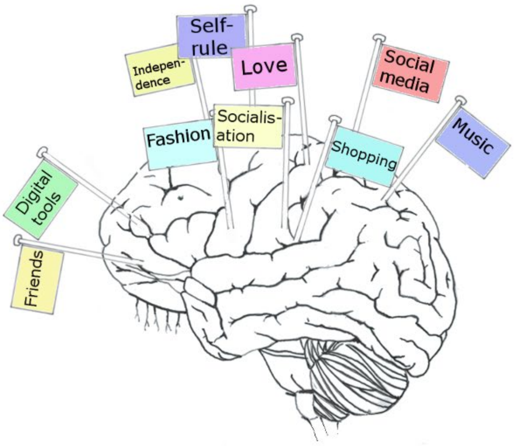

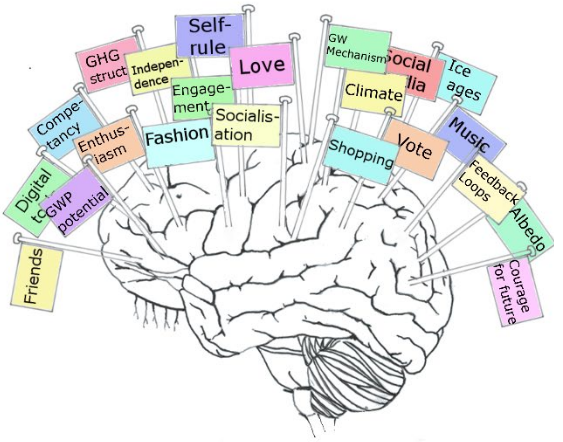

Using 3D serious gaming interventions to promote climate science literacy in the 12-13-year age group

Inez Harker-Schuch

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The Fenner School of Environment and Society

This research was supported by an Australian Government Research Training Program (RTP) Scholarship.

Declaration by author

I, Inez Harker-Schuch, declare that this thesis and the work presented in it are my own original work and contains no material previously published or written by another person except where attribution has been clearly stated in the text. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself. Where I have quoted from the work of others, a citation has been consistently provided. This thesis contains no material which has been accepted for the award of any degree or diploma in any university.

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Contributions to the thesis

Chapter 1

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Chapter 6

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Attestation of Contributions to the Thesis and Component Manuscripts

On behalf of all contributors, I certify the above accurately represents our contributions to the candidate's thesis and its component manuscripts.

Franklin P. Mills

Franklin P Mills, Chair of Supervisory Panel, Australian National University

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This thesis is dedicated to Uncle David. I hope, wherever you are, you think it matters.

Abstract

Despite more than 30 years of communication and public awareness of climate change, there continues to be a widespread lack of understanding of climate science and a lack of engagement in climate-friendly activities. Worldview bias is considered one of the most pernicious and difficult communication and education barriers with regard to public engagement in relation to climate change. For example, socio-cultural worldview is known to be the strongest predictor of adult attitudes related to climate change in the US and Australia, even stronger than educational attainment or scientific literacy. Due to this influence, efforts aimed at encouraging climate-friendly attitudes and behaviour have prioritised engagement with identity constructs such as values, ideology, and self-identity and are considered more effective at motivating climate-friendly attitudes than efforts to improve knowledge deficit. There are, however, several important considerations that have been overlooked with regard to the value and influence of the knowledge deficit model, including: knowledge deficit as a treatment or intervention; the age when such interventions should start as a factor for worldview development; and the specific content or curriculum that forms the foundation of the specific knowledge deficit intervention in relation to climate education. This thesis revisits knowledge deficit as an intervention and explores the role of knowledge deficit in the public education arena in the early adolescent age group via the interventions of a 3D interactive serious educational climate science game. In order to revisit knowledge deficit in relation to worldview development, literature pertaining to the intellectual and physiological development of early adolescents was reviewed, finding that early adolescents are a highly suitable age group for knowledge deficit interventions. To ensure this age group are receptive to learning about Earth's climate, early adolescent climate opinion data was collected and analysed (n=463), finding that early adolescents are more concerned (Austria: 85%, Australia: 89%) about climate change than their respective or proxy adult population (Austria: 71%, Australia: 63%) and their opinions (that climate change is something to worry about, is caused by humans, and is happening now) are all correlated. To examine knowledge deficit, a prototype climate science literacy (CSL) framework was constructed which measured incidental (pre-existing) knowledge and showed shared knowledge levels and patterns across borders (culture, language, education system). For the purpose of this thesis, specifically in relation to knowledge deficit interventions, CSL is defined here as a systematic and integrated understanding of how the natural climate system works, including drivers of natural variation, and the roles of feedback systems and anthropogenic emissions in driving climate change. After playing a proof-of-concept 3D interactive climate science game (n=401), results show that shared knowledge patterns persist and suggest that CSL may be able to be improved in this age group, particularly at the unistructural and multistructural levels (SOLO Taxonomy Levels 1 and 2). These results suggest that knowledge deficit interventions, for example using a 3D interactive climate science game, can potentially improve knowledge in early adolescents. Such interventions, delivered at a crucially formative age, could help counter the worldview effects that entrench climate-unfriendly attitudes in many sections of the population and help trigger a transformation towards a sustainable future.

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List of abbreviations

ANU - Australian National University

CHS1 - coded for Canberra High School 1

CHS2 - coded for Canberra High School 2

CHZ - circumstellar habitable zone

COP - Conference of the Parties

CSL - Climate science literacy

ESS – Earth System Science

GHG - Greenhouse gas

GMST - Global mean surface temperature

GWP - Global warming potential

IPCC - Intergovernmental Panel on Climate Change

KAB - Knowledge-Attitude-Behaviour

KD - Knowledge Domain

LMS - Learning Management System

LO - Learning Objectives

NASA - National Aeronautics and Space Administration

NGSS - Next Generation Science Standards

NOAA - National Oceanic and Atmospheric Administration

OECD - Organisation for Economic Co-operation and Development

PISA - Programme for International Student Assessment

SEG - Serious educational game

SEGD - Serious educational game design

SHS1 - coded for Sydney High School 1

SHS2 - coded for Sydney High School 2

SOLO - Structure of Observed Learning Outcomes from Biggs and Collis

ST - SOLO Taxonomy level

UK - United Kingdom

UNDP - United Nations Development Programme

UNICEF - United Nations International Children's Emergency Fund

UNO - United Nations Organisation

US - United States

USGCRP - US Global Change Research Program

VHS1 - coded for Vienna High School 1

VHS2 - coded for Vienna High School 2

VLE - Virtual Learning Environment

Manuscripts and publication during candidature

Peer-reviewed journal articles submitted and completed during my PhD candidature

Harker-Schuch IE, Lade SJ, Mills FP, Colvin RM. ‘Opinions of 12 to 13-year-olds in Austria and Australia on the worry, cause and imminence of Climate Change’, *Ambio*, currently under review.

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May M, Neutszky-Wulff C, Rosthøj S, Harker-Schuch IE, Chuang V, Bregnhøj H, Bugge Henriksen C. ‘A pedagogical design pattern framework for sharing experiences and enhancing communities of practice within online and blended learning’. Læring og Medier (LOM), 2016 *9*(16)

Chuang V, Ceballos A, Bundgaard H, Furu P, Bregnhøj H, Harker-Schuch IE, Bugge Henriksen C. 'Visualising the dynamics of online learning communities in online and blending learning courses; experiences from three university courses'. Læring og Medier (LOM), 2016 *9*(16)

Bregnhøj H, Neutszky-Wulff C, Ehrensvärd M, Rosthøj S, Sichlau Bruun C, Harker-Schuch IE, Lysák M, Chuang V. 'The Use of Videos in Teaching - Some Experiences from the University of Copenhagen' Læring og Medier (LOM), 2016 *9*(16)

Harker-Schuch IE, Chuang V, Bregnhøj H, Furu P, Andersen I, Bugge Henriksen C. 'Facilitating online project collaboration - new directions for learning design'. Læring og Medier (LOM), 2016 *9*(16)

Preface

This thesis has been formatted as a series of manuscripts, each focusing on a particular aspect of the thesis research. They are preceded by an introduction to the research domain and followed by a synthesis of key conclusions. Chapter 2 has been published as a book chapter from a refereed conference proceeding; Chapters 3 is currently under review with the peer-reviewed journal *Ambio*. Chapter 4 is currently under peer review with the '*International Journal of STEM education'*. Chapter 5 has been published in '*Computers & Education'*. Linking text has been included between each manuscript to provide further context and smooth the transitions between chapters. For example, although I have received the peer review for Chapter 4, I will not be able to complete the revisions to this manuscript before the deadline of thesis submission. Therefore, since these comments from the reviewer are important to the findings of the thesis, I have extended the bridging material at the end of Chapter 5 in order to address the reviewer's comments. The chapters were published (or submitted for publication) in the order 2, 5, 3, and then 4. Comments from a reviewer for Chapter 4 prompted a revised assessment of some aspects of Chapter 5. Since Chapter 5 has been published, these revisions are included in the bridging material after Chapter 5 and in the Conclusions, Chapter 6. Supplementary material, including the full survey instrument, is included in the Appendices.

1. Introduction

1.1. Overview

> ‘Well, you can say – which I think is true – people won’t care about things that they don’t know about and have never seen, and that your first job is to make it clear what a wonderful world the natural world is. You can’t expect people to spend money, or time, or worry, or concern, or political action about an issue about which they really know nothing – so one comes before the other….’
>
> Sir David Attenborough, 'The Economist Asks', 2020

Addressing knowledge deficit by education to improve knowledge on a topic can be an important pathway to motivating citizens to adopt new attitudes and behaviours. This is evident in education campaigns that have increased public political engagement or social equality (Sidanius & Sinclair, 2006; Sunshine Hillygus, 2005), reduced infant mortality (Ram et al., 2017), decreased transmission of HIV/AIDS (Gao et al., 2012; Nubed & Akoachere, 2016; The International Bank for Reconstruction and Development, 2002), and improved public health (Cutler & Lleras-muney, 2006; Hahn & Truman, 2015; Silles, 2009), amongst many others. For climate change, however, the knowledge deficit pathway has been perceived as ineffective (Hornsey & Fielding, 2020; Pearce et al., 2015; Potter & Oster, 2008), with most efforts to engage the public employing behavioural theory rather than attempting to inform or educate.

Three significant factors that may have negatively affected the perceived validity of knowledge deficit might be the mixed interpretations of the term knowledge deficit, the assumption that the effect of worldview bias applies equally to all individuals, and the tension between the cultures of climate communication and climate education research (Azevedo & Marques, 2017). Regarding interpretations, among those who argue that knowledge deficit is ineffective, a view that is predominantly found in the climate communication literature, the term is frequently operationalised as background or incidental[1] knowledge (see Section 1.3.3.7 for further discussion) or the gap between lay-people and experts (Blennow et al., 2016; Geiger et al., 2019; McCaffrey & Rosenau, 2012; Pearce et al., 2015; Potter & Oster, 2008). For those who maintain that knowledge deficit is important, particularly with regard to science or climate literacy, the term is interpreted as an intervention i.e. via learning or education (McCaffrey & Rosenau, 2012; McCaffrey & Buhr, 2008; Shi et al., 2015, 2016). These differing interpretations create definitional challenges for research at the nexus of climate communication and climate education. In order to position these interpretations within the climate communication and climate education landscape, this thesis revisits the role of knowledge deficit in the context of worldviews. This involves interrogating the interface between climate communication and climate education and re-examining the premise that challenges education as a valid intervention toward promoting climate-friendly attitudes and behaviours. As well as unpacking the tensions that exist between the disciplinary cultures of climate communication and climate education, this dissertation investigates a hitherto unexplored pathway for promoting climate-friendly attitudes and behaviours that incorporates consideration of intellectual and worldview development. It also investigates the potential role of early adolescents in the climate communication and climate education arena. Finally, these threads are woven together via the exploration of the potential contribution of educational gaming interventions developed for early adolescents, designed with consideration of their intellectual and worldview developmental stages.

1.2. Rationale

As we move further into the 21st Century, the impacts and consequences of anthropogenic greenhouse gas emissions are beginning to be felt across the planet, both increasing our vulnerability to the future and intensifying the need to reduce these emissions. While efforts have been made to reach a global agreement to prevent dangerous warming (UNFCCC, 2016), collective, international, and meaningful emission reduction is still many thousands of gigatons of CO_2-equivalent away from reducing our

---

[1] Incidental knowledge, for the purpose of this thesis, refers to background, prior or incidental knowledge that has been acquired unconsciously, or has been learned by an individual in an unintended and unplanned manner (see Kelly, 2012). I acknowledge that the terms ‘background’ and ‘prior’ have additional meanings of which further edification is beyond the scope of this thesis.

carbon footprint enough to avoid widespread dangerous climate impacts (Mahapatra & Ratha, 2017; IPCC, 2018).

Although climate change as a phenomenon is well-understood by climate scientists (IPCC, 2014), understanding and agreement on the need for urgent action in the broader public arena is far less prevalent (Hornsey & Fielding, 2020; Leiserowitz, 2007; Ranney & Clark, 2016; van Linden et al., 2015). Distrust in the findings of the climate research community (Gifford, 2011; Goodwin & Dahlstrom, 2014; Sarewitz, 2011; Shwom et al., 2010) has negatively affected public agreement and led to polarisation of the climate change issue along political lines in the United States (US) (Feinberg & Willer, 2013; McCright & Dunlap, 2011b) and, to a lesser degree, Australia (Hornsey et al., 2018). This lack of public agreement has, as a consequence, retarded the political impetus to reduce emissions in these countries (den Elzen et al., 2019). In nations where the polarisation of this issue is modest or weak, such as those in the European Union (EU), there is stronger leadership in international climate policy toward emission reduction (Oberthür & Kelly, 2008; Wurzel et al., 2016). The observed ideological polarisation in the US and Australia is widely accepted to be a result of socio-cultural worldview (Kahan et al., 2011; Kunkle & Monroe, 2019; Weber, 2010) which, according to Newman et al., ‘consists of a specific way of structuring social relations and represent a particular set of perceptions, values, emotions, and interests’ (2018, page 989). Essentially, worldview is an organising system for making sense of the world that incorporates normative preferences for how an individual believes the world ought to be. In the US and Australia, the influence of worldview on climate change attitudes has been attributed to political division over climate change which has seen ideology, interest, and identity-based drivers exerting stronger influence than scientific evidence on opinions about climate change (Colvin et al., 2020). As a result, social divides on attitudes toward climate change fall along ideological lines, meaning there is not just a gap between the lay public as a whole and expert understanding, but there are divides between different publics, based on their political alignment (Reese, 2016).

A traditional approach to building public engagement with issues of science has been the provision of more information (Guy et al., 2014). This intervention, known as knowledge deficit (Corner &

Groves, 2014), assumes there is an education or expertise gap between lay- and specialist-knowledge and, that with sufficient schooling or training and by possessing factual information, misunderstandings and conflicts arising from this deficit will be overcome. In response to this, efforts were undertaken to investigate the role of knowledge on climate change attitudes and engagement and it was found that ‘ignorance about the details of climate change is NOT what prevents greater concern and action’ (Moser & Dilling, 2012, page 163; uppercase in original text). Several factors were suggested as to why knowledge had limited effectiveness, including the diversity/size of the global audience, framing, lack of trust in science, the difficulty of understanding the science, the ‘two-sided’ perception perpetuated by the media, amongst many others. However, the effect of socio-cultural worldview has been widely accepted as the main barrier to improving climate-friendly attitudes and engagement in the public arena and Kahan’s work (2015; 2011; 2012) examining cultural cognition and its influence on climate change opinion, in particular, has provided an evidence base for this rationale (Blennow et al., 2016; Geiger et al., 2019; McCaffrey & Rosenau, 2012; Pearce et al., 2015; Potter & Oster, 2008). The core message from Kahan’s research is that when asked about their climate attitudes, people will filter their perceptions and incidental understanding through the lens of their existing worldview, even if this involves misinterpreting data. Thus, efforts aimed at encouraging climate-friendly attitudes and behaviour have prioritised engagement with identity constructs such as values, ideology, and self-identity and these efforts are placed ahead of the provision of scientific knowledge (Wolsko et al., 2016). Consequently, socio-cultural worldview interventions and knowledge deficit interventions can be perceived as zero-sum pathways for climate communication. I argue that this need not be the case.

The research that investigated knowledge in the context of the influence of worldview tended to focus on knowledge as an existing condition, rather than knowledge as an intervention. Or put differently, it focused on climate attitudes dependent on an existing knowledge base, rather than filling or modifying a knowledge gap. As shown by Guy et al. ‘many of the empirical investigations into the role of knowledge [over socio-cultural worldviews in shaping public opinion on climate change] have involved proxy measures (e.g. broad science literacy measures or self-perceived amount of climate change knowledge) rather than measures of people's specific knowledge about climate change' (2014, page 421). This was further elaborated by McCaffrey and Rosenau (2012) who state that Kahan's work on worldview did not 'examine people's understanding of climate, focusing instead on general science literacy, numeracy and cultural frames'(page 635). This distinction raises important questions about the interface between knowledge and worldview, and in addition the influence of general versus specialised knowledge.

While research shows that general science knowledge/literacy, numeracy knowledge, and/or educational attainment are frequently trumped by worldview, the same cannot be said for specific climate science knowledge, nor for knowledge deficit. For example, prominent studies have yielded findings that climate-specific knowledge is an important driver of climate-friendly attitudes (Aksit et al., 2018; McCaffrey & Rosenau, 2012; Shi et al., 2015, 2016; Tobler et al., 2012). This is even so for adults, an age group that has (1) established worldviews and (2) an existing knowledge base about climate change, regardless of whether the existing knowledge reflects the scientific consensus. Furthermore, in a review of 78 papers exploring the role of knowledge related to the climate energy budget, Mitttenzwei et al. concluded that it is 'likely that the influence of knowledge on attitudes and behaviour towards climate change increases the more specific it becomes' (2019, page 13). However, in a study exploring the effect of knowledge deficit on US middle school teachers' attitudes to teaching climate change (n=1500) Plutzer and Hannah (2018) found that personal political orientations are more likely to play a larger role in their teaching strategies than an effect of increased coursework. Not only does this support Kahan's findings, it was reported that teachers 'displaying a small government ideology are more likely to encourage debate' which, as a result, may increase the perception of scientific uncertainty in the classroom (ibid, page 313).

For young people, however, the effect of worldview on climate-friendly attitudes and engagement is unlikely to be as influential as that observed in adults because socio-cultural identities are still forming in this age group (Corner et al., 2015; Stevenson et al., 2014). As a result, the effect of knowledge, particularly that related to education since they are at an age when they are expected to be learning, may be a stronger predictor than the influence of worldview. Knowledge deficit research in adolescents and young people suggests that knowledge interventions do increase concern and engagement in relation to climate change (McCaffrey & Rosenau, 2012; Mittenzwei et al., 2019; Ranney & Clark, 2016; Shi et al., 2016; Stevenson et al., 2014). However, the workings behind this process are complicated and influenced by similar factors that impede climate communication in adults (further discussed in Section 1.3). In addition, while worldview may not be influential in early teenage years, it will exert an increasing influence as adolescents age, and several factors, chief amongst them worldview, needs to be considered when exploring climate-friendly attitudes and behaviour.

This interstitial space between worldview and knowledge deficit therefore lies with early adolescents: those who are just entering the level of cognitive development appropriate for grappling with the inherent complexity of the science of climate change, but who have not yet reached the stage of development in which worldviews are formed (Corner et al., 2015; Stevenson et al., 2014). It is this opportunity for knowledge-based interventions with early adolescents that is the focus of the present thesis.

In order to revisit the utility of knowledge deficit as an intervention and investigate the potential for a positive sum pathway between worldview and knowledge deficit, this chapter explores contributions from climate communication theory by unpacking the known barriers and avenues in climate communication research as a theoretical basis for knowledge deficit interventions (Section 1.3). For the purpose of this thesis, I use the term knowledge deficit intervention to mean active efforts in learning or education intended to improve an individual's understanding and knowledge. With public attitudes on climate change being the primary intercept between climate communication and knowledge deficit interventions (i.e. it is the aim of both disciplinary cultures to improve climate-friendly attitudes and behaviour), I examine public opinions about climate change as a measure of current attitudes and public engagement on the issue (Section 1.4). As an extension of this intercept and the need to overcome the mass communication problem of climate change, I outline why knowledge deficit interventions, particularly in a formal education setting, offer underutilised opportunities to promote climate-friendly attitudes and engagement (Section 1.5). Since this thesis examines the knowledge deficit of climate science in early adolescents, in recognition that such interventions need to include the needs and interests of those it aims to reach, the use and validity of 3D interactive digital games are then discussed (Section 1.6) both as pedagogical tools in their own right and specifically in relation to climate science literacy (CSL). The themes described here will be expanded upon in more detail in subsequent chapters in which they each receive a more thorough theoretical and/or empirical treatment. Overall, this chapter outlines the theoretical context and general review of the thesis before outlining the research aims, research questions and methodology as the lead into the substantive content chapters.

In general, there are five research tasks that are undertaken in this thesis which have collectively contributed to the development of a framework to teach climate science in formal education environments and make up the body of this work. The first of these five tasks is to review the literature on climate communication and climate education and position knowledge deficit within the context of this landscape as described in the previous paragraph (Chapter 1). The second is to select, via literature review, a suitable age group for knowledge deficit interventions (Chapter 2) which incorporates the theoretical and practical implications from the previous chapter. The third task is to investigate opinions about climate change in this age group in comparison to adult and older adolescent perspectives on climate change (Chapter 3) and explore the implication of worldview and knowledge of early adolescent risk perception. The fourth task is to test knowledge structured within a prototype CSL framework and, as a consequence, revise the CSL framework (Chapter 4) into orders of observed and tested complexity i.e. examining what this age group understands about age-relevant climate science. This structure of observed and tested complexity establishes the basis of a climate science literacy (CSL) framework which, in turn, forms the basis of a proof-of-concept 3D interactive, digital climate science game. The fifth and final task tests the CSL framework and assesses the efficacy of using this game tool as a vehicle in knowledge deficit interventions to improve climate science literacy (CSL) (Chapter 5).

1.3. Climate communication theory and practice

1.3.1. *Climate communication in its complex social context*

Climate communication, as a research endeavour is a relatively new field of knowledge (Chadwick, 2017). Prior to the early 1990s, climate communication was driven largely by research institutions, media attention, and interest-lobby groups (Moser, 2010; Weingart et al., 2000). These efforts lead to a dramatic increase in media coverage and, as a consequence, public awareness, but the issue was frequently characterised by discourse that framed climate change in alarmist and catastrophic frames (Boykoff & Boykoff, 2004, 2007; Grundmann & Krishnamurthy, 2010). With the enormous social, economic, and political upheaval that a warming planet implied, the issue in the US quickly polarised along socio-economic and political lines but unified majority views aligned with the scientific consensus in Germany, France, and the United Kingdom (UK) (Grundmann & Krishnamurthy, 2010).

Those with vested interests in industry (and, by default, their reliance on fossil fuels) began rejecting the science outright (Brulle, 2019; Rich, 2018; Supran, Geoffrey; Oreskes, 2017) while those who accepted the research findings and, according to Moser, the 'spectre of serious impacts' elevated scientists to the status of 'prophets of an ominous truth' (Moser, 2010, page 32). Mass media outlets in the US, exploiting the anxiety felt on both sides of this topic and their convention of reporting 'two sides' of a problem (Boykoff & Boykoff, 2007; Grundmann & Krishnamurthy, 2010), provoked and amplified further discord on the issue, giving particular focus to unproven science and the dependence of society on coal, oil, and gas (Moser, 2010). As a result, opinions of climate change in the broader US public arena split along the two sides of the media discourse (conservative/Republican alignment with denialist ideologies and liberal/Democrat alignment with advocacy ideologies) (Bolsen & Shapiro, 2018). The global general public were, according to Moser, 'insufficiently trained' and sufficiently distracted to follow the [media] debate...'; resulting in a 'basic understanding of the problem that remains superficial and vulnerable to frequent revision' (ibid, page 32).

In the UK, France, and Germany, climate communication aligns more coherently with the scientific consensus and, while there is evidence of ideological polarisation in the UK (though not to the same extent as in the US and Australia), this is missing in France and Germany (Grundmann & Krishnamurthy, 2010; Whitmarsh, 2008). However, similarly to the US, individual scientific understanding of the climate issue in these countries is low (Kahan, 2015; McCaffrey & Buhr, 2008) and has been negatively impacted by the increasing prevalence of a post-fact[2] society; a socio-cultural phenomenon that permits individuals to have an opinion on an issue even if they do not have any meaningful, useful knowledge or expertise on that issue (Higgins, 2016; Lubchenco, 2017).

Defined by the Oxford English Dictionary as ‘relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belief’, post-fact rhetoric undermines scientific expertise (Lubchenco, 2017). ‘Much of the public’, according to Higgins (2016, page 9), ‘hears what it wants to hear, because many people get their news exclusively from sources whose bias they agree with’. Coupled to worldview bias, which I explore later in this chapter, the post-fact society has amplified the action gap both at the individual and societal level (Harker-Schuch & Watson, 2020).

In summary, climate communication theory and practice embody the social complexity of climate change. This social complexity feeds back into challenges for effective communication strategies that establish and promote a critical and fact-based understanding of the many facets of climate change. Communication efforts have played out in various ways in different socio-cultural contexts, shaped by a range of factors including the influence of vested interests, political polarisation, and journalistic norms. In response to these challenges, climate communication research has articulated key barriers and identified means for addressing these barriers, in line with ‘best social science practice’. These insights from climate communication scholarship have value for exploring knowledge deficit pathways which are outlined in the following section.

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[2] While the term post-truth is often used interchangeably with post-fact, it is necessary to differentiate between truth and fact. In this instance we depend on the tenets of the scientific method which state that a theorem or fact is valid only as long as it cannot be disproved whereas a truth is a static absolute and, as such, cannot be revised; it is, essentially, a given (Fromm, 1949; Wittgenstein, 1953). In addition, there are theological aspects of the term truth that align more-readily with discourses on religion, faith, and other belief systems.

1.3.2. Barriers to climate communication

Climate is not only a natural science, it also has significant socio-cultural/-political dimensions that position it within a social science context that frequently conflicts or competes with strict 'science' doctrine or tenets (Azevedo & Marques, 2017). For example, although the mechanisms and causes that drive the climate system can be described by the natural sciences, the actual physical problems that climate change create are best described through a post-normal science or wicked problem lens as defined by Funtowicz and Ravetz, 'where facts [are] uncertain, values in dispute, stakes high and decisions urgent' (1993, page 744). I elaborate on this definition by referring to the 'wicked problem' criteria (Lazarus, 2009) which state that climate change:

1) has no defined stopping point in which it will cease or go away;
2) has impacts and consequences that could be beneficial and damaging at the same time;
3) cannot be tested for potential solutions;
4) solutions cannot be retracted once they are implemented;
5) has an inexhaustible variety of solutions which makes the selection of any particular solution problematic;
6) is a unique problem that we have no experience with;
7) could be considered a symptom of another problem rather than be a problem of itself;
8) discrepancies could be interpreted in many ways;
9) solutions will not be tolerated if they fail;
10) has no definitive formulation or solution that we could employ to meaningfully orient ourselves to define the problem in the first place; the longer we take to solve it, the more costly it will become;
11) is caused by those who are least incentivised to address it and will be the least likely to suffer the consequences of it; and
12) there is no existing global law-making institution with the jurisdictional reach and legal authority that equals the reach of the problem (ibid).

The post-normal, wicked attributes of anthropogenic climate change naturally affect climate communication due to inherent uncertainty, its global impact, its imminent threat, and the vast, highly diverse societies that are both the cause for, and amelioration of, its existence. As described by Lorenzoni et al. these are 'virtually intractable matters characterized by uncertainty over consequences, diverse and multiple engaged interests, conflicting knowledge claims, and high stakes'(2007, page 65). Aside from the post-normal and wicked aspects of anthropogenic climate change, climate communication is further complicated by a number of interacting factors such as:

1) there is a growing disconnect between humankind and nature;
2) it is a mass communication problem (Stamm et al., 2000) with a large, diverse audience (differing culture, language, politics, geography, gender, age) that needs to reach a clear action-consensus and agreement to limit further warming;
3) there are significant emotional and psychological pressures engendered by this issue;
4) the science is both complex and 'wicked';
5) misinformation and the difficulty for laypeople to find reliable and comprehendible information;
6) there is a lack of confidence in the scientific community;
7) there is a lack of common or shared knowledge;
8) there is a need for shareholder engagement;
9) critiques of the attitudes and roles humans adopt in relation to nature; and
10) it is influenced by one's socio-cultural worldview.

Each of these dimensions of climate change complexity are examined in the following subsections.

1.3.2.1. Nature deficit disorder

Firstly, with regard to the disconnect between nature and humankind, we have known since the mid-1980s that climate change is a threat (Weingart et al., 2000), is caused by humans, and is happening now and have not seen concerted action adequate to the challenge (Levy & Sidel, 2014; IPCC, 2018). This lack of action can be understood, at least in part, through the work of Louv (2005) in what is termed the nature deficit disorder. The nature deficit disorder is presented as a deficit of experience of, and engagement with, the natural world that may undermine the desire to protect and preserve nature, as well as lessening the desire to understand and explore nature. It is further argued that the disconnect between people and nature starts during childhood (Louv, 2005). Kahn and Weiss (2017) argue that the effect of environmental generational amnesia is decreasing our relationship with nature with each passing generation, while nature is becoming increasingly more dependent on our care, protection and stewardship. This amnesia, is it argued, is reflected in the decreasing depiction of nature in popular culture such as film storylines, books, and song lyrics (Kesebir & Kesebir, 2017), particularly for those focused on children (Prévot-Julliard et al., 2015). Furthermore, a study in Norway explored the changes of nature-based play over time, showing children spending less time in nature and that their play has shifted from 'spontaneous play to adult-controlled, planned and organised activities'(Skår & Krogh, 2009, page 340).

In addition to nature deficit disorder and environmental generational amnesia, human attitudes may be driving a disconnect with the environment and may be represented by attitudes reflecting the dominion of humans over nature (Black, 1970; Nash, 1989) (see also Section 1.3.2.9), human vulnerability to, and fear of, the environment (Brisman & Rau, 2009; Louv, 2005), and religious attitudes (Glacken, 1992). Scholars who have examined the relationship between people and nature argue that this disconnect and lack of engagement with the physical and natural world may alter our cognitive development (Wells, 2000), and affect our mental (Bratman et al., 2015), social (Cox et al., 2017), and physical health (Gladwell et al., 2013) and, more critically to this work, suggests that this disconnect poses a barrier to recognising the forces that are driving climate change (Cherry, 2011; Clark et al., 2013; Imai et al., 2018; Kabisch et al., 2016; Moser, 2010). This detachment, it is argued, can diminish the importance of nature in our everyday existence. Without this connection to nature, we not only lack a meaningful point of reference, we lack the substance of the reference itself, and, in so doing, develop a psychological disconnect as well as a physical one. As Dewey explains,

> 'The environment is always that in which life is situated and through which it is circumstanced; and to isolate it, to make it with little children an object of observation and

> remark by itself, is to treat human nature inconsiderately. At last, the original open and free attitude of the mind to nature is destroyed; nature has been reduced to a mass of meaningless details' (1900, page 143).

