questions concerning different organisms. This is an important issue that has

at least two important implications. First, several items, concerning different organisms, should be used in assessments (Nehm & Ha, 2011). Moreover, the teaching of evolution needs to include an increased focus on the unifying features of different organisms. Grasping the molecular basis and cellular language that unites all living organisms provides a powerful prerequisite for making comparisons between different taxa. A third possible implication arises from this observation. The finding that different organisms tend to stimulate students to think in different ways could possibly be used for educational advantage. If we could determine which organismal contexts lead to which types of reasoning, both in terms of correct explanations and problematic misconceptions, educational policymakers could then design teaching programs and other pedagogical content, such as textbooks, accordingly.

This idea was empirically explored in Paper IV, and we identified a couple of beneficial features relating to the use of bacteria as a context for teaching evolution. Bacteria, in comparison to most multicellular organisms, are relatively small and have short generation times. This feature could address the well-recognized problem of deep time thinking (Catley & Novick, 2009; Cheek, 2010). The pupils in our study did not seem to have problems accepting that the rare point-mutations that can give rise to resistance against specific antibiotic drugs occasionally happen given a large enough population and the passing of many generations. Assuming that a bacterial population divides every 30 minutes, two weeks of bacterial procreation corresponds to the passing of 672 generations. For humans, assuming a generation time of 25 years, the same number of generations would arise only after 16 800 years, which is still only a blink of the eye when compared to the long evolutionary history of all the organisms that have inhabited our planet. The bacterial context enables these vast time scales to be compressed to a level that is accessible to novice students, and, therefore, is applicable to the classroom environment.

Furthermore, the pupils participating in Paper IV perceived the specific trait of resistance to antibiotics as a discontinuous trait in the sense that you either carry the trait (and survive antibiotic environments) or you don't (and will consequently die in antibiotic environments). Even though antibiotic resistance can have a more gradual appearance in reality, this perception makes the trait qualitatively different from other commonly used examples when discussing natural selection. Normally, we use slight individual differences that carry small advantages in competitive environments as examples. Ongoing research suggests that students are more prone to include randomness and mutations in responses to items situated in bacterial contexts than in animal contexts (Göransson, Fiedler, Orraryd & Tibell,

unpublished data). These observations may be explained by differences in the perceived nature of the trait, since more subtle levels of fitness are usually interpreted through soft inheritance mechanisms, i.e. that they are acquired or improved during an organism's life (Gregory, 2009). Another possible explanation is that students perceive the route between gene and function to be shorter in unicellular organisms such as bacteria than in multicellular organisms.

Future studies can still provide plenty of insight into why students' attention seem to be drawn toward DNA and mutations more within the bacterial context than in the multicellular context. The lesson that DNA is a molecule that unifies all life and that genetic mutations cause new variation among all living organisms is nevertheless crucial if students are expected to transfer the general mechanisms of evolution to different organisms (Kalinowski, Leonard & Andrews, 2010). Needless to say, this could not be accomplished through a couple of lessons focusing strictly on bacteria, but would need a longer, well-developed course including multiple examples from animals, plants and bacteria. A promising approach for helping students understand the generality of natural selection mechanisms could be the comparison of situations that highlight key concepts as well as threshold concepts in different organisms. However, the research presented in this dissertation demonstrates that the bacterial context is a beneficial place to initiate the teaching of how variations arise.

6.4 Summary and conclusions

This concluding section will attempt to first summarize the discussion by addressing three key questions of science education research - what, why and how - and will then finish with a brief collection of the main messages that have emerged from a careful dissection of the research underlying this dissertation. *What* characterizes the public communication of antibiotic resistance and natural selection that is conveyed through the investigated channels? What knowledge or skills are needed to understand and act adequately with regard to antibiotic resistance, and, more importantly, are these notions made available? *Why* is this important and what are the incentives for identifying and filling gaps in communication in light of both individual and societal interests? Finally, *how* should we effectively make this knowledge available and implement the results to develop teaching that will mold scientifically literate future citizens?

The results from Paper I indicate that news reporting on antibiotic resistance primarily focuses on directing advice to actors other than the general public. Important facts, such as that antibiotics do not work on viruses, as well as an explanatory framework within which common risk-

reduction measures can be interpreted are some of the information that the public requires more of. Evolution and natural selection function as such a framework because they provide the mechanisms through which antibiotic resistance develops, can explain the causes for its occurrence and help inspire strategies to contain its spread. However, the results from Paper II show that the evolutionary background to antibiotic resistance is seldom conveyed through newspapers, websites or even biology textbooks. As a result, it is highly probable that a large proportion of the population is never exposed to this information through these channels. Furthermore, the few explanations that were encountered were hardly ever visualized, but presented only in text form. If we accept that an understanding of natural selection is crucial for deeper insight into the development of antibiotic resistance, then another problem arises. Natural selection is notoriously difficult to teach and learn. Understanding the nature and role of a few so-called threshold concepts, such as randomness and vast time-scales, can potentially enhance understanding of evolution and natural selection (e.g. Ross et al, 2010b). There are several reasons for why these concepts are easier to perceive and grasp through the visual medium (Tibell & Harms, 2017). The emerging framework surrounding threshold concepts, and the increasing popularity of web-based video streaming sites for education and entertainment, motivated us to explore which facets of natural selection that are being conveyed through accessible online videos in Paper III. We found a large variation of the extent to which different concepts were expressed across the videos and noticed that many of the sampled videos did not convey any of the key concepts of natural selection. Moreover, a majority of the videos focused on selection processes characterized by different probabilities of survival rather than the variation-generating processes characterized by random mutations on the DNA-level.

Why then, is a working knowledge of natural selection important and why should research in science education and communication address the issues raised in this dissertation? An understanding of natural selection and how it drives the development of antibiotic resistance permits wiser handling of antibiotic drugs among patients by explaining how both irresponsible and unnecessary use of antibiotics inevitably will increase the number of resistant bacterial strains. Besides practical arguments, there are motives from many different perspectives to be found in literature on scientific literacy. For example, with increasing scientific knowledge, citizens will find it easier to negotiate their way through society and are more resilient toward pseudo-scientific ideas on, for example, diet or alternative medicines (Laugksch, 2000). In terms of Vision I and II of scientific literacy (Roberts, 2007), Vision I primarily concerns a future

workforce of people with scientific careers. For medical researchers and people involved in healthcare occupations, a basic understanding of evolution and how it is involved in issues such as antibiotic resistance is crucial (e.g. Gluckman et al. 2011), albeit not necessarily accomplished today (e.g. Antonovics, 2016). With regard to Vision II, antibiotic resistance may function both as a motivational factor for studying evolution (e.g. Hillis, 2007; Krist & Showsh, 2007), as a pedagogical strategy to address some of the more difficult aspects (such as deep time or the random occurrence of variation) and as a direct evolutionary application from which to initiate and plan teaching. Using newspapers and popular web-resources as a departure point for research finds direct relevance from the often-proclaimed goal of science education to enable citizens to understand science-related reports and articles (e.g. DeBoer, 2000; Maienschein, 1998; Norris & Phillips, 2003).