In summary, it could be argued that, not only are we disconnecting from nature physically, culturally, psychologically, and intellectually, it may be affecting our physical, cultural, psychological, and intellectual health, and diminishing our ability to respond to risks associated with the natural world.

1.3.2.2. Mass communication problem

Secondly, this task of communicating climate change must relate to an entire planet of people; not only diverse in their age, gender, culture, language, education, and behaviour, but separated by enormous economic, social, and political gaps and divides. Efforts to address the mass communication problem stumble due to the diversity of this global audience (Capstick et al., 2014; Shafer, 2008), the fragmented distribution of communication research (ibid), a one size fits all approach to communicating climate change (Moser & Dilling, 2012), the complexity of the science (ibid; Liu, Varma, & Roehrig, 2014) (see Section 1.3.2.4), the distance of impacts (Moser, 2010) and economic burdens (Stern, 2007), and the failure to 'routinely track, critically evaluate, and thus demonstrate [climate communication research's] impact on the broader communication landscape' (Moser, 2016, page 361).

While efforts to reach and understand the attitudes of adults in relation to climate change have been considerable, some suggest far less attention has been given to younger groups (Corner et al., 2015; Wray-Lake et al., 2010). Although adults have the advantage that they can exercise civil responsibility, they lack adequate knowledge about climate science and have established worldviews (see Section 1.3.2.10) that make them less likely to respond to climate communication endeavours, particularly those aimed at encouraging emissions reduction.

1.3.2.3. Emotional and psychological threat-perception

Climate change is perceived, in the broader public arena, as emotionally threatening and difficult to understand. The global nature of climate change and all the phenomena that contribute to this problem, as well as its threat to our lifestyle, is very difficult to psychologically process (Gifford, 2011), particularly as it is not directly observable (Bush et al., 2016; Moser & Dilling, 2007). Moser and Dilling offer that 'the psychological purpose of fight, flight, or freeze reactions is to control either the external danger or the internal experience of fear' (2007, page 67). They further suggest that 'maybe the leading maladaptive response to threats that are particularly scary, ill understood, difficult to control, overwhelming, and in which we are complicit - such as global climate change - is psychic numbing or apathy (2007, page 68); which may drive the complex issue of climate change out of the physical world and into a psychological realm where the fear of it, at least, may be addressed. Furthermore, climate outreach and climate communication efforts often employ emotionally charged messages (text/image/video) or fear appeals in order to promote engagement and action.

Fear appeals involve scaring or alarming people into action with scenarios of disaster, threat, or ominous risk (Ojala, 2012b, 2013; Stern, 2012). The use of fear is distinct from communication of climate science (which may itself, as a result, engender fear among some people due to the extent of future impacts), and instead is the intentional cultivation of messages designed to create a sense of fear. There is evidence that fear appeals may reinforce intuitive belief systems rather than enhance understanding of climate science (Shtulman, 2017) or promote apathy and hopelessness (Azeiteiro et al., 2017). For example, when fear appeals are used without offering mitigating or adaptive actions, recipients of fear appeals attempt to reduce the perceived danger by denying the appeal or regarding the appeal as devious (Stern, 2012). There is criticism, too, that environmental education is 'unabashedly devoted to activism and politics rather knowledge and understanding' (Fortner, 2001). As a result, these underlying motivations may detract from the dissemination of scientific findings or scientific understanding (Frankie, 2014). Aside from feelings of doom and despair (Ojala, 2012b), messages that attempt to frighten or shock others may lead to 'secondary psychological responses aimed at relieving us from these negative feelings' (Kollmuss & Agyeman, 2002). The initial distress caused by such messages may elicit a defence mechanism response that can include 'denial, rational distancing, apathy, and delegation'(ibid, page 255).

Not only are fear appeals capable of paralysing us into inaction, they may also reduce our action competence, weaken our ability to construct solutions or find meaningful, constructive ways to adapt and build resilience (Ojala, 2015). With regard to the role of emotions in adolescents, which is a central theme of this work, Ojala argues that 'helplessness and hopelessness concerning global problems increase with age among young people' (2012b, page 554). This proposition strongly supports a need to include younger students (from early adolescents: ~11 years) in communication and education efforts. For specific aspects related to climate change, Sullivana et al. report that 'children have been shown to be distressed by topics inherent in climate change impacts, such as species extinction and changing landscapes' (2014, page 550). Essentially, in combination with the wickedness and post-normal nature of climate change, the emotional and psychological burden (invisibility, pervasiveness, and threat-potential) complicates the behavioural response – driving inaction, apathy (Campbell, 2012), and denialism (Ojala, 2012a).

1.3.2.4. Complexity and interdisciplinary nature of climate change

The perceived complexity of the science represents another barrier to science communication (Liu et al., 2014; Pearce et al., 2015; Porter et al., 2012) as climate science involves many scientific disciplines (chemistry, physics, biology, geology) which are wickedly connected to human society and behaviour. To improve public understanding of climate change as a phenomenon, communicators, and educators need to be sufficiently proficient in several science disciplines, recognise the terms and language used to explain different phenomena, and have the capacity to communicate their inter-relatedness and interaction (Dupigny-Giroux, 2010). Coupled to this scientific complexity, there are social, economic, and political dimensions that are at the core of the post-normal or wicked problem issue. Climate change is, inherently, a human problem, not merely a scientific one, and this presents further dilemmas in our understanding, attitudes, and behaviour (Rittel & Webber, 1973).

To understand climate change, learners also require an ability to engage in systems thinking[3] (McNeal et al., 2014). Reasoning about complex Earth-system processes 'depends upon how well new ideas are integrated with pre-existing mental models' and 'requires recognition that observed phenomena result from underlying processes, and that these processes can interact to produce complex phenomena' and 'requires one to understand that not all interactions are purely linear' (ibid, page 210 to 211).

Resolving the perceived complexity is further challenged by a low level of climate literacy in the public arena. While efforts to improve climate literacy might be resolved in the classroom, several critical factors prevent further improvement. These include the lack of system-wide teacher training in climate literacy (and an internationally accepted standard) (Boon, 2014; Boon, 2010; Papadimitriou, 2004; Plutzer, McCaffrey, et al., 2016; Ratinen et al., 2013; Teed & Franco, 2014), a need to further refine the definition of climate literacy and make it operational in an educational setting (see Section 1.5.1.4) (Azevedo & Marques, 2017), and a lack of a standard or framework that teachers can refer to when teaching climate science and climate change.

1.3.2.5. Misinformation and difficulty in accessing/filtering reliable climate information

There is also the issue of misinformation and the difficulty in accessing/filtering comprehendible, reliable material that helps laypeople make sense of the climate change problem, especially in the face of its complexity (Brulle, 2014; Cook et al., 2017; Farrell, 2016; Lewandowsky et al., 2012; McBean & Hengeveld, 2000; Plutzer, McCaffrey, et al., 2016). Misinformation, both intended and inadvertent, occurs in a number of ways, such as the piecemeal accumulation of information, circulation of rumours and fiction, top-down (government and politicians) dissemination of information, sharing of misinformation via vested interests, and the media (Lewandowsky et al., 2012). Filtering relevant and accurate information from these sources is complicated by the enormous amount of information available i.e., the internet, which makes it difficult for lay people to rationalise and organise information (whether sought or via hearsay) in a meaningful and constructive way (ibid).

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[3] Systems thinking is highlighted over critical thinking in this work as CSL in the early adolescent age group is prepatent to anchoring and focalism (see Section 1.5.2). Critical thinking skills require knowledge in order for the knowledge to be evaluated or regarded critically.

Coupled to the over-abundance of information, individuals exhibit motivated reasoning behaviour, which is the 'desire to arrive at particular conclusions consistent with previously held beliefs and leads to biased processing of information (Nisbet, Cooper, & Ellithorpe, 2015, page 287). This behaviour is likely to affect critical reasoning consistent with worldview bias but also with previously held ideas or concepts that may be confused or conflated with new ideas or concepts. Examples of unintentional misinformation or misunderstandings include conflating ozone depletion, landfill, and pollution with climate change (Reynolds et al., 2010; Tobler et al., 2012; Visintainer & Linn, 2015). For example, in a study of sixth-graders' understanding of climate change in the US (n=186), it was found that climate change processes were primarily confused with other anthropogenic processes such as ozone depletion, pollution, and landfill (Visintainer & Linn, 2015).

In addition to self-identity and worldview, access to reliable and useful information is made more problematic due to the efforts of broad-scale deception campaigns that have been deliberately designed to mislead and confuse public citizens (Brulle, 2014, 2018; Farrell, 2016; McBean & Hengeveld, 2000; Meng & Rode, 2019; Oreskes & Conway, 2010; Supran, Geoffrey; Oreskes, 2017). An example of intentional misinformation is demonstrated by Supran et al. (2017) who show that, in spite of more than 80% of internal documents within Exxon Mobil acknowledging anthropogenic climate change, 81% of their advertorials express doubt.

1.3.2.6. Lack of public confidence in science and scientists

Exacerbating both the complexity of the science and the misinformation campaigns is a lack of public confidence in the scientific community (Goodwin & Dahlstrom, 2014; Kellstedt et al., 2008; Lucas et al., 2015). As illustrated by Leiserowitz et al. (2011) in a study exploring attitudes to climate change in the US, 36% of those who doubt and 70% of those who are dismissive of the existence of anthropogenic climate change (a total of 20-25% of the US public) actively distrust climate science. This is driven, in part, by journalistic norms to cover both sides of an argument or issue (Bedford, 2010; Boykoff & Boykoff, 2007; Rahmstorf, 2012). Whether used unintentionally or to foster mistrust and uncertainty by either journalists (Carvalho, 2007) or vested interests (Hornsey et al., 2018), this has seriously interfered with efforts to inform the public on the issue of climate change (Cook et al., 2017). Like the flat-Earth concept, there is no viable counter- or alternative-argument to the theories that report the greenhouse effect phenomena, rendering the false balance reporting rationale of both sides untenable (Brüggemann & Engesser, 2017).

1.3.2.7. The lack of common or shared public knowledge

Furthermore, climate change was not widely discussed in the public arena until the mid-1980s and, accordingly, climate communication is a relatively new field (Chadwick, 2017). I note two possible outcomes of this. First, adults who do not have a knowledge-base about climate change (as it is an issue that emerged during their lifetime and they are unlikely to have learned it in school; see Section 1.5.1) may end up leaning on their worldview as a heuristic for making sense of climate change as a phenomenon, in lieu of structured scientific learning. Second, public and social discourse may be curtailed by adults not feeling sufficiently informed to discuss the topic (Goldberg et al., 2019).

Since climate change is a new knowledge arena, the climate science topic, as a school subject, has been introduced to the standard/mandatory curriculum only recently and, it has been argued, is not taught well in most classrooms in the developed world (Boon, 2014; Plutzer, McCaffrey, et al., 2016) and/or is not necessarily offered as a part of the standard/mandatory curriculum (Dawson, 2012). Teachers' (and student teachers') understanding of climate change and related system processes is also considered to be poor[4] (Boon, 2014; Boon, 2010; Papadimitriou, 2004; Ratinen, Viiri, & Lehesvuori, 2013; Teed & Franco, 2014), with few having any formal instruction in climate science (Plutzer, McCaffrey, et al., 2016) and their instruction may also be affected by their existing worldviews, leading to teaching of idiosyncratic viewpoints rather than scientific evidence (ibid; Stevenson, Peterson, & Bradshaw, 2016). In a 2010 study investigating climate literacy of pre-teachers (n = 107) and grade 10 students (n = 310) in Queensland, Australia (Boon, 2010), only 25% of pre-service teachers could correctly identify the cause of the greenhouse effect compared to 13% of grade 10 students. In a more recent 2014 study investigating climate literacy in teachers in Ohio, US (n=20),

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[4] Without a precedent CSL framework or definition describing the physical/chemical mechanisms of Earth's climate system (see Section 1.5), I make the assumption that 'poor' refers to the ability of citizens to understand anthropogenic climate change rather than an academic ability/aptitude derived from standardised testing across the mean population i.e., school or subject grade.

Teed and Franco (2014) reported a pre-test result of 38.1% correct answers by teachers in a climate knowledge survey.

In these examples, domain-specific knowledge was investigated and these findings i.e. a lack of understanding about the mechanisms that drive climate change, may explain, in part, broader misconception and lack of acceptance of the scientific consensus amongst teachers (Nicholls & Stevenson, 2015; Plutzer, McCaffrey, et al., 2016; Plutzer & Hannah, 2018; Wynes & Nicholas, 2019). With regard to the influence of worldview, Kunkle and Monroe (2019) show that teachers' intention to teach climate change (n=251) is significantly influenced by their worldview, with those identifying as hierarchical-individualists perceiving climate change as exaggerated, false, fake, flawed, alarmist and made up (amongst, other, similar major content themes; ibid, see Kunkle and Monroe (2019); page 646). Furthermore., climate literacy is also not a mandatory subject in the compulsory, public-school curriculum (see Section 1.5.1). Therefore, as a result of these conditions, knowledge about climate change remains fragmented and poor in the public arena and is perceived as complex and difficult, even amongst specialist science teachers whose task it is to prepare students for the responsibilities of adulthood and society, including civic participation on issues such as climate policy prioritisation (Meehan et al., 2018; Plutzer, McCaffrey, et al., 2016; Teed & Franco, 2014; Thompson, 2014).

1.3.2.8. The need to motivate people to take action

In addition, unlike communication for other science disciplines such as physics, chemistry or biology where the main task is to increase understanding and value-perception, climate communication also involves motivating people to engage in climate-friendly activities (Stevenson & Peterson, 2016) such as emission reduction, political action or consumer choice. This involvement responds to the wicked aspects of climate change, its interdisciplinary nature, as well as the socio-political aspects that make this task so fraught with conflict and complexity.

There are, however, ethical aspects to consider when climate communication efforts explicitly aim to encourage others to take action, especially when these efforts involve nudging, behavioural levers or choice architecture (Mols et al., 2015). There is, as Sunstein argues, 'a genuine risk that some nudges might count as manipulation' (2014, page 413) and, while there might be sound reasons for employing nudges, behavioural levers or choice architecture (or even a necessity), there is a need to consider the welfare, dignity and autonomy of those who are expected to take action. One example that considers these factors is educative nudging which encourages individuals to make better choices by giving them relevant information or knowledge. These nudges, according to Sunstein, may be more ethical, particularly when attempting to increase an individual's personal agency or encouraging an individual to exercise their choice-muscle (ibid, pages 427 and 436, respectively).

1.3.2.9. Human perceptions, attitudes, and roles in relation to nature

Woven throughout these communication barriers, is the issue of how humans perceive nature and their role, agency and place in Earth's natural systems (Nash, 1989; Taylor, 2017) and a lack of understanding of our interconnectedness with, and dependence on, the natural world. For example, anthropocentrism, which pervades western culture (Noske, 1997), frequently posits humanist perspectives, such as human well-being, survival, guardian- and steward-ship, and dualistic thinking, at the heart of attitudes on conservation and sustainability (see also Section 1.3.2.1). As a consequence, humanist perspectives can encourage divisions between 'our humanness and what makes us distinct from animals' (Sinclair, 2013, page 42). However, for sustainability education, it has been argued that anthropocentrism and 'humanist change-agency educational discourses, is no longer enough to address the complex imbroglio of twenty-first century human-environmental challenges' (Taylor, 2017, page 1458). Western ethics, argues Nash (1989, page 17), gives humankind 'dominion over nature and the right to exploit it without restraint' which impairs a synergistic relationship with nature in which interconnectedness, cognitive constructs about nature and acknowledgement of human dependence on nature are recognised. The humanist perspective is primarily one of stewardship (Taylor, 2017). Stewardship, in this context, is the belief that humans should control what happens within and to nature and that humans, alone, can and should change and improve the natural world (ibid). According to Taylor (2017), the two significant drawbacks of humanist-driven stewardship perspectives are 1. the celebration of achieving complete mastery over nature, and 2. the assumption in the western world that all cultures see themselves as separate from nature. To overcome negative influences of stewardship attitudes, Taylor (2017) recommends that humans cultivate a relation with other species that positions humankind equally within the collective community of Earth. As Taylor outlines, ‘the point is not to seek a final and heroic human-led solution (which is usually also an ultimately human-centric solution), but to pursue the more modest but still challenging goal of learning how to cohabit with difference in ways that allow all species to “flourish”’ (2017, page 1457, author's originial quotation marks within quotes). This challenges, in many ways, the current trajectory of human civilisation where domestication of nature and dominion over species sits at the heart of our economic and social development (Kareiva et al., 2007). Even if humanist stewardship offered environmental protection as an extension of humanist needs, free-market capitalism, which does not provide incentives to protect the environment or include externalities such as costs to the environment, will prioritise profit over humanist or environmental needs (Sweezy, 2004). The combination of these social constructs presents challenges for climate communication insofar that climate change may only become economically meaningful when impacts affect humans or negatively affect financial gains.

1.3.2.10. Socio-cultural cognition or worldview

Finally, I come to the matter of worldview. A worldview, according to Dilthey, is ‘an overall perspective on life that sums up what we know about the world, how we evaluate it emotionally, and how we respond to it volitionally’ (as interpreted by Makkreel, 1975). The influence of this socio-cultural worldview can present a barrier to altering attitude and behavioural change or engagement (Kahan et al., 2011, 2012) as individuals selectively curate knowledge[5] (see also the previous Section 1.3.2.5) to reinforce existing opinions and strengthen their social/cultural positions and socio-cultural/-political persuasions (Kahan, 2015). In this sense, worldview is not merely a ‘blueprint’ for how we perceive and evaluate the world. Our worldview exerts a bias on how we construct and maintain our

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[5] Knowledge and information including intended/inadvertent information, misinformation campaigns, rumours/fiction as well as that sourced from familiar others/formal and informal education/social media government, press and television, etc.

socio-cultural environment by filtering, according to Kahan, our perception of the 'credibility' and trustworthiness in the opinions, attitudes, advice, and expertise of others (2011).

For communicators and educators, worldviews present a formidable challenge because educational interventions may trigger behaviour that will attempt to align the new information with existing worldviews (Moser & Dilling, 2012; Pearce et al., 2015; Potter & Oster, 2008). If the new information conflicts with existing worldviews, individuals are likely to reject the new information in favour of their pre-existing worldview. If the information aligns with their existing worldview, individuals are likely to adopt the information and reinforce their worldview. Of particular interest to this topic, ideas or concepts that clash with existing opinions have been shown to elicit visceral disgust responses, particularly those related to moral attitudes or beliefs (Chapman & Anderson, 2013).

For the natural sciences, we generally depend on fact-based knowledge to inform and instruct our decision-making process. In this sense, a fact-based worldview is one that relies on information that has been established in accordance with scientific methodology (including critical-reasoning skills and higher-order executive function as described by Piaget (1972)). However, for issues with wicked, post-normal science dimensions e.g. vaccinations, genetically-modified organisms (GMOs), and climate change, research has shown the socio-cultural influence on our worldview can become greater than our trust in fact-based knowledge, experts, and scientific authority (Kahan et al., 2011).

In some countries (Australia and the United States), the effect of socio-cultural influences on worldview (hereafter described simply as 'worldview' as distinguished from 'fact-based' or informed worldview) has been shown to align attitudes about climate change to the ideologies of the political party with whom individuals most identify (McCright & Dunlap, 2011b; Weber, 2010). Subsequently, evidence or research that might contradict an individual's socio-political identity may be dismissed. Coupled with the liberal individualist belief that we are entitled to our opinion without any expectation to have any meaningful, useful knowledge (Condor & Gibson, 2007) which is an indication of a post-fact society, it has been argued that worldview attitudes have emboldened denialist rhetoric to reject the physical scientific basis of climate change, often delineating it along socio-political lines (Kahan et al., 2011). Therefore, interventions that attempt to counter the influence of worldview through knowledge, may polarise, paralyse, and/or entrench existing opinions and beliefs (Hart & Nisbet, 2012; McCright & Dunlap, 2011b; Moser, 2016).

As a result, knowledge deficit interventions have fallen out of favour with climate communicators who have considered that efforts to improve understanding about climate change will be less effective at changing attitudes and promoting engagement than alternative efforts or interventions (Geiger et al., 2019; Moser & Dilling, 2012; Potter & Oster, 2008). These interventions include dialogic communication which involves expert-facilitated two-way forms of discussions that avoid assertions of correctness versus incorrectness (Crayne, 2015; Lassen et al., 2011; Pearce et al., 2015), nudging (Lewandowsky et al., 2012), and behavioural theory (Dolan et al., 2011). While these interventions have provided useful advancements and novel pathways to circumvent worldview bias and to respond to the human problem of climate change, there are concerns about these approaches that need to be addressed (Mols et al., 2015).

Although dialogic communication is worthwhile for parties that are familiar or reasonably conversant with climate change, it is reasonable to expect that those who are ill-informed or have significant knowledge deficits will be at a disadvantage in an exchange of ideas and concepts and may not necessarily recognise the pervasiveness, magnitude, or urgency of the problem. Dialogic communication may be less effective, therefore, when knowledge of climate science, its causes, and its expected consequences is missing. Nudging and behavioural theory, too, offer a practical solution to worldview influence. However, there are ethical issues to acknowledge when considering nudging and behavioural theory mechanisms (Mols et al., 2015). Since nudging involves encouraging individuals to act by going with the “grain of our automatic brain” (Dolan et al., 2011, page 73) there is an element of coercion that is ethically problematic (Dolan et al., 2011; Mols et al., 2015; Sunstein, 2014) (see Section 1.3.2.8). Exploiting the social and cultural behaviours of individuals rather than giving them opportunities to learn about climate science dismisses an individual’s intellectual capacity to understand, even if the topic is complex, difficult, and confronting (see Section 1.3.2.4). In any case, both of these important communication avenues would benefit from knowledge deficit interventions either as a segue into dialogic communication or alongside nudging. In this way, I argue that knowledge deficit interventions do not need to be positioned in opposition to worldview-sensitive approaches such as dialogic communication and nudging. Instead, the multiple avenues for improving social understanding of and engagement with climate change (including knowledge deficit, dialogic communication, and nudging) should best be viewed as compatible and mutually reinforcing strategies for use in the social contexts that are best suited to their approaches.

1.3.2.11. Summary of communication barriers and potential role for education

As I have outlined above, the barriers to climate communication are many and various, however these issues together embody the definition of wickedness. That humankind is only marginally closer to a political resolution to the issue of climate change is a result, at least in part, of these barriers. In the preceding sub-sections, I have outlined a series of arguments that contend that without interactions with nature, we will lack a relationship with nature and, by default, are less likely to care (1); that there is a challenge for communicating the global problem of climate change to all 7 billion + human inhabitants of Earth given the broad ranging social contexts in which people can experience the world (2); linked to this are the psychological aspects of climate change being perceived as a threat, leading to avoidance responses (3); the inherent complexity and multidisciplinary of climate change science (4); the plethora of (mis)information (5); distrust in scientists and scientific findings (6); a general lack of understanding of how climate works as a system or natural phenomena (7); the need to motivate widespread social change in response to the exigencies posed by climate change (8); humanist and stewardship perspectives that prevent humans from developing a synergistic relationship with nature (9); and the influence of socio-cultural cognition or worldview (10). Considering and addressing these barriers may seem daunting, particularly in context with ambitious zero-emission targets.

1.3.3. Avenues to climate communication

While there are many impediments to climate communication, climate communication research efforts have uncovered many industrious and productive ways to overcome some of these barriers. These include 1) framing; 2) emotions; 3) trusted messengers; 4) domain specific science; 5) visualisations; 6) gender; 7) age and, notably, 8) worldview. In the rest of this section, I discuss recent advances in each of these areas before discussing a significant division between two arenas of climate discourse that are central themes in this thesis: climate communication and climate education.

1.3.3.1. Framing

Framing is described by Goffman (1974) as the organisation of one's experience into frameworks of interpretation that allow us to classify our place in the world and to understand and react to events. The concept of framing has been used in attempts to reduce the psychological distance between individuals and climate change (Corner et al., 2015). Framing is used extensively in climate communication to ensure the message we send corresponds to our audience (both text and visual) and, when constructed artfully, can increase both knowledge development and engagement (Corner et al., 2015; Scannell & Gifford, 2013; Wibeck, 2013). One example of framing in climate messages from Bertolotti & Catellani relates to gain-framing and loss-framing in university students (n=95), showing 'that loss-framed messages resulted in higher interest among participants and a greater intention to act in an environmentally responsible way than gain-framed messages did' (2014, Page 475).

Similarly, within nudging, framing employs an understanding of behavioural theory. Rather than aiming to change behaviour that may 'go against the grain of how [an audience might] think or act' (Dolan et al., 2011, page 7), message framing attempts to understand the contexts of the audiences' experience in order to better communicate with them (Stevenson, King, Selm, Peterson, & Monroe, 2018). One important aspect of framing is that of making an issue local and relevant. For example, the use of an image of a polar bear clinging to an ice flow as an iconic symbol of climate change (Born, 2019) would be, for the vast majority of the world's population, both irrelevant and confusing. Most people have not seen a polar bear in the wild, let alone an iceberg and, for an audience in countries like Australia, Africa, and Asia, the problem of climate change may seem impossibly distant and foreign. Framing climate change within the context of human need or threat, for example, becomes particularly meaningful when considered in context with humanist perspectives. That is, pathways toward emission reduction make sense from a humanist perspective when viewed as personally relevant and useful. However, as Brügger et al. (2015) argue, not all local and relevant messages are effective. This is because, as they describe, 'proximized' messages depend on psychological distance (i.e. soon versus later/here versus there), and because they are not necessarily associated with places that people care about, can trigger 'aversive arousal' similar to that evoked by fear appeals (see Section 1.3.2.3).

1.3.3.2. Hopeful messages

As described previously, negative emotions are a significant barrier to climate-friendly attitudes and behaviour. However, while the unwelcome associations of climate change might cause us to ignore or reject climate-associated issues and actions, positive and hopeful messages have been shown to encourage stronger attitudes and climate-friendly engagement (Stevenson & Peterson, 2016). With regard to hope, I define it, according to Ojala (2015, page 134), as 'constructive hope', or 'hope related to pro-environmental engagement'. Rather than being a blind optimism, constructive hope describes a sense of action competence, i.e., having the belief that we, as individuals, can effect change and work to reduce emissions (ibid).

Worldview, too, is linked with emotions (Makkreel, 1975). Smith and Leiserowitz (2014) found that discrete emotions (worry, interest, hope) were stronger predictors of policy support for climate action than worldview. This finding, that of discrete emotions as a stronger predictor than socio-political worldview, lends a new importance to the role of emotions – and suggests that more attention needs to be given to their influence. This is highlighted in recent work by Li and Monroe (2019) exploring hope in US adolescents (n=728), who found that perceiving oneself as being effective has a direct influence on hope and that there is a positive association between hope and concern. These findings have implications for action competence insofar as 'if educational or outreach programs can increase the students' competence as well as concern level, it is more likely that hopefulness about climate change will increase'(Li & Monroe, 2019, page 948).

1.3.3.3. Trusted messengers

Trusted messengers have been associated with a positive influence on climate advocacy and communication (Bissell, 2011; Corner et al., 2015; Malka et al., 2009). Trusted messengers are familiar others, such as family, peers, teachers, and scientists, whose knowledge, opinion and behaviour are considered 'highly credible and legitimate' (Moser & Dilling, 2004, page 41). The effect of trusted messengers was highlighted in a study in British Columbia by Porter et al. (2012) who examined the effect of familiar teachers compared to outside presenters or educators on learning outcomes for climate change. Porter et al. (ibid) found that knowledge gains were significantly higher in the teacher-based setting than for those conducted by outside presenters.

As suggested in the role of trusted messenger, the efficacy of teachers is also an important avenue for communication. Teachers who are more familiar with the physical science basis of climate change (Boon, 2014) or believe climate change is happening (Stevenson et al., 2016) are more effective at fostering climate-friendly attitudes and engagement than teachers who have little or no knowledge about climate change. However, due to worldviews, trusted messengers will not mean the same thing to all people. As Colvin et al. identify, 'Perceptions about the messenger's ideology, identity, similarity to oneself, and the potential for hidden agendas all can affect the efficacy of how a message is delivered and received' (2019, page 7). For those who distrust scientists, trusted messengers are found in family members (e.g. Goldberg et al., 2019), peers, or respected figures, rather than in the scientific community.

1.3.3.4. Domain-specific and mechanistic science knowledge

Giving coherence and structure to what we need to know about climate change in order to make an informed decision about how to address it is also an important avenue for communication and problem-solving. Domain-specific knowledge has been identified as an important foundation for improving climate-friendly attitudes and engagement (Clark et al., 2013; Ranney & Clark, 2016; Shi et al., 2015, 2016; Visintainer & Linn, 2015). Domain-specific knowledge, as defined by Tricot and Sweller, is 'memorised information [consisting of large numbers of problem states and the moves associated with those states stored in long-term memory[6]] that can lead to action permitting specified task completion over indefinite periods of time'(2014, page 266). For example:

> 'there are many different problems that can be solved by using [for example] Pythagoras' theorem. To use the theorem to solve problems, problem solvers must not only learn the

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[6] Added from an elaborated definition provided by Tricot and Sweller on the same referenced page

> theorem, they also must learn to recognise the various problems to which the theorem can be applied and the manner in which it should be applied in each case'. (ibid, same page).

For complex domains, such as climate change, domain-specific knowledge may enhance an individual's problem-solving skills as they draw upon existing knowledge that can be transferred to new knowledge domains (ibid). This transferability is important in climate change as there are many distinct knowledge domains that are interrelated, interdisciplinary, and traverse many differences in spatial and temporal scales (see Section 1.3.2.4) and many kinds of knowledge within the climate change realm. For example, understanding how the global mean surface temperature (GMST) is affected by increasing emissions includes an understanding of the role of infrared radiation in greenhouse gas excitation and associated feedbacks i.e. albedo, water evaporation etc. This mechanistic knowledge provides a rationale for why burning fossil fuels increases the temperature – and why, in consequences/impacts knowledge, we need to limit melting of the cryosphere.

Research in a US public middle school (n=15) demonstrated that a coherent scientific understanding of climate change and its related mechanisms was necessary to integrate an understanding of human activity in relation to how individual energy use impacts climate change (Visintainer & Linn, 2015).