The last question concerns how antibiotic resistance can be successfully integrated into biology education and how future citizens can be granted with a knowledge of natural selection that is sufficient for them to function in, and contribute to, society. The research presented in this dissertation provides some answers for these questions. For example, the threshold concepts underlying natural selection must become more salient in teaching. Specifically, the random subcellular processes that give rise to variation are underrepresented in explanatory videos and associated with several common misconceptions. How these imperceptible processes first influence individual traits and then entire populations is a cognitive challenge that may be easier to understand through the use of visualizations. Also, using a bacterial context seems to further highlight the role of genetic mutations in evolution. It is also important to establish a firm understanding of DNA and how the cellular machinery works if students are expected to apply these unifying features of biology to other organismal contexts. Although the biological world may seem enormously diverse, organisms begin to appear more similar when we observe them through a smaller, microscopic lens. This realization is a prerequisite for understanding the generality of evolutionary mechanisms and common descent. Although not a focus of any of the presented papers, it is probable that basic education in evolution and variation could be initiated at earlier ages than today to stimulate the acceptance of these ideas and to impede the development of future misconceptions.

In conclusion, the main messages that emerge from the studies and theories underlying this dissertation imply that:

- Evolution, and specifically natural selection, is important from a scientific literacy perspective and should be more explicitly

integrated in descriptions of antibiotic resistance available through news media and other channels.

- Aspects of natural selection could be successfully taught using a context of bacterial resistance to antibiotics. This is especially relevant with regard to understanding how subcellular processes, such as mutations, lead to variation and compressing the long time periods involved in evolution by exploiting the generation times of bacteria.
- The teaching of evolution would benefit from an increased focus on the unifying features across taxa (i.e. DNA and the subcellular machinery). This approach could impede misunderstandings coming from organism-bound surface features.
- While focusing on the general features of natural selection, different organismal contexts may help students better conceptualize certain aspects of natural selection. It is important to find examples from different organisms that will help students see how evolutionary mechanisms transcend different contexts. Threshold concepts could be a promising strategy for this teaching approach.
- The use of visualizations might help students connect organizational levels in both space and time, make the micro-scale perceptible as well as reduce the complexity associated with biology and evolution.

6.5 Future research

Given that the research presented in this dissertation is of exploratory nature, many of the patterns and findings that emerged could be studied in a more controlled setting in future research endeavors. These include empirical studies concerning if, and under what circumstances, a focus on threshold concepts aid the learning of natural selection and other aspects of evolution. This research area has recently begun to receive attention (Fiedler, Tröbst & Harms, 2017; Göransson, Fiedler, Orraryd and Tibell, unpublished data), but many aspects remain only partially investigated. The potential of using, and designing, visualizations to effectively teach and communicate abstract threshold concepts is also a promising future research area. Furthermore, the relationship between knowledge, attitudes and behavior when it comes to antibiotic resistance is an issue that needs both empirical studies and theoretical development from different perspectives including psychology, education and communication. Whether an understanding of the evolutionary mechanisms underlying development of antibiotic resistance leads to more informed actions among patients as well

as physicians is another topic that could benefit from well-planned empirical studies.

7. References

- Ainsworth, S. (2008). How do animations influence learning? In D. Robinson & G. Schraw (Eds.), *Current Perspectives on Cognition, Learning and Instruction: Recent Innovations in Educational Technology that Facilitate Student Learning* (pp. 37-67). Charlotte, N.C: Information Age Publishing.
- American Association for the Advancement of Science. (1989). *Science for all Americans*. Washington, DC: AAAS.
- American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. Washington, DC: AAAS.
- Anderson, D. L., Fisher, K. M., & Norman, G. J. (2002). Development and evaluation of the conceptual inventory of natural selection. *Journal of Research in Science Teaching*, 39(10), 952-978.
- Andersson, D. I., & Levin, B. R. (1999). The biological cost of antibiotic resistance. *Current Opinion in Microbiology*, 2(5), 489-493.
- Andre, M., Vernby, A., Berg, J., & Lundborg, C. S. (2010). A survey of public knowledge and awareness related to antibiotic use and resistance in Sweden. *Journal of Antimicrobial Chemotherapy*, 65(6), 1292-1296.
- Andrews, T. M., Leonard, M. J., Colgrove, C. A., & Kalinowski, S. T. (2011). Active learning not associated with student learning in a random sample of college biology courses. *CBE – Life Sciences Education*, 10, 394-405.
- Antonovics, J., Abbate, J. L., Baker, C. H., Daley, D., Hood, M. E., Jenkins, C. E., ... & Sloan, D. (2007). Evolution by any other name: Antibiotic resistance and avoidance of the e-word. *PLoS Biology*, 5(2), e30.
- Antonovics, J. (2016). The value of concept: Lessons from the evolution of antibiotic resistance. *Global Policy*, 7(S1), 97-106.
- Baillie, C., Goodhew, P., & Skryabina, E. (2006). Threshold concepts in engineering education - Exploring potential blocks in student understanding. *International Journal of Engineering Education*, 22(5), 955-962.
- Baram-Tsabari, A., & Osborne, J. (2015). Editorial bridging science education and science communication research. *Journal of Research in Science Teaching*, 52(10), 135-144.
- Barradell, S., & Kennedy-Jones, M. (2015). Threshold concepts, student learning and curriculum: making connections between theory and practice. *Innovations in Education and Teaching International*, 52(5), 536-545.

- Bie, B., Tang, L., & Treise, D. M. (2016). Be aware of superbugs: Newspaper coverage of NDM-1 in India, UK, and the USA. *Asian Journal of Communication*, 26(1), 58-75.
- Bishop, B. A., & Anderson, C. W. (1990). Student conceptions of natural selection and its role in evolution. *Journal of Research in Science Teaching*, 27(5), 415-427.
- Bizzo, N. M. V. (1994). From down house landlord to Brazilian high-school-students – What has happened to evolutionary knowledge on the way. *Journal of Research in Science Teaching*, 31(5), 537–556.
- Björkman, I., Berg, J., Röing, M., Erntell, M., & Lundborg, C. S. (2010). Perceptions among Swedish hospital physicians on prescribing of antibiotics and antibiotic resistance. *BMJ Quality & Safety*, 19, e8
- Blair, J. M., Webber, M. A., Baylay, A. J., Ogbolu, D. O., & Piddock, L. J. (2015). Molecular mechanisms of antibiotic resistance. *Nature Reviews Microbiology*, 13(1), 42-51.
- Blondeau, J. M., Zhao, X., Hansen, G., & Drlica, K. (2001). Mutant prevention concentrations of fluoroquinolones for clinical isolates of *Streptococcus pneumoniae*. *Antimicrobial Agents and Chemotherapy*, 45(2), 433-438.
- Bohlin, G., & Höst, G. H. (2015). Evolutionary explanations for antibiotic resistance in daily press, online websites and biology textbooks in Sweden. *International Journal of Science Education, Part B: Communication and Public Engagement*, 5(4), 319-338.
- Boyce, T., Murray, E., & Holmes, A. (2009). What are the drivers of the UK media coverage of meticillin-resistant *Staphylococcus aureus*, the inter-relationships and relative influences? *The Journal of Hospital Infection*, 73(4), 400-407.
- Brossard, D., & Lewenstein, B. V. (2009). A critical appraisal of models of public understanding of science. In L. Kahlor & P. Stout (Eds.), *Communicating Science: New Agendas in Communication* (pp. 11-39). New York, NY: Taylor and Francis.
- Brossard, D. (2013). New media landscapes and the science information consumer. *Proceedings of the National Academy of Sciences of the United States of America*, 110(S3), 14096-14101.
- Brown, E. D., & Wright, G. D. (2016). Antibacterial drug discovery in the resistance era. *Nature*, 529(7586), 336-343.
- Bucchi, M., & Saracino, B. (2016). “Visual science literacy”: Images and public understanding of science in the digital age. *Science Communication*, 38(6), 812-819.
- Bull, J. J., & Wichman, H. A. (2001). Applied evolution. *Annual Review of Ecology and Systematics*, 32, 183-217.

- Burmeister, A. R., & Smith, J. J. (2016). Evolution across the curriculum: Microbiology. *Journal of Microbiology & Biology Education*, 17(2), 252-260.
- Bybee, R. W. (2012). Scientific literacy in environmental and health education. In A. Zeyer & R. Kyburz-Graber (Eds.), *Science Environment Health – Towards a Renewed Pedagogy for Science Education* (pp. 49-67). Dordrecht, The Netherlands: Springer.
- Carroll, S. P., Jørgensen, P. S., Kinnison, M. T., Bergstrom, C. T., Denison, R. F., Gluckman, P., ... & Tabashnik, B. E. (2014). Applying evolutionary biology to address global challenges. *Science*, 346(6207), 1245993.
- Carter, R. R., Sun, J., & Jump, R. L. (2016). A survey and analysis of the American public's perceptions and knowledge about antibiotic resistance. *Open Forum Infectious Diseases*, 3(3), ofw112.
- Cars, O., Högberg, L. D., Murray, M., Nordberg, O., Sivaraman, S., Lundborg, C. S., ... & Tomson, G. (2008). Meeting the challenge of antibiotic resistance. *BMJ: British Medical Journal*, 337, a1438.
- Catley, K. M. (2006). Darwin's missing link – A novel paradigm for evolution education. *Science Education*, 90(5), 767-783.
- Catley, K. M., & Novick, L. R. (2009). Digging deep: Exploring college students' knowledge of macroevolutionary time. *Journal of Research in Science Teaching*, 46(3), 311-332.
- Collins, L. C., Jaspal, R., & Nerlich, B. (2017). Who or what has agency in the discussion of antimicrobial resistance in UK news media (2010-2015)? A transitivity analysis. *Health*. Advance online publication. doi: 10.1177/1363459317715777.
- Chan, P., Dipper, A., Kelsey, P., & Harrison, J. (2010). Newspaper reporting of meticillin-resistant *Staphylococcus aureus* and 'the dirty hospital'. *The Journal of Hospital Infection*, 75(4), 318-322.
- Cheek, K. A. (2010). Why is geologic time troublesome knowledge? In J. H. F. Meyer, R. Land & C. Baillie (Eds.), *Threshold Concepts and Transformational Learning* (pp. 117-129). Rotterdam, The Netherlands: Sense Publishers.
- Cho, H. H., Kahle, J. B., & Nordland, F. H. (1985). An investigation of high-school biology textbooks as sources of misconceptions and difficulties in genetics and some suggestions for teaching genetics. *Science Education*, 69(5), 707-719.
- Cloud-Hansen, K. A., Kuehner, J. N., Tong, L., Miller, S., & Handelsman, J. (2008). Money, sex, and drugs: A case study to teach the genetics of antibiotic resistance. *CBE – Life Sciences Education*, 7(3), 302-309.

- Covello, V. T., Peters, R. G., Wojtecki, J. G., & Hyde, R. C. (2001). Risk communication, the West Nile virus epidemic, and bioterrorism: Responding to the communication challenges posed by the intentional or unintentional release of a pathogen in an urban setting. *Journal of Urban Health*, 78(2), 382-391.
- Cummins, C. L., Demastes, S. S., & Hafner, M. S. (1994). Evolution: Biological education's under-researched unifying theme. *Journal of Research in Science Teaching*, 31, 445-448.
- Davies, P. (2006). Threshold concepts: How can we recognize them. In J. H. F. Meyer & R. Land (Eds.), *Overcoming Barriers to Student Understanding: Threshold concepts and troublesome knowledge* (pp. 70-84). Abingdon, United Kingdom: Routledge.
- Davies, P., & Mangan, J. (2007). Threshold concepts and the integration of understanding in economics. *Studies in Higher Education*, 32(6), 711-726.
- Davey, P., Pagliari, C., & Hayes, A. (2002). The patient's role in the spread and control of bacterial resistance to antibiotics. *Clinical Microbiology & Infection*, 8, 43-68.
- D'Costa, V., M., King, C. E., Kalan, L., Morar, M., Sung, W. W. L., Schwarz, C., ... & Wright, G. D. (2011). Antibiotic resistance is ancient. *Nature*, 477(7365), 457-461.
- DeBoer, G. E. (2000). Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. *Journal of Research in Science Teaching*, 37(6), 582-601.
- Delpech, R. (2009). Evolution in an afternoon: Rapid natural selection and adaptation of bacterial populations. *Journal of Biological Education*, 43(3), 129-133.
- DeSantis, L. R. G. (2009). Teaching Evolution through Inquiry-Based Lessons of Uncontroversial Science. *American Biology Teacher*, 71(2), 106-111.
- Deschepper, R., et al. (2008). Are cultural dimensions relevant for explaining cross-national differences in antibiotic use in Europe? *BMC health services research*, 8(1), 1.
- Desilva, M., Muskavitch, M. A. T., & Roche, J. P. (2004). Print media coverage of antibiotic resistance. *Science Communication*, 26(1), 31-43.
- Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *The American Biology Teacher*, 35(3), 125-129.
- Dudo, A. D., Dahlstrom, M. F., & Brossard, D. (2007). Reporting a potential pandemic - A risk-related assessment of avian influenza coverage in US newspapers. *Science Communication*, 28(4), 429-454.