Importantly, there is some evidence to suggest that a physical-chemical mechanistic knowledge of climate change may overcome the influence of worldview and align attitudes with the scientific consensus that climate change is anthropogenic and happening now (Clark et al., 2013). In a study exploring mechanistic knowledge related to changing climate change attitudes in junior-level high school students (n = 63), Clark et al. (2013) report that 'on-line survey interventions, brief curricula, and classroom lessons [providing mechanistic explanations of climate change] can have a marked and persistent effect on one's knowledge, understanding, beliefs, and attitudes about global warming'.

The physical-chemical mechanistic knowledge of climate change and the natural climate system in equilibrium is, though, routinely absent in studies of public understandings of climate change (Clark et al., 2013; van der Linden, 2015; van Linden et al., 2015). To illustrate, in a study exploring the social-psychological determinants of climate change risk perceptions in the UK public (n=808), van der

Linden (2015) examined knowledge related to causes (e.g. knowledge related to behaviour such as burning fossil fuels or deforestation), consequences/impacts (knowledge related to what will occur as a result of climate change), and response/behaviour (knowledge that involves what humans individually or collectively have to do to address climate change), which are all highly germane and significant. However, the physical science basis that describes the natural climate system is absent from the domains examined which is relevant to conceptualising the state of public understanding of climate change. This accords with the findings of a recently published synthesis of the literature on youth perceptions of climate change. In this literature synthesis, Lee et al. (2020) examined *inter alia* the range of measures of "Scientifically correct knowledge" of climate change, and found that this knowledge concerned "the most evident causes, impacts, and solutions, such as factory emissions, rising temperatures, and reducing CO2 in the atmosphere". In this case, domain-specific knowledge of the physical-chemical mechanistic drivers of the climate system in equilibrium was not evident in the literature they synthesised.

In summary, domain-specific knowledge of the physical-chemical mechanistic drivers of the climate system in equilibrium is a significant part of the broad and interdisciplinary knowledge base that underpins the phenomenon of climate change, broadly defined. However, there is a tendency for this domain to be downplayed in comparison to the domains concerning knowledge about human causes, consequences/impacts, and responses/behaviour. This is highlighted by Mittenzwei et al. (2019, page 8) in a systematic review of 78 papers exploring the role of the energy concept promoting climate friendly attitudes and behaviour who concluded that 'knowledge of energy is only insufficiently used by students to explain climate change' and, in relation to behaviour, 'it is likely that the influence of knowledge on attitudes and behaviour towards climate change increases the more specific it becomes' (ibid, page 13).

1.3.3.5. Visualisation and 3D interactive animations and simulations

As well as providing a coherent structure for climate change, communication and education is greatly improved when visualisations such as animations and 3D environments are employed (Sheppard, 2005; Wibeck et al., 2013). In a review of 26 papers exploring the impacts of dynamic visuals in comparison to static visuals, McElhaney et al. (2015, page 49), report that dynamic visualisations (i.e., those that move) have been found ‘to be better than static visuals at promoting conceptual inferences about science’. For complex science topics, such as climate change, ‘dynamic visualisations may be particularly beneficial for promoting conceptual understanding or advanced problem-solving’ (ibid, page 54). Schroth et al. employed a 3D interactive game (n=26) to explore framing (local and relevant messages) in climate change adaptation and mitigation and the potential for different scenarios, and found that ‘concern about climate change had significantly increased with regard to local climate change impacts’ (2014, page 423). McNeal et al. (2014) further argues that hypermedia, web-based learning and other technology tools could be highly germane to building systems-thinking skills that teach learners how to develop coherent mental models of climate change

Aside from responding to framing and relevance, visualisation apps and software allow students to simulate processes and observe mechanisms at play, providing a learning environment that connects causality to specific phenomena, such as a visible loss of the cryosphere (and, consequently, reduced albedo) which occurs as a result of increased greenhouse gas emissions. Visualisations allow students to observe phenomena that may be too small (e.g., atoms and molecules) or too large (e.g., planetary orbits) to observe in real life. Other features that visualisations address include safety, cost, and access concerns (Fauville et al., 2014). For example, observing and exploring a volcanic eruption can be easily and safely explored by many students through a 3D animation. It can be argued that visualisations also provide a safe, non-threatening space to experience an event objectively; allowing rational observations to form a basis for interpretation. This ability to construct non-threatening, localised places (e.g. familiar virtual worlds) works to include essential aspects of framing as outlined above, but also may overcome the negative effect of proximal threat (Bouchard et al., 2006; Cavrag et al., 2014) i.e. that the threat of climate change is close and imminent, as outlined by Brügger et al. (2015). For example, therapy work (*in virtuo* exposure) using 3D interactive spiders to overcome phobia-related anxiety has been shown to be effective in reducing arachnophobia and ‘most participants were able to touch a spider at post-treatment’ (Bouchard et al., 2006, page 25).

In summary, visualisations and 3D interactive games can visually represent phenomena, and may make learning material easier to cognitively process than text-based material. Such tools allow students to observe phenomena and causality, including between objects or phenomena that are too small/large to be seen by the human eye. Lastly, visualisations and 3D interactive games can increase the personal relevance of climate change by depicting familiar locations that players can 'visit' in psychological and physical safety.

1.3.3.6. Gender and age

The next two factors for climate communication concern gender and age. With regard to gender, many studies report that females are more likely to express pro-environmental sentiment and/or behaviour than males (Galston, 2001; Kollmuss & Agyeman, 2002; McCright, 2010; Ojala, 2013; van der Linden, 2015) and, while social-engagement and socially-responsible behaviour appear to drive this difference (Zelezny et al., 2000), other factors, such as biology (Harker-Schuch & Bugge-Henriksen, 2013) and empathy (Hoffman, 1977) may also play a role. As far as age is concerned, Stevenson et al. (2014) suggested that communicators may improve engagement by reaching out to younger audiences, particularly those who have not yet developed, or are in the early stages of development of, their worldview. The role of age-appropriate interventions is central to this thesis and is explored in greater depth in later sections and Chapters.

1.3.3.7. Worldview

Finally, there is a need to re-examine worldview as an avenue for communication, rather than a barrier. In doing so, we need to unpack the research behind worldview and knowledge in order to understand its function and influence. Kahan (2013; 2011; 2012) is recognised as the preeminent authority on worldview bias and climate change[7].

Kahan's research demonstrates that the influence of an individual's worldview is a greater predictor of climate-friendly attitudes and behaviour than their incidental knowledge or ability in scientific

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[7] As an illustration of Kahan's authority on worldview a Google search of 'Cultural Cognition' (which forms the theoretical basis of worldview bias), Wikipedia cites Kahan's work 14 out of 26 times; accessed 09.03.2020 at 14:20.

reasoning. This research is founded on cultural cognition theory, which refers to the tendency of individuals 'to form beliefs about societal dangers that reflect and reinforce their commitments to one or another idealized form of social ordering' (Kahan 2012, page 726). In essence, while an individual might possess a solid grasp of basic science and numeracy and demonstrate high scientific reasoning ability, their socio-cultural worldviews are likely to have a greater influence on their professed attitudes to climate change than any incidental knowledge or aptitude for scientific reasoning. Kahan's work has been valuable in disentangling and understanding the many human factors related to climate communication such as framing, lack of public confidence in scientists and scientific institutions, denialism, and so forth. This work has also provided context for why developed countries, with high levels of education, still appear to lack alignment between public attitudes to climate change and scientific consensus. Many studies (e.g., Chadwick, 2017; Moser & Dilling, 2012; Pearce et al., 2015; Plutzer et al., 2016; Potter & Oster, 2008; Rohloff, 2018; Whitmarsh & Lorenzoni, 2010) have interpreted Kahan's studies as showing that knowledge deficit is a poor avenue to promote public engagement around climate change. For example, Moser and Dilling asserted that 'this [knowledge deficit] model can be detrimental in particular through the condescension that may emerge if the public is seen as or portrayed by communicators as irrational or ignorant' (2012, page 163). Pearce et al. elaborated further by stating that 'Climate communication appears haunted by older 'deficit' models of science communication, with an underlying assumption that the public is somehow lacking in knowledge or is insufficiently aware of impending dangers' (2015, page 619).

However, there is debate in the literature that the view that dismisses knowledge deficit is skewed by the location of the given studies (Hornsey et al., 2016), how knowledge deficit was measured and interpreted (Corner et al., 2015; Guy, Yoshihisa, et al., 2014; McCaffrey & Rosenau, 2012; Shi et al., 2015, 2016), and the role of education as an active intervention (see Section 1.3.4; further discussed in Geiger et al., 2019; M. McCaffrey & Rosenau, 2012; Shi et al., 2016). I will explore these in turn below.

First, Kahan's studies exploring climate attitudes in relation to worldviews were undertaken only in the US and the polarisation of climate change along political lines – that has been observed and tested frequently by Kahan and others – is not necessarily present in other countries (Hornsey et al., 2018). In a recent study across 25 countries/provinces (n=5,323) exploring ideological worldviews and anthropogenic climate change attitudes, Hornsey et al. (2018) found only the US returned significant effects for worldview bias on the belief of human-caused climate change for all five ideological indices tested (conspiratorial ideation, individualism, hierarchy, left–right political ideology and liberal–conservative political ideology). Australia measured a close second (polarising on three of the five ideological indices), though the US remained a clear 'exceptional' case.

Second, in research on worldview and climate attitudes, the 'knowledge' factor that was measured typically includes incidental i.e. 'existing/background/general science' knowledge, and the respondent's opinions on the reliability/credibility of 'knowledgeable' experts as proxy measures of knowledge rather than domain-specific or mechanistic climate science literacy or knowledge (Corner et al., 2015; Guy, Yoshihisa, et al., 2014; Kahan et al., 2011; McCaffrey & Rosenau, 2012; Schultz, 2002; Shi et al., 2015, 2016) (Table 1.1).

Table 1.1: Summary of the key Kahan (et al.) articles concerning climate change attitudes and worldview, including measures tested in the experimental designs.

Author/ Year	**Measure**	**Country studied**	**Specific climate science**	**Knowledge deficit**
(Kahan et al., 2011)	Cultural values, reliability/credibility of experts; scientific consensus	US	Not tested	Not tested
(Kahan et al., 2012)	Cultural values, general science, numeracy	US	Not tested	Not tested
(Kahan, 2013)	Political identity, cognitive reflection test (CRT)	US	Not tested	Not tested
(Kahan, 2015)	What individuals think scientists believe; general climate science knowledge*	US	Partially tested	Not tested

*8 of 9 questions were related to impacts and consequences

While Kahan (2015) has measured an aspect of incidental domain-specific climate science knowledge, the questions were predominantly focused on climate change impacts and consequences with only one question out of nine referring to the underlying physical/chemical mechanisms of the climate system in equilibrium: 'What gas do most scientists believe causes temperature in the atmosphere to rise' Is it [hydrogen, helium, carbon dioxide, radon]?'. Assessing understanding or threat perception of impacts or consequences in relation to worldview is not the same as assessing domain-specific climate science knowledge i.e. knowledge that can explain the physical/chemical mechanisms of Earth's climate system in equilibrium. Research investigating worldview in relation to incidental domain-specific climate science literacy i.e. understanding the physical/chemical mechanisms that describe Earth's climate system in equilibrium, is largely missing from the literature.

Third, although a consequence of the contribution made by this body of work has been to 'cast doubt' on knowledge-deficit, knowledge deficit as an intervention was not measured. This is important because Kahan (2015) refers to knowledge deficit as an intervention and has argued that climate and evolution can both be taught in a way that disentangles beliefs from science. Kahan further argued (ibid, page 30) that instruction and practice in scientific methods and critical reasoning i.e. 'how scientists compare alternative hypotheses, their predicated consequences, and the evidence to arrive at belief', encourages 'the same important reasoning pattern – the one essential to comprehending valid science'. The context for this is that Kahan argues the comprehension of science can be taught by making comprehension independent of belief. This, however, does not imply that climate beliefs are necessarily correlated with this existing or incidental knowledge, but it also does not provide any context for knowledge deficit interventions. Kahan's research clearly demonstrates the effect of worldview as a stronger predictor than incidental knowledge on climate-friendly attitudes and beliefs, particularly in adults in the US and Australia. The key point here is that the importance of socio-cultural worldview on climate change opinion does not discount the potential contribution of a knowledge-deficit intervention approach. However, this false binary has been an unfortunate implied consequence of Kahan's research.

Therefore, considering the various interpretations of Kahan's findings, it appears necessary to distinguish 'incidental' or general science knowledge as an existing condition, given that Kahan has mostly tested for incidental knowledge, general science knowledge, or the reliability of knowledgeable experts. This is important because, as will be discussed in the next section, knowledge deficit as an intervention (i.e., pre- and post-testing that which is learned in planned, formal, mandated, or structured learning environments such as school or further education), has shown to be an important factor underpinning the development of climate-friendly attitudes and behaviour and, further, may even mitigate against worldview bias.

1.3.4. Knowledge deficit as an intervention

There are clear differences in how the concept of knowledge has been interpreted within the literature and, consequently, what is implied by the term knowledge deficit. In addition, as discussed above, there are different kinds of knowledge in climate communication and climate education (see Section 1.3.3.4) and, within these different kinds of knowledge, there are varying degrees of understanding as well as the influence of worldview bias, which is further affected by misinformation and psychological factors.

Kahan has argued that worldview leads to the selective interpretation of additional information through a socio-cultural lens which can obscure, polarise, bias, and influence attitudes in correlation to incidental knowledge – and, to some degree, climate-related knowledge. It is also known that adults 'in conditions of limited knowledge and exposure to ambiguous information' are likely, to '"process information about issues through a filter containing a range of variables relating to their predispositions"—chiefly among them is their political orientation' (McCright & Dunlap, 2011b, page 161).

Limited knowledge, however, is not the same as domain- or climate-specific knowledge, and conditions of limited knowledge are not the same as interventions that aim to improve knowledge. In this case, limited knowledge, and the conditions of limited knowledge, relate to the random or self-directed acquisition of knowledge, skills, and dispositions without guided, planned instruction. They further lack the goal to focus specifically on the knowledge topic or improve understanding of the topic over time. Specific knowledge, and the conditions to improve specific knowledge, relate to the acquisition of explicit, systemised, verified, and cohesive knowledge/skills/dispositions via structured education that focuses on a particular topic, with the aim to improve understanding of that topic over time. Limited knowledge is likely to be an inadequate foundation on which to construct an informed opinion due to the barriers outlined in Section 1.3.2, such as misinformation, perceived complexity of the science, emotional and psychological barriers and, of course, worldview filters. Furthermore, as climate change does not appear to have been taught effectively in the classroom and climate literacy programmes are only now forming part of national curricula (Colliver, 2017; Hess & Collins, 2018; Meehan, Levy, & Collet-Gildard, 2018; Osborne & Dillon, 2008; Wolfe, 2001; Wynes & Nicholas, 2019 and see Section 1.5.2), knowledge of climate change (as incidental knowledge) is unlikely to be a valid measure of the knowledge factor in relation to worldview, even for adults. Alternatively put, possessing some knowledge that is idiosyncratic, dubious, and fragmented is very different from a knowledge that is explicit, systematised, verified, and cohesive. The former accords with that which has been acquired in everyday life and, for the case of climate science, has a reasonable likelihood of being incorrect, incomplete, or biased, while the latter accords with that which has been acquired through guided, structured education.

Since worldview influences have been presumed to persist across knowledge interventions even though interventions have not been explored in relation to worldview, there is a theoretical justification to explore knowledge deficit interventions. Thus, it becomes imperative to understand how formal education and an individual's worldview may interact. The evidence base provided by Kahan offers exceptional insights into how worldview can override general science knowledge, but it has not interrogated the relationship between worldview and domain-specific knowledge about the physical-chemical mechanisms of the climate system in equilibrium. Therefore, there is potential value in examining the role of domain-specific knowledge-deficit interventions in contributing to broad social understanding of climate science and, as a result, engagement with climate change.

The potential value of domain-specific knowledge deficit interventions is encouraged by a small number of extant studies (Aksit et al., 2018; Guy et al., 2014; Ranney & Clark, 2016; Shi et al., 2015, 2016; Stevenson et al., 2016; Stevenson et al., 2014; Visintainer & Linn, 2015). Stevenson et al. argued that ‘worldview is associated with polarized climate change beliefs at low levels of climate change understanding [amongst adolescents], but climate education appears to eliminate ideological differences once adolescents understand key scientific concepts associated with climate change’ (2016, page 2). When investigating worldviews in relation to knowledge amongst 11-14 year olds in

North Carolina (n=378), Stevenson et al. (ibid, 2014) also found that when knowledge was high for both individualists, i.e., those that prioritise individual needs over society, community or group needs (79% knowledge level), and communitarians, i.e., those that prioritise societal and group needs over those of the individual (88.7% knowledge level), there was no significant difference in the acceptance of anthropogenic climate change.

The same findings are being replicated for adults, as well. For example, in a US study exploring knowledge and climate-friendly attitudes in undergraduates (n=104), Ranney and Clark (2016) found that, when providing information on the mechanistic processes of climate change, there was an increase in both concern about, and acceptance of, climate change with no evidence of polarisation, and this increased concern persisted for at least 34 days. In a study in the south eastern US exploring domain-specific knowledge in undergraduates (n = 190), Aksit et al (2018) found, following an introductory course to Earth Science, domain-specific content knowledge was the dominant predictor of students' risk perception while (individualism/hierarchy) worldviews were not. Earlier research undertaken with south eastern US graduates (n=15) demonstrated that after instruction in a specific climate science course, there were significant gains in knowledge which is associated with a stronger alignment of respondent attitudes to the scientific consensus of climate change (Lambert & Bleicher, 2014).

A similar study exploring climate-related knowledge within the Australian general public (n=335) showed that respondents who had a greater knowledge of climate change causes (such as destruction of forests, pollution, auto emissions, use of fossil fuels) were more willing to accept that climate change is occurring and expressed a decreased negative relationship between individualistic attitudes (which typically align along with conservative ideologies) and acceptance of climate change (Guy et al., 2014).

The relationship between knowledge and worldview in the climate communication arena (see Azevedo & Marques, 2017) was further explored by Shi et al. (2015) within Swiss households (n=1,065; median age= 57 years) who found that both knowledge and worldviews are 'important for people's willingness to change behaviours and to accept climate change policies' and 'knowledge [about the causes of climate change] increases public concern about climate change independent of cultural worldviews' (page 1). Shi et al.'s study highlighted that, although public divisions over climate science and policy do not necessarily originate in a general lack of comprehension of science, these divisions may be driven, in part, by a lack of specific climate science literacy (Clark et al., 2013; Shi et al., 2015, 2016).

Earlier work by Clark, Ranney and Felipe (2013, page 2070) strongly challenged the influence of worldview over knowledge deficit and argued that 'even a small amount of true information can quickly act as a cognitive 'lever' to enhance one's understanding and perspective on climate change', (ibid, same page). In addition, they provided evidence for the role of knowledge in 'historically driven major social changes—from heliocentrism replacing church doctrine to the acceptance of a tobacco-cancer link in spite of industry obfuscation' (ibid, same page).

These studies indicate there is a role for interventions that provide domain-specific knowledge within planned, formal, mandated or structured learning environments. This has significance when we consider that the topic of climate science in the contemporary classroom is relatively new and often poorly-structured and -embedded within the curriculum (Colliver, 2017; Hess & Collins, 2018; Meehan, Levy, & Collet-Gildard, 2018; Osborne & Dillon, 2008; Wolfe, 2001; Wynes & Nicholas, 2019; and see Section 1.5.2). It is postulated that we may expect to find differences in the effect of general science knowledge (that which has been included in the compulsory public-school curricula) compared to domain-specific science knowledge (such as regards the physical-chemical mechanisms of the climate system in equilibrium) on climate attitudes and concerns.

Furthermore, while climate change may be complex and difficult to cognitively grasp (see Section 1.3.2.4), other topics in the classroom are also complex – and may be less personally relevant as global climate change is to all learners. As we may expect for climate literacy, these other complex topics require multiyear instruction to build on levels of complexity. For example, to learn algebra, one must learn that symbols represent quantities without fixed values and have a solid understanding of basic arithmetic (Fonger et al., 2018). Staggering the level of complexity via learning progressions may help, for example, to overcome difficult and highly complex concepts like climate change and climate science (Biggs & Collis, 1982; Parker et al., 2015). By starting with ideas and concepts that are familiar to the learner before progressing on to more complex topics once the learner has acquired the prerequisite understanding allows learners to gradually build more complex understanding in a topic. Deciding where to start, however, requires an understanding of prior incidental or background knowledge and the intellectual level of students to ensure they have cognitive ability to process these concepts and systems and, in the case of climate communication, important theoretical factors, as well. as well (see Section 1.5.1).

Climate literacy and education may offer a unique avenue to address these concerns. If we are better able, for example, to understand natural processes such as albedo, we may improve our appreciation of the mitigating effect of snowfall i.e., increasing surface reflectivity and decreasing infrared radiation, rather than perceiving cold weather as evidence against 'global warming'. It stands to reason that knowledge about nature, even when abstract, reduces the gap between nature and humankind and provides meaning towards conserving and protecting it (Cherry, 2011; Clark et al., 2013; Imai et al., 2018; Kabisch et al., 2016; Moser, 2010). Domain-specific knowledge interventions may be particularly useful for overcoming barriers to climate communication (see Section 1.3.2). Using the example of albedo, the concept of winter/snow/ice as a positive feedback toward temperature reduction could be a valid pathway to minimise the conceptual effect of nature-deficit by making salient the seasonal changes experienced across the world. Since school children are required to attend school and early adolescents are the largest group of climate-vulnerable people on Earth (UNICEF, 2015), we may overcome the mass communication problem that thwarts other communication efforts. Teaching climate change initially as a science may also assist learners in meaning-focused coping by providing context for their meaning and an improved psychological response to climate change. The purpose of education is to resolve the complexity (particularly if taught conceptually) and interdisciplinarity and to surmount misinformation (both intended and inadvertent). Furthermore, by focusing on science we may improve confidence in scientists and the scientific community and, in doing so, increase the overall share of common climate knowledge, particularly in the interpretation of scientific findings and uncertainty, and establish substantial justifications for engagement. Lastly, as argued by Kahan (2015), climate education may disentangle worldview bias and knowledge via a solid comprehension of the scientific method and how this explorative process arrives at evidence, discovery and knowledge. Climate education could reduce the perception that climate change is a 'belief' in favour of a rational, objective perspective; similar to perceptions of trust held by the public for public health[8] and for medical practitioners as trusted messengers.

Naturally, without an extant evidence-base which outlines the effect of such knowledge on an individual's attitude, the role of domain-specific knowledge deficit as an influence on attitudes and perceptions invites further investigation. Critically, we need to explore when worldview develops – and if, during an individual's development, there are opportunities when planned, formal, mandated, or structured knowledge deficit interventions might be useful.

In summary, this thesis argues that there is promise that the knowledge deficit model remains a useful component of the climate communication and climate education toolbox. Rather than a reversal of gains made through the body of work on worldview that has been led by Kahan, this work becomes a complement to climate risk and communication work. As highlighted by Potter and Oster (2008) who claim (though challenging the assumptions underlying knowledge deficit) that 'the provision of [relevant] information…is vital for a politically and environmentally literate public' (page 124).

1.3.5. Climate communication vs climate education

As an extension of the worldview topic (particularly in context with communication and education) it seems necessary to address the tension between worldview and knowledge which, according to Azevedo and Marques (2017, page 2), derive from conflicts between science communication and science education. It is therefore to this disciplinary and practice-based distinction that I now turn.

In a systematic review of 22 papers dedicated to climate literacy between 2007-2015, Azevedo and Marques conclude that, 'there is a deep division between two cultures' of science communication and

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[8] Differences in public trust for scientists and health professionals varies amongst nations, which is evident in vaccination programmes such those issued during childhood or for COVID-19 (Hornsey et al., 2020; The Royal Society, 2020). Overall, however, 73% of the global population report a trust in doctors or nurse over other sources of health advice (e.g. family, friends, religious leaders, celebrities) *(*Gallup - Wellcome Global Monitor 2018 : How Does the World Feel about Science and Health?, 2018).

science education (ibid, same page). They define science education as ‘the transmission and acquisition of something – knowledge, skills, and dispositions – helping someone to become qualified to live in our complex modern societies’ (ibid, same page) and climate communication as ‘on the person, as subject of action and responsibility, practices, ways of doing and being – such as cultural practices, political practices, professional practices, and so on’ (ibid, same page). Applying this distinction to my exploration of the relationship between knowledge and worldview positions knowledge in the arena of climate education and worldview in the arena of climate communication. In response to these divisions, Azevedo and Marques highlighted (amongst other recommendations) ‘new interfaces between science, technology, society, environment and ethics are necessary’ and that science literacy ‘should overcome definitions and models strictly connected with education or communication approaches and include knowledge, attitudes, contents, as well as communication issues in complex models, providing societal capacity-building and bridging the growing gulf between many areas of research and the public’ (page 12).

Based on the review by Azevedo and Marques (2017), it becomes clear that there is a need to reconcile and integrate worldview and educational interventions and to reconcile climate communication with climate education. In view of these recommendations, this thesis now explores the role of public opinion in climate communication and climate education in order to establish a baseline upon which we may explore the opinions of early adolescents. Public opinion is an important metric that outlines the overarching tendency in a population with regard to key topics, ultimately acting as one of many levers to influence policy prioritisation and prosecution (Beiser-McGrath & Bernauer, 2019).

1.4. Public opinion and climate change

> ‘What disturbs and alarms man are not the things, but his opinions and fantasies about things’.
>
> Epictetus

The efficacy of climate communication in the broader public arena is typically determined by public opinion polls, consumer choice and, in theory[9], by the election of political candidates to public office who acknowledge the importance of climate change. Of these measures, the most reliable and immediate are opinion polls and surveys. Since adults can effect change faster due to their intellectual development, and social and legal status, and since they are considered self-sufficient, independent, and accountable for their behaviour, adults are frequently targeted to provide information and data for public opinion polls. Since adult opinions related to climate change are well-studied and frequently gathered, they provide a useful starting point with regard to assessing the opinion signals of other groups, particularly for under-studied groups e.g. early adolescents (Nature Editorial, 2018).

The opinions of adults on climate change vary from nation to nation (Howe et al., 2015; Leiserowitz, 2007) and fluctuate within those nations over time (Brulle et al., 2012; Whitmarsh, 2011). Determining the opinions of adults in relation to climate change allows science communicators to assess communication strategies and examine internal and external influences on opinions within communities (local to global) and monitor changing attitudes and perceptions. This process can be constructive for the science communication discipline by offering worthwhile insights into improving strategies for countering climate change as well as implementing strategies in other areas or for other science-related issues (e.g., GMOs, vaccinations).

Although many surveys have been undertaken to monitor opinion in relation to climate change, there are differences in how they are constructed and how respondents are recruited. One difference is whether the response is yes/no or scaled on a preferential Likert-style scale (e.g., ranging between strongly agree to strongly disagree) (Leviston, Price, & Bishop, 2014). Such measurement differences

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[9] Disconnects between public opinion and public policy are well-documented, i.e., J.V Hughes Jr., H.O Hughes, 2004 ‘Out of Touch: The Presidency and Public Opinion’, Texas A&M University Press

make comparisons of results between surveys difficult. We can, however, see signals in those results that serve to inform science communicators and strengthen communication strategies within those respective countries. For some surveys, data has been collected for several countries, and national comparisons are made easier. Unfortunately, although opinion data has been collected over time from many nations, some countries lack sufficient data on the issue to gain more than cursory insights (Rhomberg, 2016).

Before proceeding it is necessary to foreshadow the empirical work that is undertaken in subsequent chapters. Chapters 3, 4, and 5 will all present new analyses undertaken on data collected in two countries: Australia and Austria. The discussion on adult climate opinion now focuses on these two countries as context for the subsequent empirical research. These countries were chosen for this work as Austria and Australia show marked differences in their adult opinions about climate change, there is evidence of differences in the influence of political ideology on worldviews, my prior research with Austrian schools, the funding of this thesis by the Australian government and the established relationship the Australian National University (ANU) has with the Canberra and Sydney high schools.

Overall, adult Australians show that there is an influence of worldview with regard to climate change; political affiliation is a predictor of climate-related opinion (Leviston et al., 2011; Zehr, 2015) and there is a strong sceptic faction in Australia (Capstick et al., 2014). It is worth noting that since the research underpinning this research was conducted prior to the Australian bushfires, Australian adults' concern about climate change has increased (The Australian Institute, 2020). I use, for the purpose of comparison, the same (or similar) year across country and age group.

While Australia has a plethora of literature on adults opinions with large-scale surveys going back to the early 1990s (Kassam, 2019; Leviston, Greenhill, et al., 2014; O'Neill, 2013; Oliver, 2017; Pietsch & McAllister, 2010; Renault, 2018; Taylor, 2014) literature on public opinions related to climate change in Austria, 'is scarce and often focuses on Alpine regions' (Rhomberg, 2016, page 8). For the two studies in Austria that examined adult opinions in broader terms, i.e., as a concern in comparison to other concerns such as terrorism, there is evidence of a very strong concern for issues related to climate change with 70% of respondents perceiving climate change as the world's most significant problem (European Commission, 2014). In addition, following a recent EU-wide poll, 70% of Austrians consider climate change a 'very serious problem' (European Commission: Eurobarometer Climate Change, 2017). This concern reflects the amplified warming that Austria is currently experiencing in comparison to most other European countries (Gobiet et al., 2014) but it provides little insight into the nuances of public opinion, such as whether Austrians think climate change is anthropogenic, or if it is a phenomenon that is currently taking place.

Since the adult opinion data from Austria is not as robust as data from other European Union (EU) nations, I adopted opinions from France and Germany as a proxy measure in lieu of more specific opinion data from Austria to obtain some understanding of European opinions as a whole. These countries comprise 29.2% of the total EU population (World Bank, 2018), are both long-term members of the EU, have had strong social-democratic political leadership since the end of the Second World War, are politically-significant EU members, and are situated in close proximity to Austria. The most similar country to Austria is arguably Germany with a population of 82.6 million people (World Bank, 2018) (16.1% of EU population). As well as sharing a border, language, and heritage as part of the Holy Roman Empire, Austria shares a similar form of government to Germany with the Chancellor as Head of Government in the federal parliamentary republic and the President in a largely ceremonial role as Head of State. With a population of 67.1 million people (World Bank, 2018) (13.1% of EU population) France also has important historical and cultural ties to Austria. Similarly to Germany, France has maintained diplomatic relations to Austria since the Middle Ages (Vilain, 2002) and shares a great many traditions and cultural associations with Austria (ibid), not least those related to architecture, literature (Brunt, 1983), art, and music. The current growth in support for right-wing populist parties is also something these three countries share (Bornschier, 2010; Oesch, 2008).

France and Germany have very strong support for action on climate change (Schäfer et al., 2016; Steentjes et al., 2017). In France, all major candidates in the last presidential election supported efforts to mitigate and adapt to climate change (Timperley, 2017). Germany, as an early advocate for emission reduction (Weingart et al., 2000), is a world leader in political efforts to develop the climate accord and, according to Schäfer et al. (2016), the ‘dismissive segment’, which in the United States and Australia most strongly believes that climate change is not occurring or not caused by humans, is non-existent in Germany’ (page 18).

Opinion data from the United States has also been included for comparison with a non-EU Western nation and because Australia and the US have been shown to present similar tendencies in the influence of socio-cultural worldview on climate change opinion (Hornsey et al., 2016).

Opinion surveys have tended to measure the extent to which the public is worried or concerned, in relation to whether climate change is caused by human actions, and if the climate is already changing (Arnold et al., 2016; European Commission: Eurobarometer Climate Change, 2017; Steentjes et al., 2017). To foreshadow the content once again in later chapters of this thesis, I used the same measures in my empirical research presented Chapter 3. Data across these three dimensions are presented in the following sections.

1.4.1. Adult climate opinions

For the opinion on whether climate change is something to worry about, the European countries all show stronger positive alignment with this opinion than Australia or the US (Figure 1.1a). For sources, correlation, and tables of adult data in relation to opinion topics (worry = is climate change something to worry about; human = is climate change human-caused; imminence = is climate change happening now), please see Appendices I and II.

The opinion on the anthropogenic nature of climate change is quite different across the countries (Figure 1.1b). Australia indicates a stronger opinion toward the influence of human-induced climate-change than the US, but, again, the European countries all show much higher consensus with this opinion.

For opinions on whether climate change is happening now (Figure 1.1c), a greater proportion of Australians believe it is happening now than their US counterparts – although the proportion of people in Europe holding this opinion is higher still. Overall, we see that opinions supporting the belief that climate change is happening now are higher in Europe compared to Australia and the United States (which is generally lower again than Australia). This is in line with findings that show a strong polarisation of opinion on climate change along political lines in Australia and the US (Feinberg & Willer, 2013; Hornsey et al., 2018; McCright & Dunlap, 2011b; Moser, 2016).

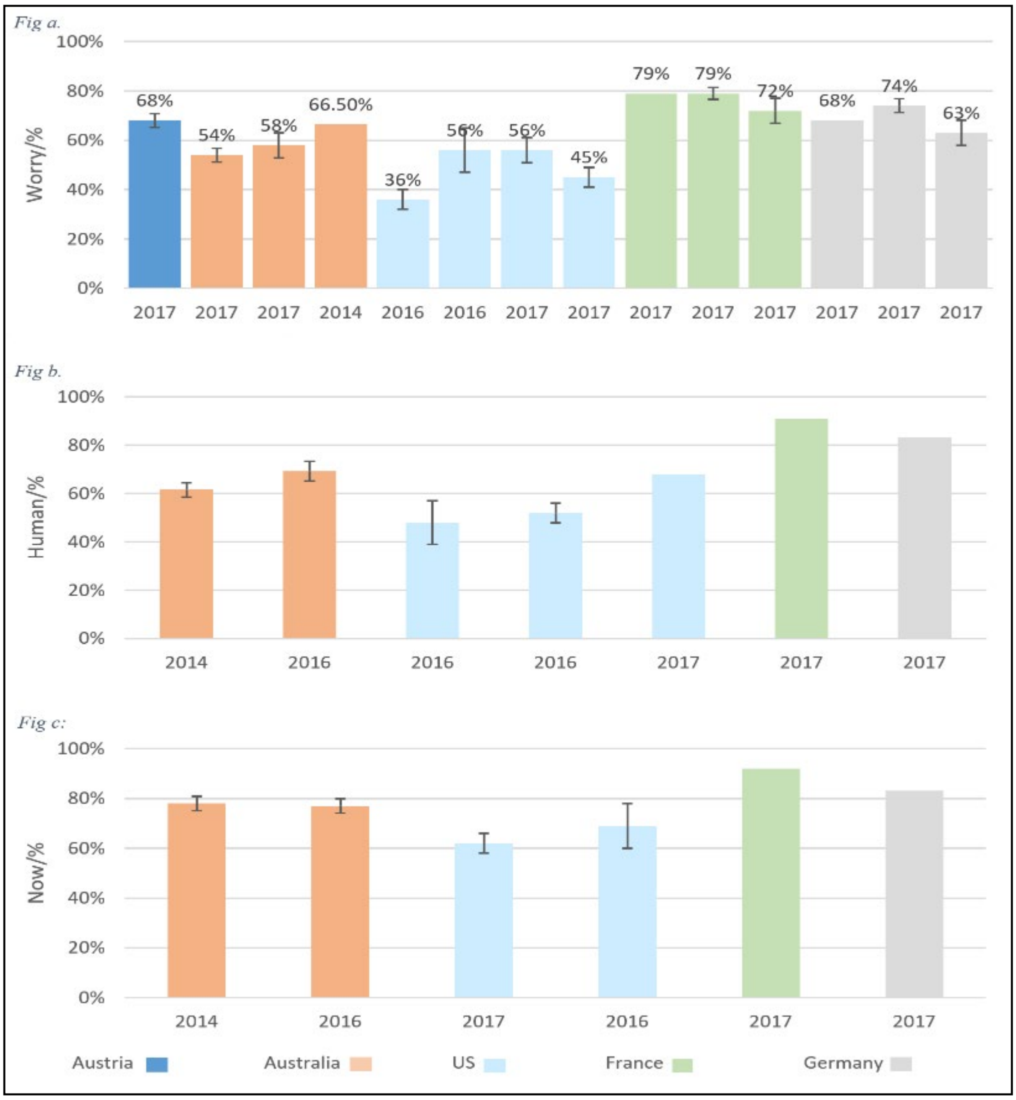

Figure 1.1: Collation of adult opinions in developed countries on whether (a) climate change is something to worry about (b) climate change is caused by human activity and (c) climate change is happening now. For data sources see Appendix I. Error bars indicating uncertainty from propagating across the average of multiple surveys. For further details see Appendix II.

Figure 1.1 demonstrates that opinions in adults vary considerably – and over time. Understanding the dynamics that influence the development and maintenance of adult opinions is beyond the scope of this research, but adult opinions will be compared and contrasted with the thesis' findings on adolescent opinions.

1.4.2. Public opinion research – including knowledge as a metric

There appears to be a lack of studies exploring domain-specific knowledge in adults while, at the same time, an abundance of opinion data for the same group. In addition to this, studies rarely include both opinion and knowledge as metrics.

As has been outlined earlier in this Chapter, there are several forms of knowledge of relevance to climate change, including the physical-chemical mechanics, causes, consequences/impacts, and responses/behaviours. Although we are 30 years into an awareness of the problem of climate change, the differences, effects, application, type of audience for each of these knowledges has not yet been defined or positioned within a theoretical framework. Democracy depends on a public that is adequately, and equally, conversant on topics that have a broad social, economic, and cultural impact. As Wetters explained, 'in any conceivable theorization of democratic form, it would never be the existence of the vote alone that defines democracy, but the quality of the public forum out of which the vote emerges' (2008, page xi). In essence, providing the vote to all citizens is not a sufficient pre-condition for democracy to take place, as each citizen needs to be equipped with the requisite knowledge to take part in the democratic process. While some may argue that the 'knowledge deficit' model treats citizens as irrational or ignorant (Pearce et al., 2015; Sturgis & Allum, 2004) and is a form of condescension (Moser & Dilling, 2012), it could be countered that dismissing an individual's intellectual capacity to participate in public and political life is equally demeaning. In any case, opinions about climate change in the absence of an expectation to know anything about climate science dismisses the role of education both as a public good and as a means to build resilience and social stability, which prevents individuals from accessing climate education and becoming 'qualified to live in our complex modern societies' (Azevedo & Marques, 2017). Without an adequate understanding or provision of climate science literacy, we may expect a public to default to emotions or personal belief as a means to make sense of the climate problem (Lubchenco, 2017; Tasquier & Pongiglione, 2017).

There are, however, several challenges to this. The first is defining what 'adequate' or 'requisite' knowledge is (curriculum) in order to ably take part in public life i.e. 'the quality of the public forum', as described by Wetters (2008, page xi). The second challenge relates to revising the climate communication interpretation ascribed to knowledge deficit so that the intervention (education) can be clearly distinguished from a general lack of incidental knowledge or understanding. This is important because knowledge deficit interventions will continue to be conflated with incidental knowledge unless a revision of – and distinction between – these two knowledges is made. The third, as recommended by Azevedo and Marques (2017), is the need to find common ground between climate communication and climate education i.e. combining the socio-political/-cultural aspects of climate change with shared, common knowledge, and the transmission of new ideas and concepts.

Since the first challenge relates specifically to education, this will be elaborated further in Section 1.5.3. However, since public opinion on climate change is an intercept between climate communication and climate education, i.e., it is the aim of both disciplines to improve climate-friendly attitudes and behaviour, the second and third challenges can be aligned along common goal orientations.

There is a need, as recommended by Azevedo and Marques (2017), to reconcile the divisions between climate communication and climate education. To do this, we must meet in the middle, investigating the role of knowledge deficit and its interface with public opinion in context with, and in consideration of, socio-cultural/-political identities and the 'human event of communication, meaning-making and interpretation' (ibid, page 2). Central to this is the role of education. As highlighted in their model for fostering education and communication for sustainability (ibid, page 11), 'science literacy is the key concept for this new integrative, inter/transdisciplinary epistemological approach, necessary to allow autonomous citizenship'. However, it is also considered that this literacy needs to 'overcome definitions and models strictly connected with education or communication approaches and include knowledge, attitudes, contents, as well as communication issues in complex models, providing societal capacity-building and bridging the growing gulf between many areas of research and the public' (Azevedo & Marques, 2017, page 12).

Recognising the importance of domain-specific knowledge (i.e., elevating physical-chemical mechanisms alongside knowledge of the human causes, impacts/consequences, and responses/behaviours) leads to a need to consider how to conceptualise a Climate Science Literacy (CSL) suitable for the 21st century.

In light of these recommendations, this research endeavours to re-balance the knowledge-attitude-behaviour dynamic by investigating both domain-specific knowledge and opinion.

1.5. Developing a Climate Science Literacy (CSL) framework

Conceptualising climate science literacy for the 21st century in a manner that considers worldview influence, including cultural cognition bias (Kahan, 2015) and domain-specific knowledge (Shi et al., 2016), also requires higher-level abstraction to perceive both the whole, and the domains within the whole. The Earth System Science (ESS) approach, which perceives the Earth System as the ‘suite of interlinked physical, chemical, biological and human processes that cycle (transport and transform) materials and energy in complex, dynamic ways within the system’ (Steffen et al., 2020, page 57), offers a meaningful path towards developing a framework and has been used for several other concepts and frameworks including planetary boundaries (Steffen et al., 2015), tipping elements (ibid) and the Anthropocene (Steffen et al., 2020). For example, planetary boundaries share the common framework of a safe operating space for human activity, but each planetary boundary is defined within specific domains by the distinct bio-physical processes of that boundary. The specific domains of the planetary boundaries, as outlined by Steffen et al (2015), include ‘atmospheric aerosol loading’, ‘change in biosphere integrity’, ‘biochemical flows’, ‘climate change’, ‘fresh-water use’, ‘land-system change’, ‘ocean acidification’, ‘stratospheric ozone depletion’, and ‘introduction of novel entities’. Critically, the ESS approach includes the “natural” physical/chemical mechanisms that describe Earth’s climate system, and the influences and human processes that are currently causing anthropogenic climate change; offering a potential pathway to reconcile the divisions between climate communication and climate education as outlined by Azevedo and Marques (2017). The ESS approach has been used in education for many years (Edwards et al., 2021; Finley et al., 2011; Hoffman & Barstow, 2007; Libarkin & Kurdziel, 2006) and in climate education, also (McNeal et al., 2014). Applying the ESS approach to CSL, we can define a common CSL framework that comprises three specific knowledge groups:

1. The physical-chemical mechanisms of Earth's climate system in equilibrium (process);
2. Natural climate change and variability/instability and feedbacks (natural perturbations); and
3. Anthropogenic causes, impacts and consequences of climate change (anthropogenic impacts).

These are distinct divisions as the first group describes the underlying processes and mechanisms that drive the climate system, the second group describes natural climate perturbations and system transitions, while the third group describes the impacts of human activity on Earth's climate system that are distinct from natural perturbations and variability. Ranney and Clark (2016) focus predominantly on the first group, while the work of Shi et al (2016) focuses on some aspects of the first group but focuses more strongly on the third group. Ranney and Clark (2016) have shown that knowledge in the first group, i.e., that related to the physical-chemical processes that describe Earth's climate system, is important in the acceptance of climate change, showing that mechanistic knowledge deficit interventions can increase climate change acceptance and inhibit the influence of worldview. The second group, natural climate change and feedbacks, is included as a knowledge group in order to promote Earth systems thinking and provide context for why humans need to engage quickly to reduce greenhouse gas emissions (Frankie, 2014; Harrington, 2008; Jarrett & Takacs, 2020; Leiserowitz et al., 2010; Shepardson et al., 2011, 2013; Teed & Franco, 2014; "UNESCO: Climate Change in the Classroom," 2016). For example, distinguishing between natural influences and the influence of anthropogenic activities on Earth's climate helps learners recognise the role humans play in anthropogenic climate change and provides context for why the current changes are different from previous variations and perturbations. Both the EU Erasmus+ project (European Union's Erasmus+ Programme: European Erasmus+ Climate Literacy, 2015) and the US Global Change Research Program (USGCRP, 2009) include knowledge group 2 in their climate literacy programmes with the Milankovitch Cycles and the effect of volcanoes on Earth's energy budget included in the EU programme and natural warming included in the USGCRP programme. Understanding feedbacks, such as the water vapour feedback, is essential in understanding the urgency for why humans must act quickly to reduce emissions and provides context for developing knowledge about abrupt climate change and tipping points and establishes a base for attributing modern era climatic changes to natural vs anthropogenic influences, a component of knowledge group 3. As argued by Frankie (2014, page 19) ‘climate literacy begins with an understanding of climate as a system and how changes to even one piece of the system cascades into climatic and environmental changes and feedbacks’. Knowledge group 3, related to anthropogenic impacts and fossil fuel emissions, is likely the most widely communicated knowledge of these three groups (Lee et al., 2020; Mittenzwei et al., 2019; Azevedo & Marques, 2017; Wu, Lee, Chang, & Liang, 2013, see also Section 1.3.3.4 and Section 1.5.1.4) and is important to provide context for why urgent action on emission reduction is needed. Knowledge group 3 forms the main component of the EU (European Union’s Erasmus+ Programme: European Erasmus+ Climate Literacy, 2015) and the USGCRP (USGCRP, 2009) climate literacy programmes. The approach proposed in this thesis defers consideration of the human influence on Earth’s climate until students understand how the natural climate system operates (knowledge groups 1 and 2) and then allows consideration of human influence and impacts on Earth’s climate (knowledge group 3) without the value judgements associated with humanist approaches like stewardship. This may promote a more respectful relationship with nature.

All three knowledge groups are essential in a comprehensive CSL framework, however there is no agreed-upon, nor well-established, guidance on the order in which they should be taught, nor consistent guidance on what should be included within these different knowledges. When we consider the influence of worldview and the role of emotions, however, it becomes apparent that teaching the physical-chemical mechanisms of the climate system in equilibrium before teaching the other knowledge groups might be the most constructive approach. To understand feedbacks and knowledge related to group 2, learners need to have an adequate understanding of the biophysical processes before they can grapple with water vapour feedback, albedo, and ice-loss feedback. Therefore, the logical teaching sequence is to teach the physical-chemical mechanisms of the climate system in equilibrium first. In terms of worldview and the role of emotions, teaching concepts related to climate change impacts such as sea-level rise, increased global atmospheric temperatures and increase in frequency, magnitude and duration of extreme weather events, irrational responses are more likely to occur if learners attempt to cope with this knowledge before they have a coping strategy in place.

While Shi et al (2016) found incidental causal knowledge i.e., that related to anthropogenic impacts, to be a strong a predictor of climate-friendly attitudes in adults (n=2495), it would likely be an unwise starting point for CSL instruction for early adolescents due to an absence of worldview bias (as outlined in Section 1.3.2.10) and psychological factors (as outlined Section 1.3.2.3). Teaching the biophysical mechanisms of Earth's natural climate system in early adolescence, and continuing to develop these concepts throughout high school may further enhance the positive correlation that Shi et al (2016) reported between knowledge of anthropogenic climate effects and climate-friendly attitudes. I reiterate that all these knowledges are essential towards developing CSL but starting with the physical-chemical mechanisms of Earth's climate system in equilibrium may be most constructive. Harrington (2008, page 576) supports this order of divisions:

> 'Planetary citizens need improved science and climate literacy to better understand the implications of these anthropogenic changes and related system feedbacks. Improved climate literacy requires knowledge of the nature of science as a way of knowing and the scientific foundations that drive important processes within the climate system'.

Knowledge groups 1 and group 2 correspond to the climate education division (the transmission and acquisition of something – knowledge, skills, and dispositions – helping someone to become qualified to live in our complex modern societies) and group 3 corresponds to both climate education and communication (on the person, as subject of action and responsibility, practices, ways of doing and being – such as cultural practices, political practices, professional practices, and so on) as described by Azevedo and Marques (2017). Consequently and, in spite of a lack of a prior definition for CSL or a precedent CSL framework, this approach aims to reconcile these divisions and work towards a constructive and integrated CSL framework that considers both climate education and climate communication as valuable and essential components of the whole CSL system.

Combining climate communication theory, as outlined in Section 1.3, with knowledge deficit interventions, the focus of this thesis concerns the physical-chemical mechanisms of the climate system in equilibrium from group 1 (see Section 1.3.3.4) as distinct from knowledge areas concerning natural climate change and feedbacks in group 2, and the human impacts (i.e., the political economy of the fossil fuel industry), the impacts/consequences (i.e., the changes to human-valued systems as a result of climate change), and the responses/behaviours (i.e., policy options and behavioural changes with mitigation benefits) from group 3. Further discussion related to the effect of anchoring and knowledge deficit interventions which provides additional context for ordering the three groups in this way can be found in Section 1.5.1.6. and Section 1.5.2.

Having presented the rationale for ordering CSL knowledge groups, the next step is to establish where the CSL framework can be most effectively deployed. As previously explored in this Chapter, the aim of climate education and climate communication is to increase public awareness and understanding of climate change and to foster climate-friendly engagement and actions (Azevedo & Marques, 2017; Chadwick, 2017). Since we need to reach a global and diverse audience, one of the most effective ways to increase public awareness and understanding is through the public education system. As argued by Kahan, science communicators are not likely to 'figure out how to disentangle apprehension of climate science from cultural identity as quickly in the realm of politics as educators are likely to do it the classroom' (2015, page 30). Therefore, the environment of an evidence-based culture that is found in the public-school science classroom is more likely to foster attitudes that align with the scientific consensus via knowledge-propagation processes.

In a 2013 study that examined the role of mechanistic information and numeric evidence as a 'lever' to promote concern and engagement on climate change, Clark et al. (2013), demonstrated that a 'well-considered educational approach is critical for public engagement' (page 2071) and 'on-line survey interventions, brief curricula, and classroom lessons can have a marked and persistent effect on one's knowledge, understanding, beliefs, and attitudes about global warming' (page 2075). While many schools provide climate change education in some form, little research has been done on when, how and what a Climate Science Literacy (CSL) curriculum or pedagogy looks like (Azeiteiro et al., 2017; Azevedo & Marques, 2017; Milér & Sládek, 2011).

Despite a strong focus on innovation in terms of digital environments and online learning, the 2017 book 'Climate Literacy and Innovations in Climate Change Education', missed the opportunity to incorporate lessons learned from climate communication research and theory. Of the 101 references to pedagogy in this book none referred to important climate-specific pedagogical considerations as outlined in Section 1.3. Framing was mentioned eight times, with no mentions in the context of the vast body of knowledge on framing effects produced by climate communication research. This would suggest there is benefit to be gained from an integrated perspective that draws together climate communication and climate education research.

Therefore, in the following sections, I will explore climate education research to draw new insights for integration with climate communication research (for context, please see Section 1.3) on potential strategies to inform a CSL framework. In addition, research related to intellectual and cognitive development, pedagogical- and curriculum-design also offer valuable contributions regarding the appropriate calibration of a CSL framework to learners' needs.

The first step is to explore the barriers in climate education, as well as how it is informed by climate communication. Following on from this, the section will then consider, as recommended by Azevedo and Marques (2017), how to reconcile the cultural division between climate communication and climate education. The reconciliation involves incorporating climate communication research, tools and practice into the climate education framework and showing how climate education might assist in constraining or overcoming many of the barriers that have plagued climate communication for so long. In the subsequent sections the work will draw upon research from several disciplines in order to lay the groundwork for a CSL framework.

1.5.1. Barriers and factors to consider for climate education

As may be expected, there are several barriers and issues that need to be considered with respect to climate education that are unique to formal or structured learning that could, if resolved, resurrect knowledge deficit as a valid climate change mitigating intervention (Clark et al., 2013; Ranney & Clark, 2016; Shi et al., 2016; Stevenson et al., 2014). These relate to:

1) the age when students are normally introduced to the climate change topic (Corner et al., 2015; Lee et al., 2020; Stevenson et al., 2014);
2) the competency of teachers to provide instruction on climate change (Sullivana et al., 2014);

3) the content of the curriculum (Azevedo & Marques, 2017; Shi et al., 2016);
4) the further development of a climate science literacy definition (Azevedo & Marques, 2017; Milér & Sládek, 2011);
5) climate change teaching tools and the delivery method (Tasquier et al., 2016);
6) the ongoing debate on the direct efficacy of knowledge-deficit interventions on climate-friendly attitudes and behaviour i.e., discussions related to the knowledge-attitude-behaviour (KAB) model; and
7) the pedagogy that guides students in their learning (Busch et al., 2019)

1.5.1.1. The age climate change is taught in the classroom

In most public schools in developed countries where climate change is included in the national curriculum, the topic is seldom introduced before upper secondary school (15-17 years) (Bieler et al., 2018; Whitehouse, 2013; Wynes & Nicholas, 2019) (Table 1.2). While some aspects related to climate change are introduced earlier in some schools in the United Kingdom and Austria, the main subject (specifically referred to as 'climate change' in both the UK and Austria) is reserved for older adolescents from the age of ~15 years onward. For those who remain in school, only those who specialise in subjects that include climate change within the curriculum will receive climate change instruction.

Table 1.2: Overview of climate change ins elected national curricula

Country	Grade	Starting age	Mandatory topic	Reference
Canada	10	15	No	(Bieler et al., 2018; Seth Wynes & Nicholas, 2019)
United States			No	(Sharma, 2012)
Australia	10	15**	No	(Boon, 2010; Colliver, 2017)
Austria	6†	15**	No	
Indonesia	10	15	No	(Sofiyan et al., 2019)
United Kingdom	10	14-16*	No	("The UK Department of Education," 2015)

Note: 1* Although most climate change-related topics are taught from 14-16 years, 'the production of carbon dioxide by human activity and the impact on climate' and 'the composition of the atmosphere' is taught as part of the UK national curriculum in Chemistry between the ages of 11-14. **Climate change is specifically taught from the age of 15 onwards but some topics are introduced such as 'Description of the effects of climatic changes on the living environment'. † equivalent to grade 10 in the Australian system

For example, while the United States includes climate change in the middle school and high school curricula in the Next Generation Science Standards (NGSS), many of the standards, according to Busch (2017, page 7), ‘are placed within the high school earth science course, which is not typically required for high school graduation’ and, as a result, only 11% of students will encounter climate change as a topic in the classroom (see also Hestness et al., 2014).

Furthermore, while it may appear that older adolescents (15-18 years) are a suitable age group for climate science classes due to their proximity to legal age (i.e. full adult legal rights), this age group may be too old to fully benefit from the instruction as they may have already established worldviews (Corner et al., 2015; Neundorf & Niemi, 2014; Vollebergh et al., 2001) and are less likely to be receptive to altering their opinion when presented with new information (Kahan et al., 2011).

1.5.1.2. Teacher competency to teach climate change

Teachers are not always confident (or properly schooled/trained) to teach climate science and may lack knowledge about the underlying physical processes and mechanisms that underpin the science of climate change (see also Section 1.3.2.7). In addition, some may wish to teach ‘both sides of the argument’ or claim the science is false or misleading (Bissell, 2011; Crayne, 2015; Meehan et al., 2018; Sullivana et al., 2014) depending on their own worldview. This then has implications for potential influence on students’ acceptance of scientific findings (Kunkle & Monroe, 2019).

1.5.1.3. Climate change curriculum

Efforts to improve climate literacy will often focus on the misconceptions, the consequences and impacts of climate change i.e., knowledge related to group 3, rather than on the underlying physical-chemical mechanisms that drive it (Lee et al., 2020; Mittenzwei et al., 2019; Azevedo & Marques, 2017; Wu, Lee, Chang, & Liang, 2013). Many countries, such Canada (Bieler et al., 2018), Australia (Colliver, 2017), and the United States (Sharma, 2012) have no central curriculum that is mandated to be taught in all schools across the country which means that schools/regions/states can frequently decide which topics are taught. This often means that teacher advocacy plays a significant role in whether students are introduced to the topic. In Australia, according to Boon, ‘science teaching in the compulsory years of schooling is so “flexible” that it might be difficult to examine whether [curriculum content] policy has been translated directly into practice’(2009, page 46).

1.5.1.4. Refining and developing the Climate Science Literacy (CSL) definition for compulsory education

The fourth barrier to climate education is a lack of a Climate Science Literacy (CSL) definition that can be used in schools (both in theory and practice) that is internationally recognised (Milér & Sládek, 2011). The lack of guidance due to a lack of a standardised definition may lead to the teaching of incorrect or unsophisticated information about climate change, rather than a structured curriculum (Azevedo & Marques, 2017; Clark et al., 2013; Liu et al., 2014; Ranney & Clark, 2016).

While a definition from the US Global Change Research Program (USGCRP) in collaboration with the National Oceanic and Atmospheric Administration (NOAA) proposes that Climate Science Literacy ‘is an understanding of the climate's influence on you and society and your influence on climate’ (USGCRP, 2009) and has been widely accepted (Clifford & Travis, 2018), it has not been, according to Miler and Sládek (2011, page 151), ‘defined and agreed upon worldwide’. In other words, it has not been institutionalised across contexts. Additionally, for public education, the USGCRP/NOAA definition lacks essential core competences including knowledge that describes the natural climate system in equilibrium or knowledge related to the procedural causes[10] of climate change. A two-part instalment on themes of climate literacy provided by the Journal of Geoscience Education in 2014 explored many important factors in relation to the USGCRP’s ‘Climate Literacy: The Essential Principles of Climate Science’. Specifically within the USGCRP’s definition of climate science literacy, there is a focus on variability, impacts and consequences and knowledge related to group 3. For the physical/chemical mechanisms that describe Earth’s climate system in equilibrium, the greenhouse effect is explained as ‘Sunlight reaching the Earth can heat the land, ocean, and atmosphere. Some of that sunlight is reflected back to space by the surface, clouds, or ice. Much of the sunlight that reaches Earth is absorbed and warms the planet’. While this explanation offers a broad

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[10] For the purpose of this thesis, we refer to procedural causes as the physical/chemical mechanisms that describe Earth’s climate system in order to distinguish causes from those referring to human causes related to anthropogenic climate change.

introduction to some factors that describes Earth's natural climate system in equilibrium, there are important mechanistic processes (e.g. greenhouse gas as molecules, albedo, Earth's atmosphere) that are missing or are necessary to explain the whole.

It is worth noting that, as an extension of the USGCRP/NOAA, a 3-year project funded by the National Aeronautics and Space Administration (NASA), Innovations in Climate Education (NICE) program tested a climate literacy intervention in middle and high schools in the United States (DeWaters et al., 2014). Although this project was well-structured and incorporated aspects of CSL (namely, questions related to greenhouse gases, greenhouse gas absorption of infrared and warming effect; see: supplementary materials from DeWaters et al., 2014), a thorough and comprehensive investigation of CSL and pedagogical design considerations were not evident. In an associated study exploring CSL in 13-15 year olds (n = 868) based on the USGCRP's 'Climate Literacy: The Essential Principles of Climate Science', Bodzin et al (2014) found that 'urban eight grade students did not have a sound understanding of important climate change concepts'. While their research instrument incorporated many crucial aspects of CSL and explored domain-specific knowledge explicitly within a systems-thinking context, specific domains or learning units were defined in relation to the USGCRP's definition and not in relation to the needs of classroom practice.

The EU Erasmus+ project (European Union's Erasmus+ Programme: European Erasmus+ Climate Literacy, 2015), which provided information about climate change to citizens and member states in the European Union, reflects many of the same aspects of the USGCRP/NOAA climate literacy programme. While it does not offer a climate literacy definition, per se, the project information states that the programme is founded on the belief 'that the society would benefit if people: 1) understand how our climate works; 2) know how to distinguish fact from fiction; 3) talk about climate in a meaningful way; and 4) make informed and responsible decisions. The publicly available learning modules cover eight topics, including 'Introduction to climate change', 'The ecological footprint', 'Sustainable Mobility', 'Housing', 'Household energy', 'Food and Waste', 'Shopping' and 'Promoting climate literacy'. Of these, only two relate directly to climate literacy and education but, on closer inspection, include little information on the physical-chemical mechanisms of the climate system in equilibrium. For example, while the sub-module ‘What does climate change mean’ (under module ‘Introduction to climate change’) takes a broad look at the Milankovitch cycles and the greenhouse effect which is related to group 2 knowledge and the sub-module ‘What can change the climate’ briefly covers Milankovitch Cycles and volcanoes, the programme largely relates to impacts and variation.

Accordingly, further development and refinement of the USGCRP’s climate science literacy (CSL) to include domain-specific knowledge can be viewed as a related, but distinct, endeavour. Furthermore, the underlying explanation of the physical-chemical mechanisms that describe the climate system in equilibrium is missing, a gap that this thesis aims to fill.

In a systemic review of 22 papers describing climate literacy in the literature, Azevedo and Marques (2017) reported that misconceptions in content knowledge related to climate science (i.e. ‘myth busting’) are emphasised over other knowledge (such as ‘procedural knowledge’, defined as ‘know-how’ knowledge that refers to ‘knowledge of procedures, including action sequences and algorithms used in problem solving’ (Banks & Millward, 2007; Star & Stylianides, 2013); and ‘epistemic knowledge’, refers to an ‘understanding of the constructs and defining features of science and how these can be used to justify scientific claims’ (Yang et al., 2018, page 326). They additionally found that there was no requirement in any of these endeavours, as per the Programme for International Student Assessment (PISA) by the Organisation for Economic Co-operation and Development (OECD), ‘to explain phenomena scientifically’ (page 9).