- Dunwoody, S. (2008). Science Journalism. In M. Bucchi & B. Trench (Eds.), *Handbook of Public Communication of Science and Technology*. Abingdon, United Kingdom: Routledge.
- Elena, S. F., & Lenski, R. E. (2003). Evolution experiments with microorganisms: The dynamics and genetic bases of adaptation. *Nature Reviews Genetics*, 4, 457-469.
- Elo, S., & Kyngäs, H. (2008). The qualitative content analysis process. *Journal of Advanced Nursing*, 62(1), 107-115.
- European Centre for Disease Prevention and Control. (2015). *Antimicrobial resistance surveillance in Europe 2014*. Annual Report of the European Antimicrobial Resistance Surveillance Network (EARS-Net). Stockholm, Sweden: ECDC.
- Evensen, D. T., & Clarke, C. E. (2012). Efficacy information in media coverage of infectious disease risks: An ill predicament? *Science Communication*, 34(3), 392-418.
- Everitt, B. S., Landau, S., Leese, M., & Stahl, D. (2011). *Cluster Analysis, 5th Edition*. Hoboken, NJ: John Wiley & Sons.
- Feinstein, N. W. (2015). Education, communication, and science in the public sphere. *Journal of Research in Science Teaching*, 52(2), 145-163.
- Fiedler, D., Tröbst, S., & Harms, U. (2017). University students' conceptual knowledge of randomness and probability in the contexts of evolution and mathematics. *CBE – Life Sciences Education*, 16(2), ar38.
- Fleming, A. (1945). Penicillin. In: *Nobel Lectures, Physiology or Medicine 1942-1962*. Amsterdam, The Netherlands: Elsevier.
- Fletcher, J. D., & Tobias, S. (2005). The multimedia principle. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (Vol. 1, pp. 117-133). Cambridge, United Kingdom: Cambridge University Press.
- Fowler, S. R. (2009). *College students' use of science content during socioscientific issues negotiation: Impact of evolution understanding and acceptance* (Doctoral Dissertation). Retrieved from:
<http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=2969&context=etd>
- Fowler, S. R., & Zeidler, D. L. (2010). *College Students' use of Science Content During Socioscientific Issues Negotiation: Evolution as a Prevailing Concept*. Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Philadelphia, PA.

- Futuyma, D. J. (1995). The uses of evolutionary biology. *Science*, 267(5194), 41-42.
- Garvin-Doxas, K., & Klymkowsky, M. W. (2008). Understanding randomness and its impact on student learning: Lessons learned from building the biology concept inventory (BCI). *CBE - Life Sciences Education*, 7, 227-233.
- Genereux, D. P., & Bergstrom, C. T. (2004). *Evolution in Action: Understanding Antibiotic Resistance*. Paper presented at the Evolutionary Science and Society: Educating a New Generation, Chicago, IL.
- Gibbs, G. R. (2007). *Analyzing qualitative data*. Thousand Oaks, CA: Sage.
- Gilbert, J. K. (Ed.). (2005). *Visualization in Science Education*. Dordrecht, The Netherlands: Springer.
- Gilbert, J. K. (2008). Visualization: An emergent field of practice and enquiry in science education. In J. K. Gilbert, M. Reiner & M. Nakhleh (Eds). *Visualization: Theory and Practice in Science Education* (pp. 3-24). Dordrecht, The Netherlands: Springer.
- Gilbert, J. K., & Treagust, D. F. (2009). Introduction: Macro, submicro and symbolic representations and the relationship between them: Key models in chemical education. In J. K. Gilbert & D. F. Treagust (Eds.), *Multiple Representations in Chemical Education* (pp. 1-8). Dordrecht, The Netherlands: Springer.
- Gluckman, P. D., Low, F. M., Buklijas, T., Hanson, M. A., & Beedle, A. S. (2011). How evolutionary principles improve the understanding of human health and disease. *Evolutionary Applications*, 4(2), 249-263
- Godfrey-Smith, P. (2007). Conditions for evolution by natural selection. *The Journal of Philosophy*, 104(10), 489-516.
- Graneheim, U. H., & Lundman, B. (2004). Qualitative content analysis in nursing research: concepts, procedures and measures to achieve trustworthiness. *Nurse Education Today*, 24(2), 105-112.
- Grigoryan, L., Burgerhof, J. G. M., Degener, J. E., Deschepper, R., Lundborg, C. S., Monnet, ... & Haaijer-Ruskamp, F. M. (2007). Attitudes, beliefs and knowledge concerning antibiotic use and self-medication: A comparative European study. *Pharmacoepidemiology and Drug Safety*, 16(11), 1234-1243.
- Gregory, T. R. (2009). Understanding natural selection: Essential concepts and common misconceptions. *Evolution: Education and Outreach*, 2(2), 156-175.
- Gualano, M. R., Gili, R., Scaioli, G., Bert, F., & Siliquini, R. (2015). General population's knowledge and attitudes about antibiotics: A

- systematic review and meta-analysis. *Pharmacoepidemiology and Drug Safety*, 24(1), 2-10.
- Ha, M.-S., Lee, J.-K., & Cha, H.-Y. (2006). A cross-sectional study of students' conceptions on evolution and characteristics of concept formation about it in terms of the subjects: Human, animals and plants. *Journal of the Korean Association for Science Education*, 26(7), 813-825.
- Hamid, J. S., Meaney, C., Crowcroft, N. S., Granerod, J., & Beyene, J. (2010). Cluster analysis for identifying sub-groups and selecting potential discriminatory variables in human encephalitis. *BMC Infectious Diseases*, 10, 364.
- Hayes, A. F., & Krippendorff, K. (2007). Answering the call for a standard reliability measure for coding data. *Communication Methods and Measures*, 1(1), 77-89.
- Hidaka, B. H., Asghar, A., Aktipis, C. A., Nesse, R. M., Wolpaw, T. M., Skursky, N. K., ... & Schwartz, M. D. (2015). The status of evolutionary medicine education in North American medical schools. *BMC Medical Education*, 15(1), 1.
- Hillis, D. M. (2007). Making evolution relevant and exciting to biology students. *Evolution*, 61(6), 1261-1264.
- Hoffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, 17(6), 722-738.
- Infanti, L. M., Lynn, M., & Wiles, J. R. (2014). "Evo in the news": Understanding evolution and students' attitudes toward the relevance of evolutionary biology. *Bioscene: Journal of College Biology Teaching*, 40(2), 9-14.
- Islam, M. M., Valderas, J. M., Yen, L., Dawda, P., Jowsey, T., & McRae, I. S. (2014). Multimorbidity and comorbidity of chronic diseases among the senior Australians: Prevalence, and patterns. *PLoS One*, 9(1), e83783.
- Johnstone, A. H. (1982). Macro- and microchemistry. *School Science Review*, 64, 377-379
- Jördens, J., Asshoff, R., Kullmann, H. & Hammann, M. (2016). Providing vertical coherence in explanations and promoting reasoning across levels of biological organization when teaching evolution. *International Journal of Science Education*, 38(6), 960-992.
- Kalinowski, S. T., Leonard, M. J., & Andrews, T. M. (2010). Nothing in evolution makes sense except in the light of DNA. *CBE – Life Sciences Education*, 9, 87-97.