In a study exploring how the energy concept relates to climate literacy (i.e. energy transfer, transformation, conservation and degradation associated with mechanistic/process knowledge and the underlying physical science basis of the climate system in equilibrium), Mittenzwei et al. (2019, page 10) ‘show that previous research has predominantly been limited to describing alternative conceptions without investigating their causes’. These alternative conceptions include misunderstandings about longwave and shortwave radiation on greenhouse gases, misconceptions about non-uniform global climate change (i.e. some regions experiencing amplified warming compared to others experiencing little or negative net warming) and confusion about how thermal energy is held in Earth’s atmosphere.

They further argue that knowledge of the underlying drivers of the climate system i.e. the physical-chemical mechanisms, is essential in understanding climate change (ibid). Without a useful and applicable climate literacy definition that describes the fundamental physical-chemical mechanism of the climate system in equilibrium, it is difficult for individuals to position their understanding or to imagine solutions to climate change that are based on an understanding of the science. With these considerations in mind, it might be wise to first introduce the physical-chemical mechanisms that describes the natural climate system in equilibrium and extend, as students acquire knowledge, to the modifications to the mechanisms that lead to the climate system being shifted into disequilibrium.

With regard to public education, a definition of CSL would enable teachers to develop course work, prepare their students for the task of managing potential psychological impacts of engaging with this issue and, when aligned with the Organisation for Economic Co-operation and Developments (OECD) Programme for International Student Assessment (PISA) Science Framework recommendations, help to reinforce the validity of scientific findings. These factors – the ability to design coursework and prepare students for content and accord with international standards – offer practical benefits that a CSL framework could contribute to providing.

1.5.1.5. Mode of content delivery

The mode of content delivery is also an important consideration. Because climate change is such a complex and interdisciplinary subject, conventional teaching materials (books, lectures, and videos) do not lend themselves well to teaching the topic (Tasquier et al., 2016). Innovative educational media therefore offers a promising avenue for aligning teacher content with the needs and desires of learners. Interactive 3D games, for example, may be a better vehicle for teaching climate change (Squire & Squire, 2006; Wu & Lee, 2015) as they can represent visualisations of phenomena and provide context and scope for interdisciplinarity and can segue easily through space and time. As outlined in Section 1.3.3.5, interactive 3D games allow players to explore objects that are beyond the scope of the human eye and remain psychologically and physically safe. Well-designed 3D games can provide 'experiences where players can learn through doing and being, rather than absorbing information from readings and traditional lecture formats' (Wu & Lee, 2015, page 413) and have demonstrated that ‘first-hand experience is a much better teacher than exposure to information because of the emotional pathway it triggers’ (ibid, same page).

1.5.1.6. The knowledge-attitude-behaviour (KAB) debate

There is much discussion within the respective fields of climate communication and climate education on the direct effect of knowledge deficit interventions on climate-friendly attitudes and behaviour (i.e. the effect of knowledge without the influence of worldview bias). The relationship between knowledge, attitude, and behaviour (the KAB model) in relation to emission reduction activities or other pro-environment activities is known to be complex and difficult to assess as many factors are involved in the process (Jakučionytė-Skodienė et al., 2020; Tasquier & Pongiglione, 2017). Individuals become less likely to take action when the personal costs to undertake actions increase (Herman, 2015). In a study investigating the role of the KAB model on energy consumption in Lithuanian households (n=230), Jakučionytė-Skodienė et al. (2020) found that incidental knowledge of various aspects of environmental factors (e.g. ‘The main reason for the smog formation in the big cities is factories’ or ‘Usual plastic bags do not decompose in landfill’), were not correlated with consumption and emission reduction activities. Similarly to research on worldview, incidental knowledge is frequently used to measure knowledge and understanding rather than domain-specific knowledge. However, in the aforementioned study by Shi et al (2016) which explored the correlation between incidental knowledge and climate attitudes across six countries (Canada, China, Germany, Switzerland, the UK and the US; n=2495), ‘causal knowledge’ (group 3) was a predictor of climate-friendly attitudes and behaviour in adults, even when controlling for socio-cultural worldview.

Research that has explored the role of knowledge-deficit as an intervention i.e., via education, has found a positive effect of knowledge on attitude and behaviour. For example, Tasquier and Pongiglione (2017) found that knowledge on behaviour had a significant effect on upper secondary students in Italy (n=48), especially when knowledge gaps in the causes of climate change are reduced. With regard to both knowledge and attitudes and willingness-to-act in US college students (n=69) and public park visitors (n=201), Ranney and Clark (2016) reported that respondents who have more mechanistic knowledge of climate change were significantly associated with two of the four willingness-to-act items, and those who accept that climate change is caused by humans, were significantly associated with all four willingness-to-act items. While the role of knowledge in the KAB dynamic is complex, the following evidence shows that the discussion is incomplete because climate change has not been effectively introduced into the public-school classroom.

The first obstacle is that incidental knowledge on climate change is recognised to be poor. This means that the existing evidence base about the role of climate change knowledge is likely predicated on incidental, rather than structured knowledge. Secondly, as is the case with knowledge measures used in studies of the influence of worldview, active interventions that attempt to support individuals in decision-making by providing them with pertinent, relevant, and domain-specific knowledge are largely omitted from KAB research. Further resolution of the KAB model would benefit from further exploration on the role of knowledge deficit interventions in developing attitudes and behaviours associated with climate change, particularly in relation to the effect of knowledge deficit interventions over time i.e. retention of knowledge over time and resultant long-term effect on attitudes and behaviour.

1.5.1.7. Climate communication theory and climate pedagogy

Lastly, there are many aspects of climate change that need to be considered when teaching it that should be informed, as previously discussed, by climate communication research and theory (Busch et al., 2019) (Section 1.3.2). These aspects include, but are not limited to:

- Framing (Corner et al., 2015; Wibeck, 2013);
- Avoidance of fear appeals (Ojala, 2012a; Stern, 2012);
- Structured guidance on the complexity, i.e., teaching the easy things first to promote competence and develop mastery of a topic over time (Dahl, 2008; Hestness et al., 2017);
- Providing suitable imagery (Leiserowitz, 2006);
- Establishing the value of ‘trusted messengers’ instead of external educators, i.e., visiting lecturers are less effective than familiar teachers (Brabrand & Dahl, 2009; Corner et al., 2015; Fiske & Dupree, 2014; Hermans, 2015);

- Visualisations – particularly of a 3D, interactive nature, as use of this media shows potential for improving learning outcomes when teaching climate change (O'Neill & Smith, 2014; Wibeck, Neset, & Linnér, 2013);
- Process-oriented systems that assist in understanding climate science (Svihla & Linn, 2012); and
- Avoidance of scientific jargon as it is unwelcome and confusing (Corner et al., 2015; Shulman et al., 2020).

By developing an appropriate CSL framework, we move towards a reconciliation of climate education with climate communication that incorporates both knowledge transmission objectives as well as socio-cultural and -political identities (Azevedo & Marques, 2017, page 12). The questions arising from this discussion include:

1) When do we start teaching this topic?
2) What is included in the topic?
3) How should this topic be taught?
4) Which assessment should be used both to assess the approach and to ensure knowledge transmission takes place?

In the following sections, I present a draft CSL framework.

1.5.2. *Knowing where to start*

As discussed in Chapter 2, developments unique to early adolescence suggest this age group may be the most appropriate for CSL interventions. As this age group is undergoing significant cognitive changes and poised on the edge of adulthood, they possess many unique characteristics that could make them suited to knowledge deficit interventions. For example, although human physiological cognitive development takes place throughout childhood and adolescence, adolescence (~11 years) is a period that heralds the formal operational stage (Piaget, 1972) or second critical stage of intellectual development (Jensen & Nutt, 2015). It is also believed during this time that an individual's worldview is still developing, meaning that individuals in early adolescence have not yet made up their minds about their attitudes or have yet to establish a firm socio-cultural worldview (Corner et al., 2015; Lee et al., 2020; Stevenson et al., 2016; Stevenson et al., 2014). This period of indecision may provide an opportunity for educators to anchor important concepts, insights and knowledge related to climate change that may assist in the development of an informed or fact-based worldview.

The anchoring heuristic (or focalism), in this sense, is defined as ‘the disproportionate influence on decision makers to make judgments that are biased toward an initially presented value’ (Furnham & Boo, 2011, page 35; see also Tversky & Kahneman, 1974). Basically, when students encounter new information or knowledge, its value is amplified in comparison to additional knowledge in that topic. Therefore, the first information on a topic delivered to learners is of great importance in influencing their knowledge.

Climate change is a threatening topic for many people and, for developing brains that are undergoing drastic physiological changes in all aspects of their physique, the perception of risk may make this age group particularly vulnerable to anxiety and other psychological ailments (Ojala, 2012b). While threatening topics can be taught with appropriate support and guidance (Ojala, 2012a, 2013, 2015; Ojala et al., 2017), it may be wiser to introduce the basic physical science of Earth’s climate i.e. climate science, before introducing variability and the anthropogenic factors of climate change. As well as helping learners to establish climate-friendly attitudes that are grounded in a scientific appreciation of the cycles, limits, and feedbacks of the climate system, we may also overcome other adverse psychological costs associated with climate change such as anxiety and unhealthy threat perceptions.

1.5.3. Selecting appropriate curriculum content for early adolescents

In the preceding sections I have summarised the knowledge divisions related to CSL and several key considerations that are important in designing a CSL framework. These considerations include the need for a fundamental knowledge base regarding the physical-chemical mechanisms of the climate system in equilibrium and designing this via a structured curriculum for an age group which is developmentally suitable in terms of academic preparation, intellectual capacity and the lack of an established worldview that could lead to rejection of scientific information. I wish to flag at this point, however, that these recommendations are not simply based on academic research. I have taught climate science to primary, secondary and tertiary students since 2007. My lived experience as a climate science teacher has informed the development of the hypotheses that this thesis tests. Initially teaching climate change as a catastrophe (and witnessing the psychological impact on my students), my content gradually changed to foster a scientific rationale for climate-friendly attitudes and engagement. While this is merely anecdotal, parents contacting me out of concern for their child is something every practicing teacher needs to consider in relation to their role as an educator. To ensure students are supported and provided with context to consider the impacts and threats and to consider learners' psychological responses (see Section 1.3.2.3), my teaching experience informs me that a physical science basis of the natural climate system in equilibrium is an appropriate place to start. By beginning climate science instruction in this way, the emotional and psychological aspects/factors, such as feedback-systems/impacts/anthropogenic nature of current global climate change, can be delayed until students have established a solid scientific understanding of the underlying physical phenomena. This assertion is not only drawn from my review of the literature (see Section 1.5), but also from my own practical experience in the classroom.

A clear rationale for the selection of instructional materials is necessary to ensure the selection of appropriate curriculum content. To this end, any material or content that instructs students on the physical-chemical mechanics of the climate system in equilibrium could form the basis of instructional material. Starting the educational journey for learners with this material offers a sequential approach that will allow for later educational instruction on natural climate change, feedbacks, and anthropogenic climate change to establish a logical cause-transition-effect relationship. This cause-effect sequencing in learning is useful in promoting knowledge development and retention (Clark et al., 2013). In addition, the threat and potential for anxiety in the early adolescent age group speaks strongly against starting with future and anticipated impacts/consequences in curricula for early adolescents – even if there are methods to manage that anxiety (Ojala, 2012a, 2013, 2015; Ojala et al., 2017). Therefore, the focus here is on fundamental climate science and the stable climate during the

Holocene as a departure point for understanding climate change. Knowledge domains related to change, such as natural variability, feedbacks, and anthropogenic climate change, would be taught after a basic climate science understanding has been provided.

For the selection of instructional material within the physical-chemical mechanics of the climate system in equilibrium we look first to the literature and the efforts of others involved in CSL interventions. Several themes have been identified that exclusively explore the physical science basis i.e. those that can be explored, observed, and examined without threat perception, and these can be broken down into main themes and topics. From these themes a complete picture of the whole can describe the physical-chemical mechanisms of the climate system. These form the basis of the instructional material. Relevant and appropriate themes identified within the literature are:

- The role of greenhouse gases (GHGs) in atmospheric warming (particularly abundance) i.e. higher GHG abundances lead to higher surface and lower atmospheric temperatures (Azeiteiro et al., 2017; Bodzin et al., 2014; Plutzer & Hannah, 2018; Sullivana et al., 2014);
- The role of albedo in temperature regulation at the Earth's surface (Clark et al., 2013; Harrington, 2008; McCaffrey & Buhr, 2008; Reynolds et al., 2010; Shepardson et al., 2013; Sullivana et al., 2014);
- Earth's position in the Solar system i.e. the Circumstellar Habitable Zone (CHZ), and insolation (Christ, 2020; Nielbock & Türk, 2017);
- The greenhouse effect in equilibrium i.e. distinct from anthropogenic influences (Azeiteiro et al., 2017; Bodzin et al., 2014; Shepardson et al., 2011, 2013);
- Comparisons of Earth, Mars and Venus as a basis to understand the effect of mass, atmosphere, GHG abundance on the presence of stable bodies of liquid water at the terrestrial surface (Christ, 2020; Nielbock & Türk, 2017);
- Global warming potential (GWP) and molecular structure of GHGs (NOAA - Teaching climate: Greenhouse Gas Molecules; European Commission - Carbon detectives); and
- The characteristics and composition of Earth's atmosphere i.e. particularly distinctions between climate change and the ozone layer as misconceptions about ozone depletion are

frequently conflated with climate change (Bodzin et al., 2014; Harrington, 2008; Lin, 2017; Visintainer & Linn, 2015).

These themes can be sorted into four knowledge domains which encompass, or share, aspects of these key themes: 1) Earth in the Solar System; 2) Earth's atmosphere; 3) Albedo; and 4) Greenhouse gases as molecules. The selection and design of Knowledge Domains is examined in greater detail in Chapter 4. It is the aim of this thesis to test these knowledge domains as a baseline for CSL in the public-school classroom and to provide context for further development of a CSL definition. Themes in these knowledge domains have also been identified as important themes to understand climate science by agencies and institutions involved in climate education/communication (Table 1.3). The themes that explore the physical science basis that have been identified in the literature and by agencies and institutions involved in climate education/communication form the main parts for group 1 knowledge with regard to the overarching ESS approach (see Section 1.5.) and the need for learners to recognise 'that observed phenomena result from underlying processes, and that these processes can interact to produce complex phenomena' (McNeal et al., 2014).

Table 1.3: Alignment of knowledge domains with pre-existing modules developed by agencies and institutions involved in climate education/communication in the broader public arena.

Knowledge domains	**Title and weblink (accessed 16.03.2020)**	**Agency/Institution**
Earth and water in the solar system	How Venus and Mars can teach us about Earth	European Space Agency
	Earth in Space	Earth System Research Lab, NOAA
	The greenhouse effects of Earth, Venus, and Mars	Earth System Research Lab, NOAA
Earth's atmosphere	Earth's atmosphere	Earth System Research Lab, NOAA
	10 interesting things about air	NASA Climate Kids
Albedo	What is the greenhouse effect?	NASA Climate Kids
	What does climate change mean	Erasmus+ Climate Literacy
	Energy from the Sun	Earth System Research Lab, NOAA
	Earth's Radiative Heat Budget	Earth System Research Lab, NOAA
Greenhouse gases as molecules	The greenhouse gases	Earth System Research Lab, NOAA
	The Greenhouse Effect	University Corporation for Atmospheric Research (UCAR) , Center for Science Education
	Meet the Greenhouse gases	NASA Climate Kids

For example, ‘Earth in the Solar System’ relates to the physical phenomena of the circumstellar habitable zone and Earth’s proximity to the Sun, the physical effect of gravity on forming an atmosphere and the comparison of Earth’s climate system to those on the other terrestrial planets and aims to helps students build a conceptual understanding of the underlying processes that contribute to Earth’s habitable temperatures.

It is worth noting that, as a prototype instructional framework, the selection of these themes is limited by the lack of research in CSL knowledge deficit interventions and the lack of an existing comprehensive CSL framework. To my knowledge, no material relating to the physical/chemical mechanisms that describe Earth’s climate system in equilibrium was excluded. This is not to say that the selected knowledge domains are exhaustive. Rather the literature, as well as outreach programmes, and my personal climate science teaching experience have been collated to provide a baseline for investigating CSL. Further review, elaboration, testing and development of the framework is needed. Since the time required to learn all aspects of CSL would be greater than that provided in one class lesson, it is expected that the CSL framework would be broken into separate knowledge domains or learning units. However, while it is the intention to teach each knowledge domain in one class sitting, this would require further refinement of the CSL framework once learning progressions have been determined. For further discussion on learning progressions and the design of the CSL framework, please see Section 4.3.3.

Therefore, the selection of the knowledge domains and the rationale behind their selection is based on these findings from climate communication and education literature, climate science outreach programmes (Table 1.3) and, finally, my experience as a climate educator. By starting with group 1, as described in Section 1.5, this selection of knowledge domains provides an anchor for understanding natural climate change, feedbacks, and the impacts of anthropogenic climate change at later stages of learning. Anchoring knowledge related to the physical and chemical mechanisms that describe Earth’s climate in equilibrium is a pre-emptive measure to clarify concepts or prevent misconceptions identified in the literature that can be employed by deniers to obfuscate and create misunderstanding about climate science. For ‘Earth in the Solar System’, the trace amounts of greenhouse gases in

Earth's atmosphere have been used by climate deniers to argue that there are too few of them to have an effect (Contoski, 2017) which comparison amongst Mercury, Venus, Earth and Mars serve to rectify. 'Earth's atmosphere' resolves misunderstandings between climate change and ozone depletion (Bodzin et al., 2014; McNeill & Vaughn, 2012; Meehan et al., 2018; Stevenson et al., 2014; Tobler et al., 2012) 'Albedo' addresses the poor understanding of this factor in the public arena (Harrington, 2008; Reynolds et al., 2010; Varma & Linn, 2012; Visintainer & Linn, 2015). 'Greenhouse gases as molecules' highlights the structure of greenhouse gases and global warming potential as important factors in student understanding (Mittenzwei et al., 2019; Varma & Linn, 2012). In particular, Bodzin et al. (2014) recommend that middle school curriculum be structured to 'explicitly focus on a sequence of topics that include: weather and climate, the atmosphere, Earth system energy balance, greenhouse gases, paleoclimatology, and natural and human climate change impacts (page 423)'. The recommendations of Bodzin et al. (2014) encompass three of the four identified knowledge domains (weather and climate, the atmosphere, Earth system energy balance, greenhouse gases), and indirectly refer to the fourth (Earth system energy balance) when only group 1 knowledge is included for early adolescents. By starting with the domains that describe the physical and chemical mechanisms that describe Earth's climate in equilibrium followed consequently with those proposed, for example, by the EU Erasmus+ project and the USGCRP climate literacy programme, which include natural climate change and system transitions, and then those by Shi et al (2016) related to causal knowledge and action-related knowledge, we formulate a prototype CSL framework. In this way, we aim to encompass the 'suite of interlinked physical, chemical, biological and human processes that cycle (transport and transform) materials and energy in complex, dynamic ways within the system' (Steffen et al., 2020, page 57) in relation to the climate system and the socio-cultural anthropogenic aspects as well.

While each knowledge domains encompasses a specific learning unit, it can share common phenomenon/concepts/knowledge with other knowledge domains. This means that knowledge, when pertinent to both knowledge domains, can be taught within that knowledge domain in context with the background of that knowledge domain. Similarly, phenomenon/concepts/knowledge within a knowledge domain may be useful in explaining or justifying another aspect of phenomenon/concepts/knowledge in a different knowledge domain. Once again, this knowledge can be taught in context with the background of this other knowledge domain. This follows the ESS approach (Finley et al., 2011; Gosselin et al., 2019) that considers the system as a whole and linked to other systems. Essentially, the four knowledge domains 'Earth in the Solar System', 'Earth's atmosphere', 'Albedo' and 'Greenhouse gases as molecules' form the essential knowledge foundation needed for developing a conceptual model of Earth's climate system as a basis for understanding variability and anthropogenic climate change at later stages of learning. While this is a departure from teaching the greenhouse effect as a learning unit, the greenhouse effect is embedded in the knowledge domains. The different components of the greenhouse effect are broken down into constituent parts in order to examine these individually before connecting them into a conceptual whole. In many ways, the knowledge domains are an ontology i.e. the set of concepts and categories of the greenhouse effect that shows their properties and the relations between them (Libarkin & Kurdziel, 2006).

These four knowledge domains (see also Section 4.3.4) that encompass the physical science basis of the natural climate system align with many of the descriptive learning objectives (LO) set by the respective national curricula in Austria and Australia (Table 1.4; please see Appendix III for further detail). It is worth noting that these are LOs that align with content that helps to explain the physical science basis of the natural climate system in equilibrium but are unlikely to be taught in context with climate science. For example, while important aspects of albedo could be taught in Australia's year 9 science curriculum under the heading 'Energy transfer through different mediums can be explained using wave and particle models', only 3 of 74 related resources are associated with climate change (i.e. topic names include 'renewable energy', 'fossils to fuels') and only one resource includes albedo within the physical-chemical mechanisms of climate science under the, 'climate change – creating critical thinkers…not sceptics!' resource. While the physical-chemical mechanisms of the climate system in equilibrium is largely missing from the curricula, the topic of climate change as a result of anthropogenic emissions is taught. This is, however, more commonly taught at an age when worldview bias may already have begun to influence an individual's opinion (Corner et al., 2015;

Stevenson et al., 2014). For example, the greenhouse effect is taught explicitly in year 10 in Australia and climate change is taught explicitly in Austria in the 6. Klasse: both at age 15-16 years.

Table 1.4: Overview of the learning objectives (LOs) in the National Curricula of Australia and Austria that align with concepts, understanding, and basic knowledge that describe the physical science basis of the natural climate system in equilibrium.

		Earth and water in the Solar System	**Greenhouse gases as molecules**	**Albedo**	**Earth's atmosphere**
Australian curriculum*	Year 5 (10-11 years)	x		x	x
	Year 6 (11-12 years)				
	Year 7 (12-13 years)	x			
	Year 8 (13-14)		x		
	Year 9 (14-15)			x	
	Year 10* (15-16)	x	x	x	x
Austrian curriculum**	1. Klasse (10-11 years)	x			
	2. Klasse (11-12 years)				
	3. Klasse (12-13 years)	x		x	x
	4. Klasse (13-14 years)		x		
	5. Klasse (14-15 years)		x		
	6. Klasse** (15-16 years)			x	

*Where greenhouse effect is mentioned explicitly in the curriculum **Where climate change is mentioned explicitly in the curriculum.

In order to select appropriate material for a climate science curriculum for early adolescents, there is a need for this age group to have the ability to understand the science in terms of physics, mathematics, chemistry and earth science. In this regard, both the Australian and Austrian curricula cover material associated with ‘Earth and water in the Solar System’, ‘Albedo’, and ‘Earth’s atmosphere’ but do not teach knowledge associated with ‘greenhouse gases as molecules’ until after the age of 13 (see Appendix III for further detail). In other countries, however, knowledge about molecular structure is taught. For example, in the Nature and Technology subject of the Danish national curriculum, 12-13-year-old students should be able to ‘explain the molecular structure of individual substances. The student has knowledge of some atoms and molecules’ (Børne- og Undervisningsministeriet (Danish

Minstry of Education), 2019). We may presume that students of this age share similar cognitive abilities and while molecular knowledge is not present in the Australian and Austrian curricula, the presence of this topic in the Danish curriculum indicates that this age group are able to understand this knowledge domain.

Since a CSL framework for public education is lacking, there is a need to test the knowledge domains to ensure that the material and content is within the intellectual scope of this age group, can be used in the classroom (see Section 1.5.1), and if knowledge domains are affected by socio-demographic factors, e.g. country/regions, or gender. By pre-testing different groups of schools in order to establish what they know in each of the knowledge domains, the relative levels of complexity of each of the knowledge domains (from easy to difficult) and how these knowledge domains relate to one another, helps to determine the most suitable level at which to begin instruction. This technique, known as the background knowledge probe (Angelo & Cross, 1993, page 121) provides feedback on the existing background knowledge of students at a particular age range or subject topic. This pre-testing may provide insights into specific knowledge domains (defined here as learning units (Guskey, 2015), or the systematic organisation of concepts and skills in declarative, procedural, and conditional knowledge of a specific learning topic (Alexander, 1992)) whereby knowledge signals are shared across nationality, gender, and school. Will students in this age group across different demographic factors (for example, country, and/or gender) demonstrate similar strengths and weaknesses that can be categorised into one knowledge domain or will curricula need to be individually tailored to specific countries or demographic groups? Understanding the knowledge domains, and how students perform, will help educators to create learning plans, which will include starting students off with material and concepts that they can readily understand before progressing to the increasingly difficult domains. Finally, students are provided with instruction in climate science after which they are post-tested, and their results then compared to pre-test performance. This comparison may reinforce or deconstruct knowledge domain signals observed in the pre-testing, as well as provide insights into the best vehicles for knowledge deficit interventions and those that bring the highest learning outcomes (Biggs & Collis, 1982; Dahl, 2008; Guskey, 2015; Institute for Teaching and Learning Innovation - SOLO Taxonomy, 2012). By establishing a baseline for where adolescents are positioned in CSL in the public-school classroom, this thesis addresses the need for a tested CSL Framework and contributes to the development of a CSL definition to assist further research in this arena. The case for the suitability of early adolescents for knowledge deficit interventions will be further explored in Chapter 2 and the argument for pre- and post-testing students in order to construct the curriculum will be examined in Chapter 4.

1.5.4. Pedagogy for early adolescents

In response to the lack of climate science understanding amongst science teachers (Bissell, 2011; Crayne, 2015; Meehan et al., 2018; Sullivana et al., 2014), the teaching role needs to shift from that of subject expert to one of facilitator; at least until climate science understanding significantly improves in the science teaching community. While some teachers are familiar with the physical basis of climate change, there are many more (Hess & Collins, 2018; Plutzer, McCaffrey, et al., 2016; Sullivana et al., 2014) who are insufficiently conversant with the mechanisms and processes, which may promote confusion and misinformation amongst their students (Boon, 2014; Crayne, 2015). This need not mean that teachers forgo the role of subject expert when they are conversant with the topic, it simply means the framework plays the role of the subject expert when teachers are less proficient in the climate science topic. Due to the complexity of climate science, animations and visualisations of climate processes and mechanisms should be the basis of content delivery (Sheppard et al., 2011; Sheppard, 2015). Furthermore, since early adolescents are typically very familiar with new media and technology, tools that reflect their socio-cultural preferences are likely to be well-received (Anastasiadis et al., 2018; Areepattamannil & Khine, 2017) although an iterative approach is recommended when introducing them to the classroom (Camilleri & Camilleri, 2017). Such tools can be 3D interactive games, smartphone apps, or social media environments, to name a few. In addition to these class-room centred pedagogical considerations, there is also a need to include (where necessary and useful) climate communication theory and practice (Section 1.3.2) to ensure the pedagogical approach is constructive and effective. The rationale that describes the proposed pedagogical arrangement and its role in a CSL framework is further discussed in Chapter 5.

1.5.5. Assessment for the CSL framework

Finally, since there is a need to ensure that the curriculum (what is taught) and the pedagogy (how it is taught) are aligned and work coherently together (Bengtsson et al., 2018; Carr et al., 2000), it is necessary to assess these approaches to ensure that the method or framework enhances student knowledge as intended and can be regularly assessed and improved upon. Using the structure of observed learning outcomes (SOLO) from Biggs and Collis (1982), which measures and evaluates the quality of learning through levels of complexity (from easy-to-understand to more-complex material), we combine the testing of the knowledge domains (upon which the levels of complexity are based) with pedagogical approaches (content delivery, climate communication theory) to construct an assessment rubric that is also tested in Chapter 5.

To achieve this, a research instrument was employed to assess CSL (specifically the necessary physical-chemical mechanisms that describe the climate system in equilibrium) and to obtain opinions of respondents with the main focus on CSL, rather than climate opinion (Appendix V for research instrument). Since an instrument specifically for CSL is lacking to compare it to and there is no extant questionnaire designed to test for knowledge related to the physical-chemical mechanisms that describe the climate system in equilibrium (see Appendix V – Comparison of CSL research instruments), this research instrument offers a baseline on which further measures of CSL may take place. For example, although Tobler (2012) developed a research instrument to measure climate change knowledge (with a focus on change) in consumers in Switzerland which included important aspects of CSL such as greenhouse gases and concentrations and basic understanding of the greenhouse effect, many important CSL factors were missing, including albedo, Earth and water in the Solar System, and important features of Earth's atmosphere. Similarly, while Ranney and Clark (2016) focus on radiative forcing such as greenhouse gases as molecules, they do not include important factors such as albedo, Earth and water in the Solar System and particular features of Earth's atmosphere that are necessarily associated with CSL.

The rationale for the survey design used in this thesis is to collect as many factors as possible of the physical-chemical mechanism of climate change into one questionnaire that a class period of 45 minutes will allow. In this way, I hope to form the foundation for a CSL proto-framework based on the identified knowledge domains (see Chapter 4 for further discussion). Aside from the main aim of data collection, the survey was designed to anchor climate knowledge, attitudes and behaviours to scientific facts – which should, in ideal circumstances, form the basis of an opinion. This research instrument was designed for early adolescents who, this thesis will demonstrate, may be a pivotal group for knowledge deficit interventions in order to promote climate-friendly attitudes and behaviours.

Therefore, the research instrument includes several questions on climate opinions (opinion questions based on similar questions used to measure adult opinions: 1) Is climate change something to worry about; 2) Is climate change caused by humans; and 3) Is climate change happening now?) before the CSL assessment of 19 climate science questions. The role and current status of opinion in the early adolescent age group in Austria and Australia are further explored in Chapter 3 with particular focus on the influence of emotions and vulnerability. The current status of CSL based on the climate science questions are investigated in Chapter 4. The design and application of the research instrument are further described and discussed in Chapter 3, Chapter 4, and Chapter 5)

1.6. Digital tools and serious gaming in the realm of climate science literacy

> 'Research shows that, in order for climate science information to be fully absorbed by audiences, it must be actively communicated with appropriate language, metaphor, and analogy; combined with narrative storytelling; made vivid through visual imagery and experiential scenarios; balanced with scientific information; and delivered by trusted messengers in group settings'.
>
> Center for Research on Environmental Decisions (2009), Columbia University

Although many schools in the developed world have adopted some form of online learning capacity (Alone, 2017), there are very few 3D interactive games available for students to learn with. Most online learning environments depend on learning management systems (LMS) or virtual learning environments (VLE) which are, essentially, virtual classrooms based on brick-and-mortar environments. While LMS and VLE have been shown to have higher learning outcomes than conventional classroom settings, there has been an even higher level of tested performance outcomes for the few 3D interactive games that are used for education. These games, known as serious games, have enormous potential to alter learning and teaching in the public-school system, driving a much-needed educational reform (Robinson, 2010) that could alter the educational landscape as we know it. Development of the system (editing, adding features, etc.) can be configured to not only self-edit (adding or removing features, trigger content conflicts such as errors), it can be designed to adjust itself to a users' performance or other criteria (e.g., age, gender, complexity, language). Compared to conventional classroom materials, serious games are cheaper to create, publish, disseminate, and edit. They also have a much longer shelf-life and are easier to transport and share. For learners with special needs, serious games offer tailored learning and can keep pace with learners who struggle or race ahead. Furthermore, research has shown that serious games can be motivating for students who find conventional material boring or unengaging (Garneli et al., 2017).

1.6.1. Curriculum

With regard to the curriculum needs as outlined in the development of a CSL framework (see Section 1.5.3), 3D environments are ideal for natural science (particularly for the physical basis of climate science) as these environments are digital replicas of known or imagined environments and interactions. Processes, system-feedback and mechanisms can be easily created and, in standard game engines, have inbuilt physics engines (Boeing & Bräunl, 2007) that 'improve the realism and presence' (Seugling & Rolin, 2006, page 1) of the virtual environment. This virtual realism can reflect the physical behaviour of particles, motion, objects, and fluids and are based on the known fundamental forces and physical laws. These physical game engines include collision detection, soft body dynamics, Brownian motion, fluid simulations, animation control systems and asset integration tools. Pre-testing (to ascertain prior skills and knowledge) can be easily embedded in an interactive game by asking users to test their skills or knowledge as a precursor to new game levels. This not only reinforces the user's self-directed learning (Kim et al., 2014), it provides a starting position to assess the individual's learning progress and journey (Alexander, 1992). Lastly, game analytics can be employed to develop knowledge domains (specific learning units that relate to an aspect of a learning topic) so that learning outcomes and objectives can be constructed and applied. The roles of 3D environments for teaching climate science are discussed in Chapter 5.

1.6.2. Pedagogy

For pedagogy, the role of subject expert is a task that is especially suited to serious games. Aside from ensuring that the delivery of the content is thorough and comprehensive, it is easy for educators to see how the task has been completed and to what standard (Ifenthaler et al., 2012). Students are unable to flick through the pages but must play the game systematically. When a student shows aptitude or weakness, a serious game, when well-designed, can accelerate or slow down to adapt to their proficiency (Rosyid, 2018). In addition, all students receive the same instruction, delivery, and material, when designed to align with the scientific consensus, which helps to avoids bias and indoctrination (which is somewhat dependent on the portrayal of the game by the teacher as a trusted messenger), two very critical considerations for teaching climate science to young people. For teachers, the automation of many expected tasks such as grading, student feedback and performance can be undertaken at the backend of the game with game analytics and outputs being sent directly to teachers (Davidson & Goldberg, 2009; Shute, Ventura, Bauer, & Zapata-Rivera, 2009; Tyner, 1998; Wu & Lee, 2015). Other tasks, that are currently too labour intensive for teachers, such as individually monitoring progress in real time, can be managed also by the game system (Bellotti et al., 2013; Lester et al., 2013, 2014; Southgate et al., 2017). The use of digital environments for learning and serious games allows pedagogues to include learners in the creation, testing, and implementation of tools. For adolescents, this involvement is a necessary component of research into their lives (Nature Editorial, 2018), as well as educational frameworks; especially as they begin the process of self-determination (S. Field et al., 1997). In addition to these considerations, adolescents are also motivated by, and enjoy, using digital tools in their everyday lives (Areepattamannil & Khine, 2017).

Lastly, and perhaps the most compelling argument of all, is the preference of the human brain for visual input (Bowan, 1999; Sheppard, 2005; Wu et al., 2013). The optic nerve, or cranial nerve II, is a direct extension of the brain with, according to Bowan, ‘upwards of 50% of the neural tissue devoted to vision directly or indirectly’ requiring ‘two-thirds of the electrical activity…when the eyes are open' (Bowan, 1999, page 2). Processing the visual information from 3D objects and animations, whether in real life or virtually, will be faster than reading and writing as the latter require the interpretation of symbolism (e.g., alphabet, numerals) and/or abstract 2D graphic representations (images, graphs, charts, tables). 3D games also typically require many more combinations of activities than just reading text (Hai-Jew, 2010). In addition, interactive animations can aid in the communication of complex concepts such as climate science, for example the understanding of feedback-systems would be significantly improved by simulations or 3D models that demonstrate these phenomena visually. The role of 3D environments, curriculum, and pedagogy is further explored in Chapter 5.

1.6.3. Digital climate education in context with other forms of climate education

Digital game-based learning has become a global trend (Suson, 2019) and offers unique features and advantages that may be particularly useful for wicked, post-normal issues such as those related to anthropogenic climate change. These include:

(1) Exploring Earth Systems and climate processes beyond real-world temporal and spatial limitations (Wu & Lee, 2015; Sheppard, 2015);
(2) making the climate issue visible, personal, immediate, and tangible (Sheppard, 2015); and
(3) providing a visual medium for illustrating complex interconnected interactions, systems and feedbacks and their causes and impacts (Ifenthaler et al., 2012).

Rather than being a stand-alone educational tool, digital game-based learning is best used as a complement and extension of other types of educational activities and environments. This is illustrated in a study amongst Spanish adolescents (n=87, aged 12-15-years) which demonstrated an improvement in selective attention, concentration and sociability in students playing Pokémon GO (Ruiz-Ariza et al., 2018). As well as positively affecting cognitive performance, students improved their physical fitness and reported feeling happier with a stronger desire to go outside. When additional teaching materials are provided to the teacher to support student learning, which is also standard practice for textbooks and other educational material e.g. teachers' handbooks, answer keys, etc., teachers are better able to respond to student questions, create additional activities e.g. fieldwork or experiments, and refresh and brush up on skills or learning material they may have forgotten, missed, or not had available in their training.

Games may encounter resistance from teachers reluctant to include them in classwork (De Grove et al., 2012; Dickey, 2015; Razak et al., 2012). Reluctance stems from re-training pressures (Hayak & Avidov-Ungar, 2020), poor infrastructure or technical know-how (ibid), risk of alienation by colleagues (Stieler-Hunt & Jones, 2017), fear of loss of class control, fear of student boredom, limits to time and resources, potential student confusion that they are learning and not playing (Beavis et al., 2014), inappropriate content or violence (De Freitas, 2006), parental displeasure (Bourgonjon et al., 2011), and perceived learning efficacy of games. While the majority of these factors present challenges for implementation of digital game-based learning, many will resolve as technology and familiarity with digital media advances and as students and teachers adopt 21st-century skills (Suson, 2019). This is particularly relevant for climate education which requires wicked-problem/post-normal solutions that will emerge both as a result of technological advances and in response to climate change. As far as the efficacy of games is concerned, there is robust evidence of their value as learning tools, with many meta-studies consistently documenting better learning outcomes (see Egenfeldt-Nielsen et al., 2008, page 266). Concerning student engagement with climate education via a digital platform, it has been my experience that student experiences of recreational digital games can affect expectations of and attitudes to serious educational games (SEGs). As a result, students can feel 'unsure whether to approach the video game as play or learning' (ibid, page 262). We may expect, for example, that students who play video games for fun might perceive SEGs, such as a climate educational game, as boring or work. However, since these tools are already employed in the classroom and their use is likely to increase over time, it is likely that students will adapt to using them for educational and personal development as well as for recreation.

In summary, there is a need to connect young people to nature, but digital interactions do not preclude or hinder outdoor activities. Rather, digital game-based learning should best be considered, alongside other forms of climate education, as part of a mutually reinforcing strategy towards improving climate-friendly attitudes and behaviour. Furthermore, while there are some challenges to the use of digital games in the classroom, both for teachers and students, these are likely to resolve over time as both groups become more conversant with the tools and as infrastructure in education environments improves.

1.7. Synthesis and research questions

Climate science communication and education is a significant global challenge, due to the increasingly urgent need to reduce greenhouse gas emissions, the generally poor level of public CSL, and significant public distrust of expert scientific opinion. Climate communication theory offers many useful insights, both barriers and avenues, toward overcoming this challenge. From the perspective of this thesis, these insights are particularly useful for interventions that involve CSL. How education (especially technologically-enhanced education) can be positioned to fit within these influences (or circumvent these barriers) depends on many factors. One of the most significant is the need to reconcile divisions between climate literacy as a transmission of knowledge and cause-effect understanding and the human event of communication, meaning-making and interpretation.

One key component of this task is to establish a starting point for CSL interventions. Furthermore, the role of education – and the development of an adequate CSL framework (both curriculum and pedagogy) – needs to be addressed rapidly in order to respond to the previously identified learning gap. The role of public education is to prepare our global youth for adulthood and the absence of an effective CSL framework disadvantages those who are about to enter public life and adulthood in a world where answers to this issue are required.

As proposed by the literature reviewed throughout this chapter, communication and education on climate science require different approaches for different groups. To ensure the number of adults with adequate CSL increases and to foster climate-friendly attitudes and engagement, the role of adolescent education in CSL in the public-school system requires adjustment to fill this gap. This has been perceived as a challenge, given the need to establish at what age this learning is best undertaken and the requirement for the development of an appropriate and effective CSL framework. Therefore, this thesis examines the potential of early adolescents as a suitable group for mass climate communication and climate education. Within this examination, the work aims to assess their current opinions about climate change and their existing understanding of climate science. Using a prior- and post-questionnaire on opinions and scientific knowledge related to climate science, this research also constructs a theoretically supported and empirically grounded CSL framework for future deployment in the lower secondary public-school system. As an extension of this task, and to address the lack of an existing tested framework (curriculum and pedagogy), this CSL proto-framework is then tested in a 3D interactive game to investigate knowledge development and the validity of this new media in climate science communication and education. This thesis aims to reconcile some of the divisions between climate communication and climate education by incorporating essential components from climate communication including social and ethical approaches as illustrated by Azevedo and Marques (2017, see also Figure 2 'Science communication approaches').

The work will begin by looking at students in the first year of secondary school in Australia and the third year of secondary school in Austria as a potential group for knowledge deficit interventions as they may not have established worldviews. It will then investigate their opinions on climate change in order to incorporate established climate communication factors into the climate education framework. To explore worldview, the work will assess whether the same shared identities are found in the early adolescent age group as those found in adults (do early adolescents reflect the same climate opinions as their respective adult population). Following on from this, the work will test how well students understand climate science to establish their incidental or prior climate science literacy (CSL) and identify where their knowledge strengths and weaknesses lie. Finally, the work will examine if it is possible to improve student understanding with the use of a 3D interactive game. This will involve determining if a knowledge deficit intervention improves CSL and if the signals we determine from their prior CSL test are present in post CSL results.

The aim of this work will be addressed through the following research questions and objectives:

Finding a suitable group for mass climate science communication

1) What are the characteristics of early adolescents that make them a suitable age-group for climate science communication and education?
    a) Review the literature on physiological and intellectual development of 12-13-year-olds to investigate their capacity to grasp essential basics in climate science.
    b) Discuss the validity of knowledge deficit interventions as a means to cultivate a fact-based worldview and promote civic engagement and responsibility.

Evaluating the current opinion status of early adolescents with regard to climate change

2) What opinions do early adolescents maintain with regard to climate change (their concerns about climate change, their opinions on who is responsible, and whether or not climate change is currently occurring) and how do these opinions compare with adults and older adolescents in their respective populations?
    c) Evaluate the opinions of early adolescents.
    d) Discuss the implications of their opinions with regard to knowledge and worldview development.
    e) Compare the risk perception opinions of early adolescents with their respective adults and older adolescent population.

Testing the potential of early adolescents' intellectual development to understand the physical science basis of climate change

3) What is the current level of CSL in the 12-13-year age group?
    f) Test the level of CSL in the 12-13-year age group.
    g) Investigate how demographic and personal-identity factors affect CSL in the 12-13-year-age group.
    h) Formulate a CSL proto-framework.

Examining the efficacy of the 3D interactive game, CO2peration, to teach climate science and the validity of the proto-framework

4) Can the interactive 3D game, CO2peration, improve CSL in the 12-13-year age group?
    i) Examine the knowledge development in CSL of 12-13-year olds
    j) Discuss the potential of the CO2peration game as a valid climate communication and climate education vehicle

Assessing the validity of the framework as a CSL instrument to teach climate science in the early adolescent age group

5) Is the CSL framework a valid instrument to teach climate science in the early adolescent age group?
    k) Test how each KDs (knowledge domains) perform in relation to their respective prior score
    l) Discuss the validity of the proto-framework for use in CSL in early adolescence

Answering these research questions and objectives will contribute to understanding the potential role of early adolescents in climate communication and climate education endeavours and provide a foundation for a CSL proto-framework. The research has implications for climate educators and communicators, particularly those involved in the public education system. By establishing a starting age for CSL interventions and providing instruction on curricula and pedagogy, particularly those related to the physical science basis of climate science and the associated specific knowledge domains, the research illuminates key considerations in the climate communication and climate education fields.

1.8. Methodological approach

Since climate change is a global problem that will have significant impacts on our resilience and capacity to adapt and survive, an international perspective was deemed a key component of this research. Because a previous research project involved older secondary students in Vienna, Austria, and Copenhagen, Denmark, in 2011, the inclusion of one of those cities made practical and logistic sense. Due to existing networks and strong German-language skills (essential for the creation of documentation, interpretation of the results and further development of the German-language version of the game), Vienna was selected as the more suitable choice. In addition, Sydney and Canberra were included due to their status as major population centres and to provide country-relevant research to the sponsor of the scholarship, the Australian Federal Government.

To begin this study, it was necessary to select an age group that, according to the existing literature, had the intellectual capacity to understand the science behind climate change but had not yet developed their worldviews.

Research Question 1 (Chapter 2) was designed to respond to this dilemma. A review of the literature on worldview formation and intellectual development (from childhood to late adolescence) indicated that 12-13-year olds showed considerable promise as a group for CSL interventions and had not yet formed socio-cultural/-political worldviews. However, while these characteristics may offer a pathway towards cultivating a fact-based worldview, knowledge deficit interventions would not be useful if this age group has neither prior interest in climate change as a classroom subject nor sufficient relevant incidental knowledge to understand climate science. Therefore, to investigate both opinions and CSL in this age group, the study utilised a climate science questionnaire to quantify what their opinions were regarding climate change and what the current level of existing climate science understanding was in this age group.

Research Question 2 (Chapter 3) provides an insight into the opinions of early adolescents with regard to climate change and offers new perspectives on worldview development. Due to its suitability for ordinal data from the Likert scale, ordinal logistic regression analysis was selected.

Research Question 3 (Chapter 4) established whether early adolescents were, indeed, ready for CSL interventions and if they could respond meaningfully to the climate science questionnaire. In addition to establishing their intellectual capacity, the questionnaire allowed the opportunity to establish a baseline of their knowledge as a departure point for a CSL framework. Analysis of differences between countries was conducted with an independent t-test. Analysis of differences amongst knowledge domains (KDs) and schools, gender, and subject preference was conducted with Oneway ANOVA.

Research Question 4 (Chapter 5) investigated how the CSL framework affects CSL in the early adolescent age group through the application of an interactive 3D game. I evaluated how the results of the prior questionnaire compared to the results of the post-questionnaire, examining the validity of the knowledge-baseline and the construction of the CSL framework. Paired sample t-tests were conducted between prior and post scores. A Spearman correlation was conducted for association between knowledge domains (KDs). Linear regression was conducted to assess the relationship between performance on the prior score, school, and gender on the post score and the performance on the prior score, school, and gender on the change in score. Oneway ANOVA was conducted to compare the influence of recreational digital game play on score differences.

Research Question 5 (Chapter 5) tested the CSL framework and knowledge domains through the application of an interactive 3D game. Paired sample t-tests were conducted between prior and post KDs (knowledge domains).

The significance of Chapter 1 to the thesis

Public education is necessary to prepare students for adulthood and to aid them in their entry into public society. Since climate change is anticipated to be a significant problem in the near and distant future, providing CSL education could be an important contribution to assist in preparing students for their future and, as a result, mitigating against the anticipated impacts and consequences. Understanding when CSL interventions should begin, and exploring useful pathways to implement them, may offer both communicators and educators an additional avenue towards motivating climate-friendly attitudes and behaviour.

This chapter has reviewed factors that impede and facilitate public engagement with climate change and revisited the role of knowledge deficit in context with worldview and the intercept between climate communication and climate education. As well as re-exploring the premise that challenges education as a valid intervention toward promoting climate-friendly attitudes and behaviours, this chapter has unpacked many of the tensions that exist between the cultures of climate communication and climate education. This work proposes that knowledge deficit as an intervention is an important consideration in efforts to improve emission reduction activities, particularly when factors such as age of intervention and development of worldview are included, both of which are explored further in the following chapter.

Chapter 2:

Why is early adolescence so pivotal in the climate change communication and education arena?

2. Why is early adolescence so pivotal in the climate change communication and education arena?

The place of Chapter 2 in the Thesis

Chapter 2 aims to address research question 1 through research objectives a) and b)

1) What are the characteristics of early adolescents that make them a suitable age-group for climate science communication and education?
   a) Review the literature on physiological and intellectual development of 12-13-year-olds to investigate their capacity to grasp essential basics in climate science.
   b) Discuss the validity of knowledge deficit interventions as a means to cultivate a fact-based worldview and promote civic engagement and responsibility.

Before investigating climate science literacy (CSL) in the 12-13-year age group, it is appropriate to establish a rationale for why this age group has been selected for knowledge deficit interventions. Aside from ensuring they have the intellectual capacity to understand important basics in climate science, there is also a need to define their potential as future change agents and discuss their receptivity to cultivate informed, fact-based worldviews. In Chapter 2, these aspects are reviewed based on prior literature and then discussed for their potential to inform and cultivate worldviews in the early adolescent age group.

Chapter 16
Why Is Early Adolescence So Pivotal in the Climate Change Communication and Education Arena?

Inez Harker-Schuch

Abstract This paper explores the characteristics that make young adolescents (12–13-year olds) ideal 'change agents' in the climate science communication arena. We argue that this age group is at a pivotal age for cultivating public opinion, broadening awareness of the science and leveraging this knowledge to promote climate-friendly policy and governance. We examine the physiological and social characteristics that make young adolescents such an ideal age group. These characteristics involve intellectual development, cultivation of self-determination, and emergence of the adolescent into society—and how these characteristics can be utilised to create better communication and education tools, methods and strategies. We hope that this paper will help educators and communicators ensure climate science communication is tailored to be cost-effective, accurately designed and appropriately scaled to this key demographic. This work contributes to climate science communication and advances existing understanding of climate science communication frameworks for this specific audience.

Keywords Climate education · Early adolescence · Intellectual development · Science communication · Worldview development

Introduction

To motivate people to revise their behaviour in order to live more sustainably, communication is key—of which knowledge is the single most pivotal factor. Previous research has suggested that knowledge (specifically, the 'knowledge deficit' model as a knowledge-behaviour intervention) is largely ineffective in the climate science communication arena (Corner et al. 2015; Kahan et al. 2011). Prior knowledge, is however, the foundation of intellectual constructs regardless of how accurate or reliable that knowledge or information may be. Knowledge depends on communication,

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as argued by Wittgenstein (1953)—for how else can we know or understand anything, particularly of a socio-cultural nature, unless we communicate? We obtain our knowledge through experience, inherited worldviews, exposure and access to information, formal and informal education environments, and via individuals who act as mentors, icons, or examples: we inherit these views in the sub-culture of our community and through close friends and family. Worldview, particularly in older adolescents and adults, plays a significant role in an individuals' attitude to or engagement with climate change (Wolf and Moser 2011), and on their knowledge development (Lewandowsky et al. 2012). It is often a stronger predictor of climate change denial than how much an individual understands the scientific basis of climate change. Socio-political identity has also been shown to 'entrench' climate change denial in individuals who identify with political parties that refute the science and evidence of climate change.

Recent research is emerging which suggests that *specific* climate science knowledge may be a more useful tool in cultivating engagement than previously thought, and may correct worldview biases (Shi et al. 2015; Stevenson et al. 2014). There is an urgent need to develop more focused methods that can adequately communicate about climate change to influential groups (Karpudewan et al. 2014; Robinson 2010). Coupled with this, we need to develop effective teaching materials that can straddle the disciplines of climate science, communicate effectively and include a willingness to build emotion into the climate science topic (Carmi et al. 2015; Moser and Dilling 2007; Rice et al. 2007; Roeser 2012).

Of even greater importance, recent research is suggesting that early adolescent may be (by virtue of their current physical and social development) the pivotal group upon which true social and behavioural change can occur. They are a group, who for the most part, share the following characteristics:

- An openness to cultivating and/or reviewing their worldviews
- The ability to affect the greatest change with the longest-term effect
- Are the easiest age group to reach
- Possess characteristics that facilitate effective communication
- Have the potential for scaling, i.e., into other groups

Although targeted and tailored climate change strategies have offered many useful and insightful perspectives (Bostrom et al. 2013) they have so far been unable to provide educators or communication strategists with a clear way forward. Our approach provides a new pathway—one that focuses on the intrinsic, biological and physiological characteristics of early adolescence that preempt, and ultimately, transcend socio-cultural and worldview biases.

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The Adolescent—A Potential Candidate

In 2012, adolescents (those age was between 12 and 18) made up 0.75 billion (18%) of the world's population (United Nations (DESA) 2012). They are the largest group of climate-vulnerable people on Earth (UNICEF 2015); particularly female adolescents (Swarup et al. 2011). They are also the demographic group which the onus of responsibility for managing climate change falls on—a burden they will acquire by default (Case 1985). This obligation requires them, without exception, to confront the worst impacts of climate change as it unfolds throughout their lifetimes—and to bequeath the same legacy to their own children (Corner et al. 2015; Ferkany and Whyte 2012). A burden which they are now intellectually able to process and comprehend (Jensen and Nutt 2015). These burdens, aside from the responsibility of the physical impacts of climate change, include psychological, physical, intellectual and emotional impacts (Berry et al. 2010; Ojala 2012a; Roeser 2012; UNICEF 2015) and will involve making choices that will be far-reaching and non-retractable (Lazarus 2009). Examples of these challenges include: 'end of the world' fears (Tucci et al. 2007), increased health problems and higher mortality risks from climate-related impacts (UNICEF 2015), decreased water and food security, reduced access to education (particularly for females) (ibid.), and a general sense of worry about the future (Corner et al. 2015; Ojala 2012b, 2013). The future of their children and climate stability depends on the efforts and actions they undertake; the sheer complexity of the problem—and its 'wickedness' (Levin et al. 2012)—will require new forms of knowledge, new international cooperatives and new skills that have not existed before. These are damaging psychological burdens; particularly as they have no precedent (Ojala 2015). Within the wickedness of climate change, there is also no way of knowing if the actions they undertake will work to mitigate the detrimental effects—perhaps even within their lifetimes.

The vulnerability of adolescents to the future (and their expectations of coping with the future) are unusually acute, as they have little power to effect change. They depend on their socio-economic circumstances for the framework of their worldview. A worldview (or *weltanschauung* in the original by Dilthey (Makkreel 1975)) that can be misleading, poorly constructed and destructive (Ojala 2015; Vollebergh et al. 2001). Today's adolescent is in a precarious position, as the issue of climate change appears to hold no clear, tenable public position (Brulle et al. 2012). Currently, everyone has a steadfast, entrenched opinion, and it seems everyone is entitled to it, no matter how tenuous, idiosyncratic or unreasonable the argument may be (Ayer and Marić 1956; Postman 1985; Stokes 2012). Adolescence is also the time when each person establishes their own *weltanschauung*—a development that begins in early adolescence and slowly 'cements' before early adulthood (Case 1985; Vollebergh et al. 2001). Not only must she or he choose sides on which to stand, there will be spatial and temporal consequences of those choices that will have a real impact on our environment and future (Gowers 2005; Wray-Lake et al. 2010). It is disturbing that many adolescents are becoming increasingly less concerned about their environment—expecting governments or 'technofix' to solve the myriad of issues which currently plague our natural environment (Stevenson et al. 2014; Wray-Lake et al. 2010). It is most worrisome as their attitudes and decisions will affect every other species and habitat on our planet. No other generation has had this responsibility, nor the awareness of just what that responsibility entails.

Aside from the ethical considerations we hold for our emerging adults, there are other aspects that make adolescents essential players in climate change mitigation. Adolescents are poised on the edge of our society—a few years short of assuming the responsibilities of adulthood that will, by definition, launch their political, economic, intellectual, vocational and social identities (Checkoway et al. 2003; Gowers 2005; Quintelier 2014). These aspects include:

- Their proximity to participating in elections
- Their financial wherewithal to purchase goods and services
- The formation of personal opinions
- Their employability and gradual introduction into the workforce
- The beginnings of secure intimate and social relationships

Preparing adolescents for these tasks—and their emergence into society—is one of the main goals of society and education systems (Ghysels 2009; Shanahan et al. 2002). Adolescents also possess certain socio-cultural attributes that make them prime candidates for climate change communication. They are very adept at communication and digital technology (which are the primary avenues of information and social exchange today) and are, fortuitously, legally obliged to be enrolled in public education systems; making them a very accessible group.

Of all of these features, there are three key conditions of adolescence (and early adolescence in particular) that make this age group so ideal for climate science communication: (1) the intellectual development that takes place during adolescence; (2) as a consequence, the emergence of self-determination/self-esteem and (3) their introduction into the broader social community. These major factors are essential for developing meaningful worldviews, understanding the mechanisms of climate science, and engaging and participating in emission reduction activities towards a carbon-neutral future.

Physiological Changes—Intellectual and Abstract Reasoning Development

Similarly to very early childhood, adolescence is a critical developmental period both cognitively and socially. Cerebral changes in the human brain undergo drastic alteration during this time in order to prepare for maturation and adulthood (Steinberg 2005). Alongside augmented communication with other brain areas, the prefrontal cortex undergoes a drastic 'pruning' phase—known as the 'second critical period' of learning—signifying the traverse from childhood to maturity (Jensen and Nutt 2015). It is, according to Jensen, a 'golden age' of intellectual development (ibid.).

Throughout childhood grey matter has been increasing in various regions of the brain. This transformation peaks in the early stages of puberty, whereupon it begins the second critical ‘pruning’ period. This pruning results in a reduction of grey matter, and simultaneously, the production of white matter via myelination; heralding the commencement of scientific reasoning, executive function, social cognition and planned control behaviour, among others (Blakemore and Choudhury 2006; Burnett and Blakemore 2009; Dumontheil 2014; Field et al. 1997; Kuhn and Franklin 2008). Myelination acts as a sheath around axons, increasing the speed (up to a 100-fold) of neural impulses, insulating transmitting impulses, and reducing ‘recovery time between neural firings’.

The resultant ‘synaptic plasticity’ reinforces exercised and practiced neural pathways. In its simplest ‘use it or lose it’ form, synaptic plasticity describes the weakening or strengthening of synapses over time. It results (according to Damon and Lerner 2008) in ‘fewer, more selective, but stronger, more effective neuronal connections than they had as children’ (Damon and Lerner 2008; Kuhn and Franklin 2008; Munz et al. 2014). This ‘second critical period’ opens up essential intellectual and social development pathways. This development allows scientific reasoning and critical thinking abilities to flourish and launches the adolescent into adulthood (Case 1985; Jensen and Nutt 2015; Piaget 1972).With regard to intellectual development, abstract reasoning arises in the 11–13 year old as a consequence of the development of the ability to coordinate ‘vectorial operations’ (being able to summon abstract constructs and execute simple scientific reasoning). This skill is a precursor to reasoning with multidimensional problems and highly complex concepts (Case 1985). The work by Case is strongly aligned with the Piagetian theory on intellectual development. This theory suggests that by exposing young adolescents to multidimensional and complex concepts, we effectively ‘train’ and ‘exercise’ these neurons in preparation for synaptic pruning. This in turn, promotes the preservation of important neural pathways (Case 1985; Piaget 1972). This learning period, therefore, becomes crucial; as early adolescents are now ready for constructs and concepts that employ their intellectual development. This challenges their expanding processing capabilities and prepares them to confront and engage with such issues.

For climate science communicators this intellectual development phase is, arguably, the single most important factor in communicating with early adolescents (12–14-year olds). A young adolescent is building the scaffold on which many of their intellectual constructs will later be built. T he more equipped the brain is to conceptualise these constructs, the higher the capacity to respond, process and cope with the various elements of climate science (Jensen 2015; Ojala 2013; Stevenson et al. 2014).

The physiological changes of the adolescent brain show extraordinary potential for learning of all kinds; and could be particularly useful for education with significant social dimensions (Cheshire 2017).

Social Allegiances, Perspective-Taking and Community

As synaptic plasticity influences executive function and intellectual development, so too is social cognition and perspective-taking equally affected by this synaptogenesis. These changes launch ‘self-awareness’, ‘theory of mind’, ‘perspective-taking’ and the ‘ability to understand other minds by attributing mental states such as beliefs, desires and intentions to other people’ (Blakemore and Choudhury 2006; Frith and Frith 2003). It is theorised that these profound changes in the human brain allow an individual to empathise and vicariously participate in another’s experience (Blakemore and Choudhury 2006). For example, similar brain regions are stimulated both in first person and second person perspective as well as between first and third person perspective (e.g., seeing an image or hearing an explanation). These ‘perspective-taking’ experiences connect us to others. They help to form familial, social and romantic attachments that reinforce or revise our *weltanschauung,* and as a result, have far-reaching consequences both for society and governance.

As social cognition develops, individuals become aware of ethical and moral considerations, aside from their own survival and well-being. The nature of climate change (and the imperative towards mitigation) will very likely depend on empathetic and perspective-taking responses, as first-person perspective and experiences will be virtually impossible to attribute to the effects of climate change. For example, understanding that ‘similar’ or ‘vulnerable’ others may suffer illness, death or hardship due to climate change may motivate an individual to take action. Perspective-taking also promotes awareness of poor governance and corruption; social movements in the youth community can affect enormous social and cultural change (Checkoway et al. 2005; Ho et al. 2015). Further social cognition factors that favour communicating with this age group include example-setting and ambassadorship (youth leadership and peer-pressure for climate-friendly behaviour), community building (reinforcing group behaviours), knowledge and information sharing amongst peers, the commonality of school, and the potential of this age group to form strong social awareness constructs at the very onset of social cognition. It is, however, the maturity of the adolescent that will affect the greatest change in the world. Their emergence into society as fully matured consumers, voters, and workers ensure that their role as change agents is a very powerful one indeed.