- Kampourakis, K., & Strasser, B. J. (2015). The evolutionist, the creationist, and the 'unsure': Picking-up the wrong fight? *International Journal of Science Education, Part B*, 5(3), 271-275.
- Kinchin, I. M. (2010). Solving Cordelia's dilemma: Threshold concepts within a punctuated model of learning. *Journal of Biological Education*, 44(2), 53-57.
- Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of the Learning Sciences*, 9, 105-143.
- Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. Gilbert (Ed.), *Visualization in Science Education* (pp. 121-146). Dordrecht, The Netherlands: Springer.
- Krippendorff, K. (2013). *Content Analysis: An Introduction to its Methodology*. (3 ed.). Thousand Oaks, CA: Sage.
- Krist, A. C., & Showsh, S. A. (2007). Experimental evolution of antibiotic resistance in bacteria. *The American Biology Teacher*, 69(2), 94-97.
- Laugksch, R. C. (2000). Scientific literacy: A conceptual overview. *Science Education*, 84(1), 71-94.
- Lecky, D. M., McNulty, C. A. M., Adriaenssens, N., Herotova, T. K., Holt, J., Touboul, P., ... & Noer, M., (2011). What are school children in Europe being taught about hygiene and antibiotic use? *Journal of Antimicrobial Chemotherapy*, 66(Suppl 5), v13-v21.
- Lee, S. W. Y., & Tsai, C. C. (2013). Technology-supported learning in secondary and undergraduate biological education: Observations from literature review. *Journal of Science Education and Technology*, 22(2), 226-233.
- Lei, P. L., Sun, C. T., Lin, S. S., & Huang, T. K. (2015). Effect of metacognitive strategies and verbal-imagery cognitive style on biology-based video search and learning performance. *Computers & Education*, 87, 327-339.
- Leonard, M. J., Kalinowski, S. T., & Andrews, T. C. (2014). Misconceptions yesterday, today and tomorrow. *CBE – Life Sciences Education*, 13, 179-186.
- Levy, S. B., & Marshall, B. (2004). Antibacterial resistance worldwide: Causes, challenges and responses. *Nature Medicine*, 10(12), S122-S129.
- Lewis, J., & Kattmann, U. (2004). Traits, genes, particles and information: Re-visiting student's understandings of genetics. *International Journal of Science Education*, 26(2), 195-206.

- Lianghuo, F., & Kaeley, G. S. (2000). The influence of textbooks on teaching strategies: An empirical study. *Mid-Western Educational Researcher*, 13(4), 2-9.
- Lind Pantzare, A., Abrahamsson, M., Almarlind, P., & Lundgren, C. (2014). *Ämnesproven i grundskolans årskurs 9 och specialskolans årskurs 10: Vårterminen 2014* [National Tests in Compulsory school year 9 and Special school year 10: Biology, Physics and Chemistry, Year 9, Spring term 2014]. Umeå: Umeå Universitet.
- Lind Pantzare, A., Abrahamsson, M., Almarlind, P., & Lundgren, C. (2015). *Ämnesproven i grundskolans årskurs 9 och specialskolans årskurs 10: Vårterminen 2015* [National Tests in Compulsory school year 9 and Special school year 10: Biology, Physics and Chemistry, Year 9, Spring term 2015]. Umeå: Umeå Universitet.
- Llewelyn, M. J., Fitzpatrick, J. M., Darwin, E., Tonkin-Crine, S., Gorton, C., Paul, J., ... & Walker, A. S. (2017). The antibiotic course has had its day. *British Medical Journal*, 358, j3418.
- Loertscher, J., Green, D., Lewis, J. E., Lin, S., & Minderhout, V. (2014). Identification of threshold concepts for biochemistry. *CBE – Life Sciences Education*, 13(3), 516-528.
- Maienschein, J. (1998). Scientific literacy. *Science*, 281(5379), 917.
- Mager, A. (2012). Search engines matter: From educating users towards engaging with online health information practices. *Policy & Internet*, 4(2), 1-21-
- Marbach-Ad, G., Rotbain, Y., & Stavy, R. (2008). Using computer animation and illustration activities to improve high school students' achievement in molecular genetics. *Journal of Research in Science Teaching*, 45(3), 273-292.
- Maskiewicz, A. C., & Lineback, J. E. (2014). Misconceptions are “so yesterday!” *CBE – Life Sciences Education*, 12, 352-356.
- Mayer, R. E. (2001). *Multimedia learning*. Cambridge, United Kingdom: Cambridge University Press.
- Mayer, R. E. (2011). Instruction based on visualizations. In R. E. Mayer & P. A. Alexander (Eds.), *Handbook of research on learning and instruction*, Abingdon, United Kingdom: Routledge.
- Mayr, E. (1982). *The growth of biological thought: Diversity, evolution and inheritance*. Cambridge, MA: Harvard University Press.
- McCullough, A. R., Parekh, S., Rathbone, J., Del Mar, C. B., & Hoffman, T. C. (2016). A systematic review of the public's knowledge and beliefs about antibiotic resistance. *Journal of Antimicrobial Chemotherapy*, 71, 27-33.