Self-determination in Adolescence

As the brain matures, the adolescent slowly acquires the self-awareness and confidence that not only can one manage to live within one’s life, but that one can also determine how it is coordinated and exercised (Blakemore and Choudhury 2006). This self-determination is fostered through an emerging self-esteem (developed from ‘knowing oneself, rational/critical reasoning, and valuing and accepting the worthiness of your strengths, rights and responsibilities) that encourages us to exercise our own skills and to contribute to our own lives, and the lives of others (Gowers 2005). Recognising and achieving these self-determined contributions is a vital component in the developmental pathway of adolescence (Field et al. 1997).

There is an implicit implication in self-determination, that one can choose to act or not act. T his behaviour then results in consequences from which we learn and gain experience. We see here, the shift from cognitive processes to the realisation that one's actions [or equally, lack of them (Kuhn and Brass 2009)] have a clear and effective presence in reality, society and our environment. It is at this time that we begin to perceive the individual power that we effect or create.

Dilthey defined weltanschauung as constituting 'an overall perspective on life that sums up what we know about the world, how we evaluate it emotionally, and how we respond to it volitionally' (Dilthey, quoted in Audi 2015). Following this definition, we transpose the volition into self-determination—the exercise of one's beliefs, ideals, ambitions, and goals into physical or semi-physical realities. However, these exercises are not limited to the individual, but have enormous social and community implications (Blakemore and Choudhury 2006; Burnett and Blakemore 2009). By recognising our place in the world, and our effect upon it, we become aware of our identity and equally, our culpability. As we discuss below, recent research in social cognition in adolescents suggests that this age-range is a critical period for social development; one that has significant implications for those investigating pro-environment behavioural change and emission reduction activities.

New Approaches for Education

For those researchers and educators involved in teaching climate science, there is a general ennui with regard to education and the benefits we can obtain from structured learning environments, particularly information-based interventions (Bliuc et al. 2015; Corner et al. 2015; Stamm et al. 2000). It is generally accepted that we have 'failed' to communicate the problem effectively, or impart the knowledge and intellectual constructs necessary to process the problem (Shi et al. 2015). Rather than questioning the educational approach and 'going back to the drawing board' in light of these findings (or to methodologically reconsider to whom we are communicating), the conclusions drawn by many researchers has been that we should embark on wholly different directions, based on indications that 'knowledge deficit' is *not* one of the most significant factors in climate science understanding (Kahan et al. 2011; Potter and Oster 2008). There is, of course, no doubt that researchers are replicating findings that poor understanding and limited improvement prevail across the board; no more so than in the adolescent age group (Corner et al. 2015; Harker-Schuch and Bugge-Henriksen 2013). However, many of those findings have emerged from studies based on limited interventions (e.g. a 45 min lecture in climate science) or from correlations between 'general' science and denialism instead of s*pecific* climate science and denialism (Shi et al. 2015; Stevenson et al. 2014). Rather than dismissing the key messages of previous findings, in relation to climate science communication, they serve to highlight the need for communicating about climate science to early adolescents in the beginning stages of their *weltanschauung* cultivation. It also emphasises the need to give education the attention it deserves, particularly in this age group.

It is important to note, that this paper explores how climate literacy interventions may improve both the understanding of climate change, and the necessary actions to reduce emissions in the early adolescent age group. While the potential for education is significant, both at the individual level and in the broader public arena, we examine only a part of the wider and more complex issues related to climate communication, and emission reduction activities. For example, worldview bias will persist in older age groups, and attempting to overcome denialist attitudes with education may be counter-productive (Kahan et al. 2012). In addition, although we have distinguished between the physiological changes in adolescence (cognitive development, socialisation and self-determination) and society, in reality these cannot be isolated from each other and are functions of each other. This is manifested, for example, in the development of worldview and the context of the individual's socio-cultural environment: we are the products of the habitats that we occupy which are, in turn, shaped by our presence. However, our behaviours are typically controlled by us, particularly those related to social interactions and communication. It is therefore useful, when we explore pathways of human behaviour, physiology and society, to break the elements down into their component parts in order to assess their function and potential for alteration.

Conclusion

We have, then, a clearly defined societal group that meets vital criterion for climate science communication. Their intellectual development is at its most receptive to cultivating and adapting worldviews, they have the greatest potential to affect long-term change by virtue of their age and social position, they are highly accessible both in the educational setting and as a policy and governance requirement (through public education and the minimum education levels), and they are founding their early social allegiances that will form the basis of their adult communities: characteristics and circumstances that are found at no other time in human development.

When it comes to an individual's preconceptions, opinions, beliefs and/or ideals the effect that worldview has cannot be understated. This is particularly true in climate science, more so than any other arena. What must be examined (for the security and longevity of our civil society depends on it) is whether such worldviews can be cultivated or adapted. Particularly, whether these 'tweaks' can be made through targeted instruction and exercises aimed at fostering public engagement and better climate science understanding, at an age when worldviews are being formed and cultivated. The receptiveness of the adolescent brain is at its greatest in the early stages of puberty, and the importance of authoritative wisdom (teachers, experts, elders) diminishes as the adolescent grows older (Case 1985; Piaget 1972). As adolescents age, their willingness to adopt new concepts, broaden their worldviews and challenge their preconceptions gradually decreases and become less amenable to adapting and informing an existing worldview. It is, therefore, the younger portion of this demographic (12–14 years) that possesses the ideal physiological and social characteristics (and the strongest compatibility) for communication and education strategies. In essence, by improving climate literacy in early adolescence we are concentrating on and reaching the most biologically, physiologically, intellectually and societally ideal age group that is available. Future research endeavours may benefit from examining which aspects of climate science are cognitively easy to grasp for this age group. Studies should also evaluate how the more complex aspects of this topic can be built on top of those easier to understand constructs. Current science communication research also offers many tantalising avenues for teaching climate science that may be uniquely suitable for this age group. Evaluating these avenues (such as serious gaming) may further enhance our understanding and efficacy in communicating science to this age group.

Endeavouring to engage with climate change is a self-deterministic challenge. Accepting such a challenge involves maturity and civic courage that is a hallmark of adulthood. In addition, engaging with climate science could train cognitive function, aid in intellectual development, and promote abstract reasoning processes; further preparing an emerging adult for the tasks and responsibilities ahead. Finally, exposure to the concepts of climate change (and the science underlying the premise of climate change) may improve an individual's confidence in responding to the threat, and by default, decrease their fear and aversion to engage with it. Such exposure may provide new intellectual concepts and pathways for developing constructive and civic-conscious worldviews, or revising pre-existing ones. By teaching climate science to emerging adults, we hope to foster the development of worldviews that encompass the dimensions of civic responsibility (informed opinions, broader sociocultural dimensions, and considerations), and embolden our youth to approach climate change confidently and effectively so that the forecast of their tomorrow looks brighter than the forecast of our today.

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The significance of Chapter 2 to the thesis

This review has responded to both objectives in research question 1 and indicates that early adolescents have developed unique intellectual abilities that may enable them to understand complex scientific theories and mechanisms such as those found in climate science. Investigation shows that there are three key characteristics that make them ideal candidates for knowledge deficit interventions that may offer pathways to eventually cultivate a fact-based worldview:

1. Cerebral changes in the human brain that commence at ~11 years of age
2. Social cognition and perspective-taking
3. Self-determination

While these characteristics are essential to intellectually grasp complex scientific mechanisms, worldviews have not had time to be constructed – offering a brief window for knowledge deficit interventions to assist both understanding and the development of fact-based worldviews.

Although this age group shows promise for knowledge deficit interventions, their ability to grasp key concepts of climate science in terms of physics, chemistry, biology, mathematics, and earth and natural sciences may be challenged at this early stage of adolescence. However, this age group is not expected to grasp all the material necessary to understand Earth's climate system in equilibrium but to slowly build their knowledge and competencies as they progress through mandatory secondary school. The cerebral changes in the brain of early adolescents merely offer a starting point upon which further learning can take place.

Chapter 3:

Opinions of 12 to 13-year-olds in Austria and Australia on the concern, cause, and imminence of climate change

3. Opinions of 12 to 13-year-olds in Austria and Australia on the concern, cause, and imminence of climate change

The place of Chapter 3 in the thesis

Chapter 3 aims to address research question 2 through research objectives c), d) and e)

2) What opinions do early adolescents maintain with regard to climate change (their concerns about climate change and their opinions on who is responsible and whether or not climate change is currently occurring? How do these opinions compare with adults and older adolescents in their respective populations?
    c) Evaluate the opinions of early adolescents.
    d) Discuss the implications of their opinions with regard to knowledge and worldview development.
    e) Compare the risk perception opinions of early adolescents with their respective adults and older adolescent populations.

Chapter 2 assessed the suitability of early adolescents for knowledge deficit interventions related to CSL and worldview cultivation. While this research maintains the potential importance of CSL as a foundation for worldview development, there is a need for more understanding and research in this area. There is a need, as identified in Chapter 2, to ascertain whether or not early adolescents are apathetic to the topic of climate change. This is important as interest in this topic is likely to affect their receptivity to knowledge deficit interventions. Aside from an ethical imperative to examine adolescent opinions about climate change, adolescent opinions may inform CSL endeavours and contribute to the global body of research on public opinions about climate change. By analysing adolescent opinions, this research improves understanding in how early adolescents position information about climate change into their mental models of the world, how they are situated in relation to adult opinions and how they compare to opinions of older adolescents. This research may be useful in understanding how worldview develops, how opinions on climate alter with maturation, their role as citizens, the potential effect they will have on policy development as they mature, and how shifts in the balance of public opinion may change over time.

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REVIEW

Opinions of 12 to 13-year-olds in Austria and Australia on the concern, cause and imminence of climate change

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Abstract Early adolescence (12–13 years old) is a critical but under-researched demographic for the formation of attitudes related to climate change. We address this important area by exploring adolescent views about climate change. This paper presents opinions collected from surveys of 463 1st-year secondary school students (12–13 years old) in public secondary schools in inner-urban centres in Austria and Australia on whether climate change is (1) something about which to worry, (2) caused by humans and (3) happening now. Eligible respondents in both countries showed similar levels of agreement that climate change was probably or definitely something we should (1) worry about (84.6% Austria, 89.1% Australia), which is significantly higher than either country's adult population. Eligible respondents agreed that climate change probably or definitely is (2) caused by humans (75.6% Austria, 83.6% Australia) and that climate change is probably or definitely something that is (3) happening now (73.1% Austria, 87.5% Australia). Their response differed from the respective adult populations, but in opposite directions. Our results suggest that socio-cultural worldview may not have as much influence on this age group as it does on the respective adult populations and suggests that this age group would be receptive and ready for climate science education and engagement initiatives.

Keywords Climate change opinion · Climate science · Early adolescence · Worldview

INTRODUCTION

Despite more than 30 years at the forefront of the political and social agenda, meaningful climate change governance continues to exhibit disconnects between scientific knowledge, public knowledge and trust of climate science (Moser 2016). Aligning public opinions with the scientific consensus on the influence of anthropogenic climate change is an ongoing challenge for both science communicators and those who recognise the essential role the general public play in mitigation and adaptation (McBean and Hengeveld 2000; Moser 2016). Most studies (international and regional) ("Gallup: Social Series" 2017; Steentjes et al. 2017) that provide context for this disconnect and measure adult public opinions show marginal changes in public opinion over time. Public opinion research has shown that the influence of worldview (defined by Dilthey as "an overall perspective on life that sums up what we know about the world, how we evaluate it emotionally, and how we respond to it volitionally" (translated by Makkreel 1975)) is the primary predictor for why adults are so resistant to changing their opinions and attitudes (Cook et al. 2017). Interventions aimed at aligning adult opinions with the scientific consensus are likely to be ineffective and may even result in entrenching climate denialism and post-fact attitudes (Leviston et al. 2014). We need to reach individuals before their worldview bias prevents them from engaging with the topic of climate change in a pro-active and constructive manner. In so doing we may avoid cultivating further scepticism with the effect of delaying action to reduce global emissions. Since adolescence (12–24) is the age when individuals develop their attitudes and worldviews, this might be a period when interventions aimed at improving climate-friendly attitudes might be the most effective (Stevenson et al. 2014; Corner

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et al. 2015; Lee et al. 2020). The age range of adolescence is quite large and encompasses many significant physiological, social, emotional and intellectual changes. Selecting a suitable, more precise, age group to implement interventions depends, therefore, on obtaining an understanding of how opinions in this group alter over time (both as they age and as they change with time in this age group) and how this might correlate with worldview influence, e.g. the prevailing opinions of respective adults.

Research in older adolescents and adults indicates that, while there are differences in overall opinions (Harker-Schuch and Bugge-Henriksen 2013; Leiserowitz et al. 2011; Skamp et al. 2013), the degree of difference is not large. According to Corner et al. (2015), concern in the UK and Australia about 'the economy, employment opportunities and access to affordable education trump worries about issues like climate change for the people in 15–26 age range'. A 2011 report investigating US teenagers' opinions and knowledge of climate change (Leiserowitz et al. 2011) (13–17 years, $n = 517$) showed that 43% of teenagers think that climate change is something to be 'somewhat worried' or 'very worried' about, in comparison with 55% of adults; 57% of teenagers think climate change is anthropogenic compared to 50% of adults; and 54% of teenage think that climate change is happening compared to 63% of adults.

Differences between countries are also evident in opinions amongst older adolescents. A 2013 study exploring the opinions of 16–17-year-olds ($n = 188$) in Denmark and Austria (Harker-Schuch and Bugge-Henriksen 2013) showed that Danish students were considerably more worried about climate change (82%) than Austrian respondents (60%), were significantly more likely to think that climate change was caused by humans (Danish respondents: 90%; Austrian respondents: 73%) and somewhat more likely to think it was happening now (Danish respondents: 94%; Austrian respondents: 91%). Gender also plays a role in opinions related to climate change in adolescents. Harker-Schuch and Bugge-Henriksen (2013) found that older adolescent females are more likely to hold the opinion that governments and individuals are equally responsible for addressing the responsibilities of climate change than male students. With regard to perceptions of threat, a US study exploring the role of education in overcoming anti-climate attitudes in middle school students ($n = 378$), Stevenson et al. (2014) demonstrated that females perceive climate change to be more threatening than males. For opinions related to action-taking, Skamp et al. (2019) found in a cross-national study that early and middle secondary females students ($n = 12{,}627$) 'expressed more support for the four measures [of amelioration] which aligns with many studies that have found females express more 'environmental' concern'.

These differences in opinions across countries may be explained by the tendency of adolescents to mirror the same perceptions of risk and efficacy that are maintained by their parents (Lee et al. 2020), particularly in those families where indifference (low risk, low efficacy) and responsive (high risk, high efficacy) attitudes are familial norms (Mead et al. 2012). Taking data from 2013 for which we have data on both adults and 16–17-year-old adolescents, we find that 70% of Austrian adults, for example, are concerned about climate change (*Eurobarometer Climate change* 2017) compared to 60% of older adolescents who are also worried about climate change (Harker-Schuch and Bugge-Henriksen 2013). In Denmark in the same year, 73% of adults think that climate change is a threat compared to 82% of older adolescents.

However, research suggests that the influence exerted by adults on the younger population may be diminished due to an inherent plasticity arising from their intellectual and social development that may make them less susceptible to worldview influences than adults (Stevenson et al. 2014; Corner et al. 2015; Harker-Schuch 2020). Contrary to studies in adults which show the influence of worldview on adult attitudes to climate change, Stevenson et al. (2014, p. 293) found that climate change knowledge of middle school students in the USA ($n = 387$) was positively correlated to acceptance of anthropogenic global warming which may arise, as they argue, 'because worldviews are still forming in the teenage years'. This is further supported by Lee et al. (2020, p. 11) who in a narrative synthesis of the literature on youth perceptions on climate change tentatively argued that 'younger children's thinking about climate change is less reflective of worldview and cultural values than older children's [thinking]'.

While this is a positive indication for knowledge deficit interventions, there is little further evidence, as overall research in the adolescent age group is lacking and fragmented (Stevenson et al. 2014; Corner et al. 2015; Nature Editorial 2018; Lee et al. 2020), let alone research associated with climate opinions (a recently published narrative synthesis by Lee et al. (2020) is a notable exception). This is further exacerbated by climate change being a contentious issue in the broader public arena (Brechin and Bhandari 2011; Poortinga et al. 2011; Capstick et al. 2014), which may reduce the number of willing participants, difficulties in obtaining necessary research approvals and gaining all necessary consents (i.e. departments of education, the school, the teachers, the parents and the students themselves).

Finally, while we have information on climate opinions from older adolescents, there is little specific opinion data from early adolescents. With opinions between older adolescents and adults showing some alignment, there is a need to examine climate opinions in younger age groups.

From such examinations, we can develop an understanding of this critical age group and, potentially, identify the age at which views on climate change become the subject to the influence of worldview.

This paper aims to provide further context in the realm of climate opinions in adolescence and focuses on a significant but hitherto under-researched group: the early adolescent (Nature Editorial 2018). This age group may provide a unique and previously unexplored avenue for climate science communication (Harker-Schuch 2020); offering as-yet uncharted access to early worldview construction and, more critically, intellectual development pathways.

Why early adolescents matter

The early adolescent age group is the largest group of climate-vulnerable people on Earth and the group with the biggest portion of responsibility (Nature Editorial 2018; UNICEF 2015). In addition to their suitability for targeted climate interventions (Harker-Schuch 2020), they possess vital characteristics that play a major role in an individual's ability to comprehend the foundations of the climate change issue (Piaget 1972; Case 1985; Jensen and Nutt 2015; Harker-Schuch 2020) which may play an important role in civic action and responsibility (Field et al. 2015). The characteristics are (I) that their brains are undergoing a new intellectual development phase (Case 1985; Jensen and Nutt 2015), (II) their worldview has only just begun to form (Corner et al. 2015), (III) their high level of social trust (Wray-Lake et al. 2010), (IV) they are uniquely vulnerable to the impacts of climate change and (V) they have a budding self-determination and social activism (Piaget 1972; Case 1985; Jensen and Nutt 2015) which will eventually drive their socio-political identity and help them secure social capital and community. These characteristics of the second critical phase of development arise as a result of physiological changes in the human brain that begin shortly before the age of 12 to ensure that healthy individuals will develop the skills they need to enter and manage adult life (Jensen and Nutt 2015).

The intellectual development (I) that takes place in this age group allows adolescents to begin to process higher-order executive functions (Case 1985) and develop abstract reasoning. The mechanisms and processes that underlie climate change—particularly its 'wickedness' (Levin et al. 2012)—require an individual to intellectually perceive the scale and connectedness of those processes and mechanisms. These perceptions are usually only possible once the brain begins this developmental phase (Piaget 1972; Case 1985; Jensen and Nutt 2015).

As well as triggering executive function processing, the brain begins to form socio-political/-cultural worldviews (II) (Case 1985; Corner et al. 2015). In conjunction with the abstract-reasoning process, a proto-self-determination arises which is necessary for worldview development—making this age group an ideal 'starting point' for fact-based worldview development (Field and Hoffman 1994; Rosso et al. 2004). There is a very short window of opportunity in this age group (Harker-Schuch and Bugge-Henriksen 2013; Stevenson et al. 2014; Kahan 2015) and recent research also indicates that embedding critical reasoning at this age may cultivate a worldview that is more open to consideration of evidence (Shi et al. 2015) as opposed to one that is, for example, suspicious of knowledge institutions or dismissive of information that challenges unfettered economic growth.

In addition to improvements in intellectual reasoning and the development of worldview, early adolescents also show stronger social trust (III) than older adolescents do (Flanagan and Stout 2010). This social trust is defined as a 'beliefs that people are generally fair and trustworthy' (ibid) and is important to civic stability and the functioning of democratic societies.

As well as being vulnerable (IV) to climate change in comparison with older age groups (UNICEF 2015), adolescents are aware of this vulnerability (Thew et al. 2020). They lack political and social agency (aside from that in their homes) and the right to influence their shared future or participate as key stakeholders (ibid).

However, young people also tend to have high levels of social activism (V) and this activism can lead to significant change throughout all levels of society (Checkoway et al. 2005; Lawson et al. 2019). Aside from radical social adjustments, young people also implement gradual change as they secure relationships, find employment and exercise their rights as adults (Checkoway et al. 2003; Silva Dias and Menezes 2014). Teaching them about climate change—both as a science and as a wicked problem—will ensure they are prepared to engage with it successfully and could also drive much-needed social coalescence on this issue (Crayne 2015). For example, the recent #Fridays4Future movement, according to Fisher (2019), is associated with an increase in parental activism and engagement. This is further supported by a recent study involving 238 families in North Carolina, in the USA, which demonstrated that children may '*inspire their parents towards higher levels of climate concern and in turn, collective action*' and '*may be a promising pathway to overcoming socio-ideological barriers to climate concern*' (Lawson et al. 2019).

This paper attempts to determine the opinion signals of this age group in central urban centres and how those opinion signals relate to one another. Additionally, we explore the influence of other factors such as the effect of country of residence and gender on those opinions. The relatedness of the opinion signals to one another is important in terms of predicting attitudes in adolescence and developing communication strategies, education materials or support networks that respond to adolescent needs and concerns. We explore the suitability of this age group for science communication interventions toward improving their understanding and preparedness for the future. For example, if we know that worry about climate change is strongly associated with the belief that climate change is caused by humans and is happening now, we can develop curricula that addresses the concern (i.e. anxiety) associated with this opinion that includes other emotion-laden opinions (i.e. guilt associated with anthropogenic emissions or the imminent threat associated with it happening now). We also endeavour to determine how worried early adolescents are with the issue of climate change and how well their opinions align with their respective adult populations. Adolescence is quite daunting and anxiety-ridden, even without the pressure and uncertainty of climate change (Piaget 1972). Assessing 12 to 13-year-olds on their opinions related to climate change, therefore, becomes quite meaningful in broader social terms as one indicator of their overall emotional and mental well-being.

This research supports the UNDP Sustainable Development Goals 3: Good Health and Well-being, 4: Quality Education, 5: Gender Equality, 11: Sustainable Cities and Infrastructure and 13: Climate Action.

Objectives and hypotheses

The overarching objective of this study is to determine the current opinion state of 12 to 13-year-olds with regard to whether climate change (a) is something to worry about ('concern'), (b) predominantly has anthropogenic causes ('anthropogenic') and (c) is happening now ('imminence'). Specific interests are how opinions on these three dimensions relate to each other (H1) and differ across country, and gender (H2).

- H1: Opinions on the three dimensions ('concern', 'anthropogenic' and 'imminence') are related with each other (*H0: There is no correlation of the respective opinions with each other.*)
- H2: The opinions of early adolescents on climate change differ based on demographic factors, such as country and gender. (*H0: There is no difference in the opinions of early adolescents based on demographic factors.*)

We also discuss the alignment of early adolescent climate change opinions with their respective adult and older adolescent populations' opinions to assess their suitability for science communication interventions. Finally, we discuss the influence of demographic factors in context with risk perception in early adolescence and how these compare to risk perception in adults and older adolescents.

MATERIAL AND METHODS

To test the hypotheses, an opinion survey was created based on a previous survey by the primary researcher (Harker-Schuch and Bugge-Henriksen 2013) and administered to first-year secondary students at six inner-urban high schools in Austria (in February–March, 2017) and Australia (June–August, 2017). The opinion survey was part of a larger research project examining the role of serious-gaming interventions to improve climate science literacy in the 12 to 13-year-age group. The survey was administered within the scheduled science class time (45–50 min) and was approved by the relevant education departments and the ethics committee at the Australian National University (ANU ethics protocol number: 2015/583). All protocols were followed in accordance with the requirements: ethical approval, anonymisation of the data, certifications for working with children/vulnerable people and permissions. All obtained permissions were stringently vetted: removing any participants where permission was not obtained.

Schools and students

The research catchment criteria for this study were secondary public schools in an inner-urban setting < 10 km from the central business district. The selection of the school depended, as per requirement, on whether the school director and head of science would be willing to participate in this research. According to the requirements and procedures, 6 schools agreed to participate in this study (2 in Vienna, Austria—Coded as VHS1 and VHS2—and 4 in Australia: 2 in Sydney—coded as SHS1 and SHS2—and 2 in Canberra—coded as CHS1 and CHS2). All schools taught in the 'mother tongue' of their respective nationalities (i.e. German in the Austrian schools and English in the Australian schools) and followed the state-regulated curriculum of their respective education departments. The survey was administered in the 'mother tongue' for each nation.

The students were 12–13 years old and all first-year secondary students. A total of 901 students took part in the survey with a final 459 (208 (45.3%) 'female', 245 (53.4%) 'male', and 6 (1.3%) 'other') respondents in the dataset. Due to the small sample size, 'other' were removed, leaving 453 respondents eligible for inclusion and final analysis. Of these, 78 Austrian and 375 Australian students took part (see Table 1, see "Results"). Eligibility depended on approval from the respective department of Education and the school, as well as parental and student approval, participation in the study and valid responses to the survey.

Very little previous research has been done on the opinions and concerns of this age group about climate change (Lee et al. 2020). The difficulties obtaining permission to work with students of this age necessitated identification of a small target group of schools. Ethical considerations further limited our focus to urban/suburban schools as students at those schools were considered to have the easiest access to quality mental health support services should the survey cause distress. Therefore, in order to access early adolescents in the educational setting for participation in this research project, we engaged directly with educational institutions in Australia and Austria. By including two schools in each of three cities (Vienna, Sydney, Canberra) across the two countries, we have sought to access a cross-section of adolescents that allow us insight into comparisons across countries and within countries. In order to conduct the research within the classroom setting (as a part of a larger research project that also involved a knowledge intervention and assessment; see Harker-Schuch and Watson 2019; Harker-Schuch et al. 2020), we gained access to classes of early adolescents in the six schools. The population of our research is an approximation of the early adolescent population in the two countries, though we note that our sampling technique cannot be considered adequate to represent the country-level population. As such, we consider our population to be early adolescents in Vienna, Canberra, and Sydney, and view our present research as an insight into trends that would be ideally supported by a broader and randomised sampling of early adolescents across both countries (and others) in future research. However, due to the research ethics limitations of working with children, accessing early adolescents via the educational system, as we did, will necessarily lead to participation on a school-by-school (and/or class-by-class) basis.

The schools were ‘state suburb’ zoned (5 schools of 6) for their district or suburb (with one school allowing exceptional students to enrol alongside those in the district) (*2016 Census QuickStats* 2016). We are prevented from disclosing precise demographic information (census data) due to privacy laws as this is likely to make identification of the participating schools possible. It is, however, useful to provide some background information (*2016 Census QuickStats* 2016; *Statistisches Jahrbuch der Stadt Wien 2017* 2017) and to note a few aspects of the demographics that may assist in interpreting the findings without compromising the privacy laws. The Austrian catchment had a higher proportion of adults with non-mandatory secondary levels of attainment (approx. 18 years) compared to the zoning for the other schools. CHS1 and SHS2 both had fewer citizens in the selected age group (12–13 years). The catchments for CHS1, CHS2, and SHS1 all had significantly higher tertiary levels of attainment (Bachelor and above). Canberra residents have far higher ‘country of birth’ percentages than Sydney or Vienna and the catchments for CHS1 and CHS2 have significantly lower net immigration at present than the other schools. The catchment for CHS1 had the lowest level of unemployment. The selection of schools excluded from consideration opinions in rural regions in both countries. However, in terms of population, the urban population in Austria as of 2016 is 59.0% of the total (World Bank 2018) and urbanisation is increasing. The urban/suburban population in Australia as of 2017 is 89.6% of the total (World Bank 2018) and is also increasing. While urban population is higher in Australia than in Austria, population density is higher in Vienna (176/ha) than in Sydney (27.6/ha) or Canberra (15.9/ha) and Austria is also significantly smaller than Australia (1:92, respectively) which allows for a higher rate of idea transmission and socio-cultural interaction between urban and rural communities. Thus, the study population is likely to be reasonably representative of a large majority of the young adolescents in each country. Vienna, Austria and Sydney and Canberra, Australia, were chosen as sites for initial study because (a) European and Australian adults show significant differences in their opinions, (b), polarisation of political ideologies is evident in Australia but is low or absent in Austria (see below), (c) the lead researcher had access to Vienna high schools based on prior research with them (Harker-Schuch and Bugge-Henriksen 2013), (d) the Australian government funded the study and (e) the Sydney and Canberra high schools had established relations with the ANU.

Climate change in Australia and Austria

In Australia, climate policy remains a socially and politically contentious issue, with emissions reductions efforts that are broadly considered to be inadequate (den Elzen et al. 2019), and social divisions over climate change aligned closely with political preferences (Hornsey et al. 2018). Recently, public acceptance of the reality of climate change has grown (Kassam 2019), but political divisions remain (Merzian et al. 2019). Australia is a high per capita emitter of greenhouse gases yet has comparatively low vulnerability to the impacts of climate change (Althor et al. 2016).

In Austria, ‘*environmental preservation is a concept deeply rooted in the Austrian public conscience*’ (Keinert-Kisin 2015, p. 138) and there are few discernible social or political divisions over climate change. Denialism is low and not polarised along political lines, as it is in the USA and Australia (Rhomberg 2016) which is evidenced by the recent formation of the national Conservative and Green coalition (Murphy 2020; Schütze and Bennhold 2020). Emission reduction endeavours, in alignment with EU directives, are well established (reduction of 13 million tonnes CO_2 equivalent since 2005) and ambitious (Federal Ministry Republic of Austria Sustainability and Tourism and Federal Ministry Republic of Austria Transport Innovation and Technology 2018). Austria has moderate to high per capita emissions of greenhouse gases yet has comparatively low vulnerability to the impacts of climate change (Althor et al. 2016).

Survey

Our research instrument was three questions that were administered to early adolescents as a measure of their opinion on climate change. We developed this survey to reflect common approaches to assessing climate opinion and to deliver the survey in a way that was compatible with the educational classroom setting. We drew on the extensive research in adult opinions and we synthesised those questions (see Tables S1 and S2) and then adapted them for early adolescents. We explicitly state that the questions were related to opinion (i.e. *'In your opinion, do you think climate change…'*) in consideration of socio-cognition theory. We consider the role of emotions and proximity (O'Neill and Nicholson-Cole 2009a; Lombardi and Sinatra 2013; Brügger et al. 2015) by altering previous questions that implied explicit personal concern i.e. '…are you personally worried about climate change?', to a question which would allow respondents to feel a collective sociocultural proximity, i.e. 'is something we all should worry about') We ensured age-appropriate readability before finally testing the prospective survey with four 12-year-olds.

As our climate opinion questions were deployed as part of a larger project that also included assessment of climate science knowledge (Harker-Schuch 2020), it was our view that the research burden on participants would be too great if we were to include multiple measures of climate opinion across the three dimensions. In an ideal setting, our research instrument would have included multiple questions on each aspect of climate opinion.