- McElhaney, K. W., Chang, H.-Y., Chiu, J. L., & Linn, M. C. (2015). Evidence for effective uses of dynamic visualisations in science curriculum materials. *Studies in Science Education*, 51(1), 49.
- McNulty, C. A., Boyle, P., Nichols, T., Clappison, P., & Davey, P. (2007). Don't wear me out – The public's knowledge of and attitudes to antibiotic use. *Journal of Antimicrobial Chemotherapy*, 59(4), 727-738.
- Mead, L.S., & Scott, E.C. (2010). Problem concepts in evolution part II: Cause and chance. *Evolution: Education and Outreach*, 8, 261–264.
- Meagher, T. R. (2007). Is evolutionary biology strategic science? *Evolution*, 61(1), 239-244.
- Mendelson, M., Balasegaram, M., Jinks, T., Pulcini, C., & Sharland, M. (2017). Antibiotic resistance has a language problem. *Nature*, 545(7652), 23-25.
- Meyer, J. H. F., & Land, R. (2003). *Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines*. Enhancing Teaching-Learning Environments in Undergraduate Courses. Occasional Report 4. Edinburgh, Scotland: ETL Project.
- Meyer, J. H. F., & Land, R. (2005). Threshold concepts and troublesome knowledge (2): Epistemological considerations and a conceptual framework for teaching and learning. *Higher Education*, 49(3), 373-388.
- Miller, J. D., Scott, E. C., & Okamoto, S. (2006). Public acceptance of evolution. *Science*, 313(5788), 765-766.
- Milne, M. J., & Adler, R. W. (1999). Exploring the reliability of social and environmental disclosures content analysis. *Accounting, Auditing & Accountability Journal*, 12(2), 237-256.
- Molstad, S., Erntell, M., Hanberger, H., Melander, E., Norman, C., Skoog, G., ... & Cars, O. (2008). Sustained reduction of antibiotic use and low bacterial resistance: 10-year follow-up of the Swedish Strama programme. *Lancet Infectious Diseases*, 8(2), 125-132.
- Moreno, R. & Mayer, R. E. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity. *Journal of Educational Psychology*, 91(2), 358-368.
- Nehm, R. H., & Ha, M. (2011). Item feature effects in evolution assessment. *Journal of Research in Science Teaching*, 48(3), 237–256.
- Nehm, R. H., Kim, S. Y., & Sheppard, K. (2009). Academic preparation in biology and advocacy for teaching evolution: Biology versus non-biology teachers. *Science Education*, 93(6), 1122-1146.

- Nehm, R. H., Poole, T. M., Lyford, M. E., Hoskins, S. G., Carruth, L., Ewers, B. E., & Colberg, P. J. S. (2009). Does the segregation of evolution in biology textbooks and introductory courses reinforce students faulty mental models of biology and evolution? *Evolution: Education and Outreach*, 2(3), 527-532.
- Nehm, R. H., & Reilly, L. (2007). Biology majors knowledge and misconceptions of natural selection. *BioScience*, 57(3), 263-272.
- Nehm, R. H., & Ridgway, J. (2011). What do experts and novices “see” in evolutionary problems? *Evolution: Education and Outreach*, 4(4), 666-679.
- Nehm, R. H., & Schonfeld, I. S. (2008). Measuring knowledge of natural selection: A comparison of the CINS, an open-response instrument, and an oral interview. *Journal of Research in Science Teaching*, 45(10), 1131-1160.
- Neuendorf, K. A. (2002). *The content analysis guidebook*. Thousand Oaks, CA: Sage.
- Niebert, K., & Gropengiesser, H. (2015). Understanding Starts in the Mesocosm: Conceptual metaphor as a framework for external representations in science teaching. *International Journal of Science Education*, 37(5-6), 903–933.
- Nieswandt, M., & Bellomo, K. (2009). Written extended response questions as classroom assessment tools for meaningful understanding of evolutionary theory. *Journal of Research in Science Teaching*, 46(3), 333-356.
- Nisbet, M. C., Scheufele, D. A., Shanahan, J., Moy, P., Brossard, D., & Lewenstein, B. V. (2002). Knowledge, reservations, or promise? A media effects model for public perceptions of science and technology. *Communication Research* (29), 584-608.
- Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education*, 87(2), 224-240.
- O’Day, D. H. (2006). Animated cell biology: A quick and easy method for making effective, high-quality teaching animations. *CBE – Life Sciences Education*, 5, 255-263.
- Ogawa, M. (2011). A new age of cooperation and collaboration between school science education research and science communication research. *International Journal of Science Education, Part B*, 1(1), 9-11.
- Olander, C. (2013). Why am I learning evolution? Pointers towards enacted scientific literacy. *Journal of Biological Education*, 47(3), 175-181.
- Olson, S. (2012). Learning about evolution: The evidence base. In J. B. Labov (Ed.), *Thinking evolutionarily: Evolution education across*

- the life sciences: Summary of a convocation* (pp. 25-31). Washington, D.C.: The National Academies Press.
- O'Neill, J. (2015). Securing new drugs for future generations: the pipeline of antibiotics. *The Review on Antimicrobial Resistance*. Retrieved from: https://amr-review.org/sites/default/files/SECURING%20NEW%20DRUGS%20FOR%20FUTURE%20GENERATIONS%20FINAL%20WEB_0.pdf
- O'Neill, J. (2016). Tackling drug-resistant infections globally: Final report and recommendations. *The Review on Antimicrobial Resistance*. Retrieved from: https://amr-review.org/sites/default/files/160518_Final%20paper_with%20cover.pdf
- Opfer, J. E., Nehm, R. H., & Ha, M. (2012). Cognitive foundations for science assessment design: Knowing what students know about evolution. *Journal of Research in Science Teaching*, 49(6), 744–777.
- Orpwood, G. (2007). Assessing scientific literacy: Threats and possibilities. In C. Linder, L. Östman & P. Wickman (Eds.), *Promoting scientific literacy: Science education research in transaction. Proceedings of the Linneaus Tercentenary Symposium* (pp. 120-129). Uppsala, Sweden: Geotryckeriet.
- Ortiz-Cordova, A., Yang, Y., & Jansen, B. J. (2015). External to internal search: Associating searching on search engines with searching on sites. *Information Processing & Management*, 51(5), 718-736.
- Paivio, A. (1971). *Imagery and verbal processes*. Oxford, England: Holt, Rinehart & Winston.
- Pardo, R., & Calvo, F. (2002). Attitudes toward science among the European public: A methodological analysis. *Public Understanding of Science*, 11(2), 155-195.
- Parliamentary Assembly of the Council of Europe (2007). *The dangers of creationism in education*. Committee on Culture, Science and Education, Resolution 1580. Retrieved from: <http://assembly.coe.int/nw/xml/XRef/Xref-XML2HTML-EN.asp?fileid=17592&lang=en#>
- Phillips, L. M., Norris, S. P., & Macnab, J. S. (2010). *Visualization in mathematics, reading and science Education* (Vol. 5). Dordrecht, The Netherlands: Springer.
- Plass, J. L., Homer, B. D., & Hayward, E. O. (2009). Design factors for educationally effective animations and simulations. *Journal of Computing in Higher Education*, 21(1), 31-61.

- Potter, J. P., & Levine-Donnerstein, D. (1999). Rethinking validity and reliability in content analysis. *Journal of Applied Communication Research*, 27(3), 258-284.
- Price, R. M., Andrews, T. C., McElhinny, T. L., Mead, L. S., Abraham, J. K., Thanukos, A., & Perez, K. E. (2014). The genetic drift inventory: A tool for measuring what advanced undergraduates have mastered about genetic drift. *CBE – Life Sciences Education*, 13(1), 65-75.
- Richard, M., Coley, J. D., & Tanner, K. D. (2017). Investigating undergraduate students' use of intuitive reasoning and evolutionary knowledge in explanations of antibiotic resistance. *CBE – Life Sciences Education*, 16:ar55, 1-16.
- Roberts, D. A. (2007). Scientific literacy/Science literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 729-780). Mahwah, NJ: Lawrence Erlbaum Associates.
- Robson, R. L., & Burns, S. (2011). Gain in student understanding of the role of random variation in evolution following teaching intervention based on Luria-Delbruck experiment. *Journal of Microbiology & Biology Education*, 12(1), 3-7.
- Roche, J. P., & Muskavitch, M. A. T. (2003). Limited precision in print media communication of West Nile virus risks. *Science Communication*, 24(3), 353-365.
- Ross, P. M., Taylor, C. E., Hughes, C., Kofod, M., Whitaker, N., Lutze-Mann, L., & Tzioumis, V. (2010a). Threshold concepts: Challenging the way we think, teach and learn in biology. In J. H. F. Meyer, R. Land & C. Baillie (Eds.), *Threshold concepts and transformational learning*, (pp. 165-177). Thousand Oaks, CA: Sage.
- Ross, P. M., Taylor, C. E., Hughes, C., Whitaker, N., Lutze-Mann, L., Kofod, M., & Tzioumis, V. (2010b). Threshold concepts in learning biology and evolution. *Biology International*, 47, 47-54.
- Rowbottom, D. P. (2007). Demystifying threshold concepts. *Journal of Philosophy of Education*, 41(2), 263- 270.
- Rughinis, C. (2011). A lucky answer to a fair question: Conceptual, methodological, and moral implications of including items on human evolution in scientific literacy surveys. *Science Communication*, 33(4), 501-532.
- Rundgren, C-J., & Tibell, L. A. E. (2010). Critical features of visualizations of transport through the cell membrane – An empirical study of upper secondary and tertiary students' meaning-making of a still

- image and an animation. *International Journal of Science and Mathematics Education*, 8, 223-246.
- Ryan, G. W., & Bernard, H. R. (2003). Techniques to identify themes. *Field methods*, 15(1), 85-109.
- Ryoo, K., & Linn, M. C. (2014). Designing guidance for interpreting dynamic visualizations: Generating versus reading explanations. *Journal of Research in Science Teaching*, 51(2), 147-174.
- Scharmann, L. C. (1994). Teaching evolution: Designing successful instruction. *Journal of Science Teacher Education*, 5(4), 122-129.
- Schäfer, M. S. (2012). Taking stock: A meta-analysis of studies on the media's coverage on science. *Public Understanding of Science*, 21(6), 650-663.
- Scott, J. G., Cohen, D., DiCicco-Bloom, B., Orzano, A. J., Jaen, C. R., & Crabtree, B. F. (2001). Antibiotic use in acute respiratory infections and the ways patients pressure physicians for a prescription. *Journal of Family Practice*, 50(10), 853-858.
- Serafini, A., & Matthews, D. M. (2009). Microbial resistance to triclosan: A case study in natural selection. *The American Biology Teacher*, 71(9), 536-540.
- Shamos, M. (1995). *The myth of scientific literacy*. New Brunswick, NJ: Rutgers University Press.
- Shtulman, A. (2006). Qualitative differences between naïve and scientific theories of evolution. *Cognitive Psychology*, 52(2), 170-194.
- Shen, B. S. P. (1975). Science literacy and the public understanding of science. In S. B. Day (Ed.), *Communication of scientific information* (pp. 44-52). Basel, Switzerland: S. Karger AG.
- Sinatra, G. M., Brem, S. K., & Evans, M. (2008). Changing minds? Implications of conceptual change for teaching and learning about biological evolution. *Evolution: Education and Outreach*, 1(2), 189-195.
- Singh, N., Sit, M. T., Chung, D. M., Lopez, A. A., Weerackoon, R., & Yeh, P. J. (2016). How often are antibiotic-resistant bacteria said to “evolve” in the news? *PloS One*, 11(3), e0150396.
- Sjöström, J., Eilks, I., & Zuin, V. G. (2016). Towards eco-reflexive science education. *Science & Education*, 25(3), 321-341.
- Sjöström, J. (2017). *Vision III: Framing STEM education with moral-philosophical-existential-political alternatives*. Paper presented at the 12th conference of the European Science Education Research Association (ESERA), Dublin, Ireland.

- Skoog, G. (2005). The coverage of human evolution in high school biology textbooks in the 20th century and in current state science standards. *Science & Education*, 14(3-5), 395-422.
- Slovic, P. (1987). Perception of risk. *Science*, 236(4799), 280-285.
- Smith, J. J., Baum, D. A. & Moore, A. (2009). The need for molecular genetic perspectives in evolutionary education (and vice versa). *Trends in Genetics*, 25(10), 427-429.
- Smith, G., Golomb, M., Billstein, S., & Smith, S. (2015). The Luria-Delbrück fluctuation test as a classroom investigation in Darwinian evolution. *The American Biology Teacher*, 77(8), 614-619.
- Smith, M. U. (2010a). Current status of research in teaching and learning evolution: I. philosophical/epistemological issues. *Science & Education*, (19), 523-538.
- Smith, M. U. (2010b). Current status of research in teaching and learning evolution: II. pedagogical issues. *Science & Education*, (19), 539-571.
- Smith, M. U., & Siegel, H. (2016). On the relationship between belief and acceptance of evolution as goals of evolution education: Twelve years later. *Science & Education*, (25), 473-496.
- Swarat, S., Light, G., Park, E. J., & Drane, D. (2011). A typology of undergraduate students' conceptions of size and scale: Identifying and characterizing conceptual variation. *Journal of Research in Science Teaching*, 48(5), 512-533.
- Swarts, F. A., Anderson, O. R., & Swetz, F. J. (1994). Evolution in secondary-school biology textbooks of the PRC, the USA, and the latter stages of the USSR. *Journal of Research in Science Teaching*, 31(5), 475-505.
- Sweller, J. (1999). *Instructional design*. Camberwell, Victoria, Australia: ACER Press.
- Stevens, A. M., Smith, A. C., Marbach-Ad, G., Balcom, S. A., Buchner, J., Daniel, S. L., ... & Yarwood, A. (2017). Using a concept inventory to reveal student thinking associated with common misconceptions about antibiotic resistance. *Journal of Microbiology & Biology Education*, 18(1), 1-6.
- Tasker, R., & Dalton, R. (2006). Research into practice: Visualisation of the molecular world using animations. *Chemistry Education Research and Practice*, 7(2), 141-159.
- Taylor, C. (2006). Threshold concepts in biology: Do they fit the definition? In J. H. F. Meyer & R. Land (Eds.), *Overcoming barriers to student understanding: threshold concepts and troublesome knowledge* (pp. 87-99). Abingdon, United Kingdom: Routledge.

- The Swedish National Agency For Education / Skolverket. (2011). *Läroplan för grundskolan, förskoleklassen och fritidshemmet 2011* [Curriculum for the Compulsory School, Preschool Class and the Leisure-time Centre 2011]. Stockholm: Edita.
- Tibell, L., & Harms, U. (2017). Biological principles and threshold concepts for understanding natural selection – Implications for developing visualizations as a pedagogic tool. (*Manuscript co-submitted along with Paper III of the dissertation*).
- Tibell, L., Höst, G. E., Schönborn, K. J., & Bohlin, G. (2012). Att inSe – Om visualisering i biologiundervisningen. *Bi-lagan*, (3), 12-17.
- Trumbo, C. W. (2012). The effect of newspaper coverage of influenza on the rate of physician visits for influenza 2002-2008. *Mass Communication and Society*, 15(5), 718-738.
- Tshuma, T., & Sanders, M. (2014). Textbooks as a possible influence on unscientific ideas about evolution. *Journal of Biological Education*, 49(4), 354-369.
- Tversky, B., Bauer Morrison, J., & Betrancourt, M. (2002). Animation: Can it facilitate? *International Journal of Human-Computer Studies*, 57, 247-262.
- Vallin, M., Polyzoi, M., Marrone, G., Rosales-Klintz, S., Wisell, K. T., & Lundborg, C. S. (2016). Knowledge and attitudes towards antibiotic use and resistance - A latent class analysis of a Swedish population-based sample. *PloS one*, 11(4), e0152160.
- van der Saanden, M. C. A., & de Vries, M. J. (Eds.) (2016). *Science and Technology Education and Communication – Seeking Synergy*. Rotterdam, The Netherlands: Sense.
- van der Schee, E., de Jong, J. D., & Groenewegen, P. P. (2012). The influence of a local, media covered hospital incident on public trust in health care. *European Journal of Public Health*, 22(4), 459-464.
- Watkins, R. R., & Bonomo, R. A. (2016). Overview: Global and local impact of antibiotic resistance. *Infectious disease clinics of North America*, 30(2), 313-322.
- Welbourne, D. J., & Grant, W. J. (2016). Science communication on YouTube: Factors that affect channel and video popularity. *Public Understanding of Science*, 25(6), 706-718.
- Weibull, L., Oscarsson, H., & Bergström, A. (2012) *Swedish trends 1986-2011*. SOM-rapport 2012:27. Göteborg, Sweden: SOM Institutet.
- White, P. J. T., Heidemann, M. K., & Smith, J. J. (2013). A New Integrative Approach to Evolution Education. *BioScience*, 63(7), 586-594.

- Wilensky, U., & Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology*, 8(1), 3-19
- Wolf, A., & Akkaraju, S. (2014). Teaching evolution: From SMART objectives to threshold experience. *Journal of Effective Teaching*, 14(2), 35-48.
- World Economic Forum. (2016). *Global Risks Report 2016: 11th Edition*. Retrieved from: <https://www.weforum.org/reports/the-global-risks-report-2016/>
- World Health Organization. (2011). *Director-General Statement. World Health Day 2011*. Retrieved from: http://www.who.int/mediacentre/news/statements/2011/whd_20110407/en/index.html
- You, M., Joo, J., Park, E., Noh, G-H., & Ju, Y. (2017). Emerging infectious disease content in newspaper editorials: Public concern or leadership issue? *Science Communication*, 39, 3, 313-337.

Appendix A – Tillståndsblankett

Evolution och mediciner som slutat fungera

Presentation

Mitt namn är Gustav Bohlin och jag är doktorand vid Linköpings universitet. Jag och mina kollegor driver ett forskningsprojekt som handlar om att underlätta undervisningen och hjälpa elever till bättre förståelse av biologisk evolution. I projektet används animationer av antibiotikaresistens som ett lärandeverktyg. Du och din klass bjuds nu in att delta i projektet som en del av er NO-undervisning. Ni kommer bland annat få arbeta med en nyskapad animation.

Syfte och genomförande

Huvudsyftet är att undersöka på vilka sätt olika tekniker och exempel kan stödja elever i sin förståelse av evolutionsteorin. Vi vill också undersöka hur digital teknik kan gestalta abstrakta begrepp och hur de på detta sätt kan göras tydliga och förståeliga för elever. Studien kommer genomföras som en del av undervisningen och äga rum i skolans befintliga klassrum. Elever som deltar kommer få svara på skriftliga frågor, arbeta med en gruppuppgift och arbeta med animationer med hjälp av en dator. Ett fåtal enskilda intervjuer kan komma att genomföras vid ett senare tillfälle. Totalt kommer undersökningen inte ta mer än två timmar.

Frivilligt deltagande

För att kunna medverka i studien behöver du (och även din målsman om du är under 16 år) fylla i ett deltagandeavtal på baksidan av detta brev. Deltagande i den här studien är helt frivilligt och man kan när som helst välja att avbryta sitt deltagande.

Tack för din medverkan!

Gustav Bohlin, doktorand vid Institutionen för Teknik och Naturvetenskap
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Deltagandeavtal

Detta avtal är ett medgivande till materialanvändning från den som deltagit i en enkätundersökning, en intervju eller vid en bild och/eller ljudupptagning med avsikt att ge råmaterial till forskning vid institutionen ITN på Linköpings universitet.

Användande av materialet

Användande av materialet avser t.ex. analys av deltagarnas interaktion med såväl varandra som maskin- och mjukvara. Råmaterialet kommer att förvaras på ett säkert sätt och ej spridas utanför den inblandade forskargruppen.

☐ Jag medger

☐ Jag medger ej

att delta i studien vilket innebär att enkät- och intervjumaterial, upptaget bild- och ljudmaterial där jag medverkar samt det material jag varit med och skapat under projektet får användas i *forskningssyfte*, förutsatt att det hanteras i enighet med vedertagen svensk forskningsetik.

Presentation av resultat från studie

Text Ja ☐ Nej ☐

Bilder Ja ☐ Nej ☐

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Jag medger att enkät- och intervjumaterial såsom avidentifierade och anonymiserade citat från video och ljudupptagningar får användas i samband med *presentationer* och *publicering* av studiens resultat.

Ångerrätt

Jag kan när jag vill ändra mina nuvarande medgivanden och avbryta mitt deltagande i studien. Förändringar i avtalet blir giltiga när de tas emot av kontaktpersonen och gäller inte retroaktivt avseende publicering utförd enligt tidigare avtal.

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