In the first three survey items, the students were asked to put in an anonymous tracking code and gender. Following this, the next three items were Likert-style questions pertaining to their personal opinion with regard to their concern (In your opinion, do you think Climate Change is something we all should worry about?), their belief that it is anthropogenic (In your opinion, do you think humans cause Climate Change?), and its imminence (In your opinion, do you think the climate is changing now?). The Likert scale ranged along a five-point scale:

No—Probably not—Maybe—Probably yes—Yes

For analyses, the Likert scale was converted to a numerical scale with No = 1, Probably not = 2, Maybe = 3, Probably yes = 4, and Yes = 5.

Statistical methods

Due to the lower numbers of respondents who selected 'no', 'probably not' and 'maybe', the response data were aggregated ('yes' with 'probably yes' and 'no' with 'probably not') and the responses 'maybe' was used as a neutral reference point. Chi-square tests were conducted to examine whether there was a relationship (i.e. dependent structure) between concern/anthropogenic, concern/imminence and anthropogenic/imminence. Since Chi-square tests only provide information if there is dependent structure between the variables and do not provide information on the effects (both magnitude and direction of the effects), further analysis was required as the Chi-square test showed a relationship. Ordinal logistic regression (OLR) (IBM SPSS statistics 23.0) was selected due to its suitability to ordinal data from the Likert scale. OLR allowed further analysis of respondents' opinions about climate change and to assess whether country and gender may affect opinion responses, i.e. to control for demographic factors while investigating the connections amongst the opinions. For the OLR, the 3 variables examined in the Chi-square analysis, 'concern', 'anthropogenic' and 'imminence' were considered as the response variables (5-point Likert scale aggregated as described above) as well the main effects of country and gender.

In summary, the analysis approach consisted of the following stages:

1. Aggregate response data ('yes' with 'probably yes' and 'no' with 'probably not'), using 'maybe' as the neutral reference point.
2. Descriptive statistics on trends in overall opinion of early adolescents.
3. Chi-square test to determine dependent structure between concern/anthropogenic, concern/imminence and anthropogenic/imminence.
4. Ordinal logistic regression to determine the relationship between the responses and the predictors.

RESULTS

Descriptive data

In total, 401 students, corresponding to 88.5% of the students (total $n = 453$), were of the opinion that climate change is something to worry about (regarding variable "concern") (yes = 299 students, 66%; probably yes = 102 students, 22.5%) (Table 1a). The remaining responses (maybe= 3.1%, probably not/no= 8.4%) totalled 52 students, or 11.5%.

In total, 374 students, corresponding to 82.5% of the students, were of the opinion that climate change is anthropogenic in nature (regarding variable "anthropogenic") (yes = 252 students, 55.6%; probably yes = 122 students, 26.9%) (Table 1b). The remaining responses ('maybe' = 10.6%, 'probably not'/'no' = 6.9%) totalled 81 students, or 17.5%.

In total, 386 students, corresponding to 85.2% of the students, were of the opinion that climate change is happening now (regarding variable "imminence") (yes = 264 students, 58.3%; probably yes = 122 students, 26.9%) (Table 1c). The remaining responses (maybe = 11.7%, probably not/no = 3.1%) totalled 67 students, or 14.8%.

Statistical analysis

Relationship between climate opinions regarding worry, imminence and human causation

Analysis shows high Chi-square test statistic results, with high significance ($p < .001$) in all pairs of variables between the three opinion items (Table 2). Due to the low number of observations for 'no'/'probably not'/'maybe', Fisher's exact test (which is suitable for analysis with fewer observations (Kim 2017)) was also run. This test also found that the opinions regarding concern, anthropogenic and imminence are significantly related ($p < .001$). Therefore, we can reject the null hypothesis that the effect between the opinions concern/anthropogenic, concern/imminence and anthropogenic/imminence are independent of each other. As discussed above, the results of the Chi-square tests do not provide further insights such as the nature of the dependent structure amongst the variables, or whether this dependent structure differs amongst demographic factors.

Table 1 Frequencies of responses for concern, anthropogenic and imminence opinions and for country and gender. Aggregated values group negative and positive responses together ('yes' with 'probably yes' and 'no' with 'probably not') with 'maybe' kept as a neutral reference point

	Response	Frequency (*n*)	Frequency (%)	Aggregated (%)
(a) Concern	No	4	0.9	3.1
	Probably not	10	2.2	
	Maybe	38	8.4	8.4
	Probably yes	102	22.5	88.5
	Yes	299	66.0	
	Total	453	100.0	
(b) Anthropogenic	No	17	3.8	6.9
	Probably not	14	3.1	
	Maybe	48	10.6	10.6
	Probably yes	122	26.9	82.5
	Yes	252	55.6	
	Total	453	100.0	
(c) Imminence	No	9	2.0	3.1
	Probably not	5	1.1	
	Maybe	53	11.7	11.7
	Probably yes	122	26.9	85.2
	Yes	264	58.3	
	Total	453	100.0	
Country				
Austria		78	17.2	
Australia		375	82.8	
Gender				
Female		208	45.9	
Male		245	54.1	

Effect of opinions, country and gender on opinions about climate change

Here, we present the results of ordinal logistic regression (OLR) to examine the relationship between outcome variables, i.e. opinion on climate change, and predictor variables, i.e. country and gender. We report the coefficient estimates, its standard error and 95% confidence interval, as well as the Wald test statistic, testing the null hypothesis that the regression coefficient equals 0 and noting its p-value. Since we are mainly interested in the effects of the independent variables (gender and country) on the response variables (concern, imminence, anthropogenic), we will focus on the direction and magnitude of the coefficient estimates and statistical significance for these. In the upper section of the regression table, we report the threshold coefficient estimates of the dependent variable as they represent the intercepts, i.e. the level of the latent y variable where an observation is predicted to fall in the higher categories of the y variable, when all independent variables equal zero. These values predict the cumulative logits and could be transformed for obtaining category probabilities, i.e. the probability that an observation falls into one specific category of our y variable, setting all x variables to zero. Since this is not of much interest for our analysis, we

Table 2 Chi-square and Fisher's exact tests for concern/anthropogenic, concern/imminence and imminence/anthropogenic, for all data aggregated across schools ($n = 453$)

Variables	Chi-square test statistic	p-value	Fisher's exact test	p-value
Concern and Anthropogenic	111.835	< .001	99.275	< .001
Concern and Imminence	94.398	< .001	65.641	< .001
Anthropogenic and Imminence	78.775	< .001	54.697	< .001

focus on the lower section of our regression table which presents the regression coefficients on the independent variables. Since all independent variables are modelled as factor variables, the regression coefficient on any x variable tells us how much the logarithm odds of y change, when we switch from the baseline group to another group of the reported variable holding all other variables constant. This means that, when significant, responses are affected by an order of one category, e.g. positive estimates raise the likelihood (i.e. from 'probably yes' to 'yes') and negative estimates lower the likelihood (i.e. from 'yes' to probably yes'). In other words, we can use the OLR (Table 3) to assess whether an independent variable can predict a type of response in the dependent variable, and this can take account of the direction between the ordered responses of the dependent variable.

In the first model, we regress the concern variable (Table 3a) on anthropogenic, imminence, country and gender and find significant effects on the Anthropogenic (yes/probably yes, $\beta = 1.674$, $p < .001$) and imminence variables (yes/probably yes, $\beta = 0.751$, $p = .010$). This finding aligns with the outcome of the Chi-square tests, by showing the three dimensions of opinion are correlated. However, it also identifies that the candidate predictor variables, i.e. country and gender, do not have a significant effect on the opinion variables. Therefore, regardless of students' country and gender, those who respond yes/probably yes for the anthropogenic and imminence variables are more likely to respond similarly for concern. As per the coefficient estimate, the effect is greater in the anthropogenic variable than in the imminence variable, i.e. the association between concern and anthropogenic is stronger than the association between concern and imminence, though both are significant.

For the second model, we regress the anthropogenic variable (Table 3b) on concern, imminence, country and gender and find significant effects on the concern (yes/probably yes, $\beta = 1.325$, $p < .001$) and imminence (yes/probably yes, $\beta = 1.070$, $p < .001$) variables. Again, this reiterates the strong correlation amongst concern, anthropogenic and imminence found from the Chi-square analysis (and the first model). For the gender variable, we find a significant negative coefficient estimate with female students ($\beta = -.431$, $p = .021$) less likely to have the opinion that climate change is anthropogenic than male students.

For the third model, we regress the Imminence variable (Table 3c) on concern, anthropogenic, country and gender and find less, but still significant, effects on the concern ('yes'/'probably yes', $\beta = .586$, $p = .071$), and anthropogenic ('yes'/'probably yes', $\beta = .739.$, $p = .011$) variables. Once again, this supports the findings of the Chi-square analysis and the two previous models. For the Ccuntry variable, we find a significant negative coefficient estimate with Austrian students ($\beta = -.668$, $p = .005$) less likely than Australian students to have the opinion that climate change is happening now.

DISCUSSION

Opinions of early adolescents on climate change are related with each other

The study explored the opinions, and determinants, of 12 to 13-year-olds in relation to climate change, across the three opinion arenas of worry (concern), human causation (anthropogenic) and imminence. In the light of the findings that each of the opinions (concern, anthropogenic and imminence) increases the likelihood that 'yes' or 'probably yes' is selected in the other opinions, we reject the H1's null hypothesis that there is no influence on the opinions for one another. The responses for this age group in these areas indicate that the vast majority shares the concern that climate change is something to worry about, is caused by humans and is happening now—and these relate positively to one another insofar that when a respondent selects 'yes' or 'probably yes' for any one of the opinions, they are highly likely to select 'yes' or 'probably yes' for the other opinions. The relation of the opinions to one another is an important finding as it may allow us to extrapolate the same relationship to studies that have looked at only one aspect of these opinions. Our results also are important as they suggest that worry regulation and emotional support would be worthy interventions in this age group—particularly those that foster hope and concern (Crayne 2015; Stevenson and Peterson 2016) as these are associated with stronger climate change beliefs, increased engagement and life satisfaction (Ojala 2012b). Finally, our results strongly reinforce previous research on emotional reasoning and associated changes in early adolescence which indicate that this age group are beginning to use 'objective', abstract-reasoning information to perceive threat (Rosso et al. 2004; Harker-Schuch 2020).

From an educational perspective, it is also worth considering how we may be adding to students' worry in the classroom and in their daily lives. While many researchers highlight the need to increase knowledge about the consequences and impacts of climate change (Shi et al. 2016; Meehan et al. 2018), they also show that this increases concern (Milfont 2012). We propose that positioning climate change as a concern, i.e. teaching the consequences, *before* providing context on how the climate system works, i.e. teaching the causes, is likely to increase concern and decrease rational responses to climate change. This is largely due to the fact that the consequences and impacts of climate change are inherently uncertain and fear-inducing.

Table 3 Parameter estimates (β) for the ordinal logistic regression analysis for (a) concern, (b) anthropogenic and (c) Imminence opinions. Data are aggregated when the opinions are treated as independent variables, i.e. aggregated values group negative and positive responses together (‘yes’ with ‘probably yes’ and ‘no’ with ‘probably not’) with ‘maybe’ kept as a neutral reference point. Threshold represents the response variable, e.g. for a), y-axis: concern that is assessed against independent variable data (x-axis: anthropogenic (aggregated), imminence (aggregated), country and gender)

(a) Concern		β	Std. error	Wald	df	Sig.	95% confidence interval	
							Lower bound	Upper bound
Threshold, i.e. response variable	Concern = ‘no’	– 3.213	0.619	26.937	1	< .001***	– 4.426	– 2
	Concern = ‘probably not’	– 1.884	0.446	17.812	1	< .001***	– 2.759	– 1.009
	Concern = ‘maybe’	– 0.358	0.39	0.842	1	0.359	– 1.123	0.407
	Concern = ‘probably yes’	1.224	0.395	9.628	1	0.002	0.451	1.997
Independent variables, i.e. predictor variables	Anthropogenic (aggregated) = ‘no/probably not’	– 0.027	0.426	0.004	1	0.949	– 0.863	0.808
	Anthropogenic (aggregated) = ‘yes/probably yes’	1.674	0.297	31.861	1	< .001***	1.093	2.255
	Anthropogenic =‘maybe’	0^a	–	–	0	–	–	–
	Imminence (aggregated) = ‘no/probably not’	– 0.612	0.561	1.192	1	0.275	– 1.711	0.487
	Imminence (aggregated) = ‘yes/probably yes’	0.751	0.294	6.55	1	0.01**	0.176	1.327
	Imminence =‘maybe’	0^a	–	–	0	–	–	–
	Austria	– 0.076	0.269	0.079	1	0.779	– 0.602	0.451
	Australia	0^a	–	–	0	–	–	–
	Females	– 0.078	0.206	0.144	1	0.704	– 0.481	0.325
	Males	0^a	–	–	0	–	–	–

(b) Anthropogenic		β	Std. error	Wald	df	Sig.	95% confidence interval	
							Lower bound	Upper bound
Threshold, i.e. response variable	Anthropogenic = ’no’	– 1.726	0.437	15.573	1	< .001***	– 2.583	– 0.869
	Anthropogenic = ‘probably not’	– 1.038	0.408	6.471	1	0.011*	– 1.838	– 0.238
	Anthropogenic = ‘maybe’	0.118	0.394	0.09	1	0.764	– 0.655	0.891
	Anthropogenic = ‘probably yes’	1.593	0.404	15.556	1	< .001***	0.802	2.385
Independent variables, i.e. predictor variables	Concern (aggregated) = ‘no/probably not’	– 0.548	0.585	0.879	1	0.348	– 1.694	0.597
	Concern (aggregated) = ‘yes/probably yes’	1.325	0.315	17.651	1	< .001***	0.707	1.943
	Concern (aggregated) = ‘maybe’	0^a	–	–	0	–	–	–
	Imminence (aggregated) = ‘no/probably not’	– 0.098	0.564	0.03	1	0.863	– 1.204	1.009
	Imminence (aggregated) = ‘yes/probably yes’	1.07	0.276	14.986	1	< .001***	0.528	1.612
	Imminence (aggregated) = ‘maybe’	0^a	–	–	0	–	–	–
	Austria	– 0.319	0.244	1.714	1	0.19	– 0.796	0.158
	Australia	0^a			0			
	Females	– 0.431	0.187	5.291	1	0.021*	– 0.799	– 0.064
	Males	0^a	–	–	0	–	–	–

Table 3 continued

(c) Imminence		β	Std. error	Wald	df	Sig.	95% confidence interval	
							Lower bound	Upper bound
Threshold, i.e. response variable	Imminence = ‘no’	− 3.16	0.512	38.07	1	< .001***	− 4.164	− 2.156
	Imminence = ‘probably not’	− 2.693	0.472	32.559	1	< .001***	− 3.618	− 1.768
	Imminence = ‘maybe’	− 0.939	0.413	5.169	1	0.023	− 1.749	− 0.13
	Imminence = ‘probably yes’	0.556	0.411	1.83	1	0.176	− 0.25	1.361
Independent variables, i.e. predictor variables	Concern (aggregated) = ‘no/probably not’	− 0.389	0.584	0.443	1	0.506	− 1.534	0.756
	Concern (aggregated) = ‘yes/probably yes’	0.586	0.324	3.259	1	0.071	− 0.05	1.222
	Concern (aggregated) = ‘maybe’	0^{a}	–	–	0	–	–	–
	Anthropogenic (aggregated) = ‘no/probably not’	− 0.122	0.432	0.079	1	0.778	− 0.968	0.724
	Anthropogenic (aggregated) = ‘yes/probably yes’	0.739	0.292	6.406	1	0.011*	0.167	1.311
	Anthropogenic (aggregated) = ‘maybe’	0^{a}	–	–	0	–	–	–
	Austria	− 0.668	0.241	7.718	1	0.005**	− 1.14	− 0.197
	Australia	0^{a}			0			
	Females	− 0.225	0.189	1.410	1	0.235	− 0.596	0.146
	Males	0^{a}	–	–	0	–	–	–

***$p < .001$, **$p < .01$, *$p < 0.05$

[a] This parameter is set to zero because it is redundant as it is the neutral reference point against which the other variables are analysed

As O'Neill and Nicholson-Cole (2009b) argue, 'although such representations [i.e. fear] have much potential for attracting people's attention to climate change, fear is generally an ineffective tool for motivating genuine personal engagement'.

Efforts to prepare children need to include their emotional well-being and their action competence, which also includes managing their anxiety and feelings of worry. In a study exploring the coping strategies of early adolescents ($n = 293$), Ojala (2012a) demonstrated that problem-focused (looking for solutions or searching for answers) and meaning-focused coping (finding benefits in the situation or drawing on belief systems to sustain well-being) strategies are positively related to pro-environmental behaviour and efficacy. There is a need to provide avenues for individuals to take action or improve action competence, as described by van Valkengoed and Steg (2019), who show that climate adaptation behaviour is motivated by descriptive norms (i.e. everyone else is doing it), negative effect (i.e. the desire to ameliorate bad feelings and thoughts), self-efficacy (i.e. the feeling that one can do something about a problem) and response efficacy (i.e. the sense that the actions that we take will actually work).

Opinions of early adolescents on climate change differ based on country/gender

The findings on the influence of demographic factors on opinion about climate change partially reject H2's null hypothesis and there is no difference in the opinion of early adolescents based on demographic factors, such as country and gender. This is because some demographic factors correspond with significant differences in opinion on climate change, while others do not.

Although there is no signal in the statistical analysis for country with regard to the opinion for anthropogenic (meaning that it didn't matter which country the student came from with regard to the opinion that climate change is caused by humans), it does matter, in this sample, which gender you are with regard to the opinion for whether climate change is caused by humans or not. Although research shows that late adolescent and adult females are more likely to be pro-environmental (Hine et al. 2013; Scannell and Gifford 2013; Carrier et al. 2014; Stevenson et al. 2014; Skalík 2015; Chadwick 2017; Stevenson et al. 2018a, b; Skamp et al. 2019), our study suggests that this is not necessarily the case for younger adolescents in relation to the opinion that climate change is anthropogenic, with 12–13 year-old males (84.9%), more likely to report the opinion that climate change is caused by humans than their female peers (79.8%), (see Table S3). Regardless of the differences between males and females, there is still a large majority that share the view that climate change is anthropogenic. These findings suggest that research and tailored interventions aimed at targeting gender may be useful in promoting a better understanding of climate change. For example, serious gaming with a climate science topic may provide gender-specific gameplay that responds to known gender differences—or, more usefully, are derived from game analytics that interact at the individual student level to tailor learning to the learner's needs.

The most surprising finding of this study is the stronger opinion amongst 12 to 13-year-old Australian public-school students living in central urban districts that climate change is happening now than is shared by their Austrian peers (87.5% Australian respondents vs 73.1% Austrian respondents; see Table S3). It is especially remarkable that, in the light of the amplified warming that is taking place in Austria (Nemec et al. 2013; Rhomberg 2016), that Austrian students are less likely to have the opinion that it is happening now. While the findings from the demographic factors are atypical and do differ for anthropogenic from previous findings in relation to gender the opinions of early adolescents in general tend to show a high levels of concern, a strong belief that its cause is anthropogenic and a strong belief it is happening now.

Comparison of climate change opinions with other peers, adults and older adolescents

A lack of existing data specifically from early adolescent opinions necessitated a comparison of the opinions of early adolescents to adults (see Tables S1, S2 and S3 for additional information) to obtain an idea of where the early adolescent opinions are positioned in the climate change opinion realm. The following table (Table 4) provides an overview of early adolescent opinions in comparison with their respective (or proxy) adult population.

Both student groups in Australia and Austria (Table 4a) show a strong alignment with one another, a stronger positive concern level than Australian (63.3%) and European (71.3%) adults (Table 4c) which strongly supports the scientific consensus in the concern opinions related to climate change. Regarding the anthropogenic and imminence opinions, the Australian student group demonstrates a much higher level of belief that climate change is happening now and is anthropogenic than their Austrian peers and the European and Australian adults. Overall, Australian 12 to 13-year-olds were more likely than their respective adult population to think climate is something to worry about (89.1% respondents vs 63.3% adults), is caused by humans (83.6% respondents vs 63.7% adults) and is happening now (87.5% respondents vs 77.7% adults). In comparison, although Austrian 12 to 13-year-olds show a higher level of opinion for concern to their adult population (84.6% respondents vs 71.3% adults), they are less likely to have

Table 4 Comparison of 12–13-year-old adolescents with respective older adolescents and adult population. $^{@}$Data have been averaged from 2 or more surveys. See Tables S1, S2 and S3 for more information

	Concern (%)	Anthropogenic (%)	Imminence (%)
(a) Early adolescents (this study)			
Austria	85	76	73
Australia	89	84	88
(b) Older adolescents			
US	43	57	54
Austria	60	73	91
Denmark	82	90	94
(c) Adults			
Austria	71	87	87$^{@}$
Australia	63$^{@}$	64$^{@}$	78$^{@}$

the opinion that climate change is caused by humans (anthropogenic: 75.6% respondents vs 87.2% adults) and happening now (imminence: 73.1% vs 87.0%) compared to their respective European adult neighbours.

Although we might have anticipated a strong alignment with the respective political position on climate change in each country (i.e. strong positive adolescent and adult opinions in Austria in line with EU climate policy and weaker positive adolescent and adult opinions in Australia in line with weaker Australian climate policy), we found that Austrian students were less likely to have the opinion that climate change is happening now and is caused by humans—both in comparison with their proxy adult population and with their Australian peers. This finding challenges the anticipated influence of their adult populations—especially as the comparison shows, Australian 12 to 13-year-olds think climate change is something to worry about, is caused by humans and is happening now, more than their adult cohort. In contrast, although Austrian 12–13-year-olds are more worried than their respective adult population, they show lower opinion levels for Anthropogenic and Imminence than their proxy adult population. These findings are at least partially consistent with some previous studies (Stevenson et al. 2014; Lawson et al. 2018).

There may be differences in culture or lifestyle between adolescents in Austria and Australia, such as differences in population density or interactions with nature (Saltzman et al. 2011), that lead to the observed differences in opinion. However, it would be likely to see any such effect reflected in the adult populations if it is simply an effect of place. Instead, if there is no methodological or measurement error responsible for the difference, then these results indicate there is an interaction between the adolescent experience and place which shapes the attitudes. For example, curriculum content or norms around adolescents' awareness of climate change or other key policy issues. Both Australian and Austrian 12–13-year-olds show higher rates of reporting the concern opinion when compared to their respective adult populations—and with a stronger positive response than for the other opinions (imminence and anthropogenic), particularly for Australian adolescents. This concern signal is an important one as it suggests that, although Austrians in this age group are attuned to the emotional aspect of climate change as a threat, they do not possess the fundamental understanding of climate change processes to recognise the major dimensions of climate change which make it worthy of concern—the imminence of the threat (Imminence), and the fact that the observed warming and climatic changes are resulting from human activities (anthropogenic).

Opinions in older adolescents in Austria, Denmark and the USA (Table 4b) in comparison with early adolescent opinions (Table 4a) show that both Australian (89%) and Austrian (85%) early adolescents are more worried about climate change than older adolescents in Austria (60%) but they share a similar level of concern to older adolescents in Denmark (82%). Older adolescents in the USA report an even lower degree of concern (43%) about climate change than their peers in other countries and the younger adolescent group. For opinion that climate change is anthropogenic, we see that older adolescents in Denmark (90%) and early adolescents in Australia (84%) share a strong belief that climate change is caused by humans. For the same opinion, we see that older (73%) and younger (76%) Austrian adolescents also share a similar level of belief, but with a lower shared consensus. Once again, older adolescents in the USA indicate a lower shared belief that climate change is caused by humans (57%). For the opinion that climate change is happening now, we find that early adolescent Australians (88%) share a similar high level of opinion that climate change is currently occurring as the older adolescents in Austria (91%) and Denmark (94%). As reflected in the previous opinions, older adolescents in the USA show a lower shared belief (54%) that climate change is happening now than their respective peers and the early adolescent age group.

With clear differences amongst the adult, older adolescent and early adolescent age groups so apparent, more work needs to be done to determine the drivers and forces that create this disparity. Of import is the apparent disconnect between the attitudes of adults, older adolescents and younger adolescents. This disconnect may be used to assist young people in the development of attitudes and viewpoints that better reflect scientific findings and evidence. These findings reinforce work by Stevenson et al. (2014) who argue that 'while worldviews are well entrenched amongst adult populations, during teenage years they are still forming and this 'plasticity' may explain why climate change knowledge mitigates worldview-based scepticism amongst young people' (summarised by Corner et al 2015, p. 525).

Potential limitations to this study

It is necessary to note that certain potential biases may have influenced the data and affected the findings. The first is that the selected students were from a total of six schools, and as a result cannot be considered a geographically or demographically representative sample of either country. Despite this, the results are useful, especially as data on the 12 to 13-year-old age group is scarce in the literature. It would be beneficial for future studies focused on early adolescents to adopt compatible methods to allow for aggregation of data, developing a more robust dataset.

One of the barriers to more geographically and demographically representative data from 12 to 13-year-olds is the (necessary) challenge posed by research ethics of working with young and vulnerable people. Those who maintain climate-friendly sensitivities are, therefore, more likely to participate in this research than those who do not. The level of teacher engagement was, perhaps, the most influential of all the potential biases for the teachers were the essential driver behind participation numbers in each class. The researchers observed that the teachers who were not enthusiastic had a far lower number of participants in their class than those who were favourable towards the research. This observation was apparent in anecdotal negative criticism of the project by those teachers who returned fewer participation notes from their students and, in some cases, suggesting to the researcher that climate science was not a 'settled' science. In addition, one of the schools in Vienna (VHS2) had parents that were very sceptical about their children's involvement in a research project, with all parents for students in two out of the four classes returning notes that denied permission. Many of these parents were new residents in Vienna (and very recent arrivals to Austria), so it was difficult to discern whether declining to participate was on account of their vulnerability as new residents, language barriers, anxiety over new administrative procedures or negative attitudes toward climate change. If the last, then these important perspectives were not able to be captured in the study.

Curiously, nearly all permission notes were returned by the parents in the Austrian schools (even those stating that their child could not participate) whereas just over half were returned from Australian schools (with nearly all saying their child could participate) even though the recruitment process had been the same. The researcher speculates whether the unreturned notes in Australia are in lieu of a returned note that does not allow their child to participate or a lack of procedure between the school and home that results in lost or misplaced permission notes—or a mix of both. These unavoidable challenges of working with schools and their adolescent students are useful for other researchers to note when engaging with similar samples for future research.

Due to our deployment of these questions in the classroom setting, as necessitated by our engagement with specific educational institutions, they may not reflect the broader populations of early adolescents in Austria and Australia. Such a study would require replication of our research with a nationally representative, randomised sample of early adolescents in the two countries. We encourage such an undertaking in future research efforts in this topic area. Furthermore, the comparison of adult opinions to adolescent opinions in this study may not be a determinant of worldview influences, particularly for Austria as it lacks country-specific data on adult opinions related to the human cause of climate change and whether it is happening now.

Implications of this study

The attitude of these early adolescents is interesting in context with the recent rise in youth climate activism. The data for this study were collected prior to the global public appearance of the #FridaysForFuture movement which began in 2018 and made international news headlines in 2019 (Fisher 2019; The Lancet Planetary Health 2019; Thew et al. 2020) and go some way toward explaining this strong wave of support for political action on climate change from young people around the world. The stronger alignment of attitudes with the scientific consensus in this age group in comparison with those of the respective adult populations provides context for why young people, such as Greta Thunberg (TIME Magazine 2019), and many others, are so prominent in the current wave of social and political activism and resistance across the world (Holmberg and Alvinius 2020).

With adolescent activism currently at centre stage in the global political forum in relation to climate change, this study reinforces the deep concern and anxiety about climate change in early adolescents and provides context for their recent political will and activity. Efforts to address their concerns are warranted and these efforts require a strategy that responds to the emotional, psychological and physiological needs of this age group. Without any formal political agency such as voting rights or inclusion in policy development, they are extremely vulnerable to the decisions being made today about their future—and will be tasked with cleaning up a mess they opposed without recourse for restitution or reparation.

While coping strategies (Ojala 2012a) and improving action competence (Valkengoed and Steg 2019) show promise for support interventions, our results suggest that both action competence and coping strategies could be delivered via climate science literacy efforts that focus on causes and the mechanisms that describe climate change. Due to the association of worry with climate change, efforts that focus on causes (teaching the physical science basis: mechanisms, processes and basic climate science) ahead of consequences (highlighting the impacts: sea-level rise, increased temperatures, extreme weather events) may diminish negative emotions associated with threats (Shi et al. 2016), improve action competence and allow individuals to engage with the issue more optimistically and to perceive it and approach it in the future as a solvable problem. If adolescents require coping strategies in order to demonstrate pro-environmental behaviour, we propose that students are more likely to find benefits associated with a warming climate if they are given the intellectual foundation to imagine these benefits—and will be more likely to envisage solutions to reduce emissions toward climate equilibrium (Visintainer and Linn 2015). For early adolescents entering puberty, this method attempts to respect both their physiological transition as well as their need to be prepared for future climate change.

While there has been ongoing discussion about the value of knowledge deficit in the climate communication arena (Potter and Oster 2008; Moser and Dilling 2012; Pearce et al. 2015; Plutzer et al. 2016; Rohloff 2018; Whitmarsh and Lorenzoni 2010), domain-specific climate science literacy has been shown to be an effective intervention to motivate climate-friendly attitudes and behaviour (Clark et al. 2013; Guy et al. 2014; Stevenson et al. 2014; Corner et al. 2015; Shi et al. 2015, 2016). For young people in the early stages of worldview development, science-based education may help them anchor important climate-specific concepts and knowledge as a departure point for the development of pro-climate attitudes and behaviours. As highlighted by Stevenson et al. (2014, p. 302) ‘Climate literacy efforts can overcome worldview-driven scepticism amongst adolescents, making them a receptive audience for building climate change concern’. Likewise, Ranney and Clark (2016) demonstrated that an increase in knowledge about climate science was associated with a higher willingness to accept financial sacrifices. In order to consider both opinions and knowledge dimensions, as recommended by Azevedo and Marques (2017), we are exploring the effectiveness of climate science literacy interventions that focus on causes and mechanisms of climate change in other work.

With worldview playing such a significant role in the behaviour and attitude of adults (Kahan et al. 2011), the high concern about climate change amongst early adolescents presents an avenue for interventions that may overcome the bias seen so frequently in adults (Harker-Schuch 2020). While interventions to improve attitudes and engagement amongst adults can polarise or paralyse an individual’s opinions (Kahan et al. 2011), interventions in the early adolescent age group may be more receptive to educational or communication efforts (Stevenson et al. 2018a, b). Providing context about the causes and mechanisms of climate change in the early adolescent age group may also diminish anxiety and provide an avenue for coping and action competence; particularly when solutions and explanations about the problem are identified, investigated and resolved.

CONCLUSION

The suitability of the 12 to 13-year-old age group for science-based climate change education is clear. Not only do we have an age group whose opinions already align well with the scientific consensus, but also we have a group with the requisite intellectual knowledge and capability to begin learning climate science who would greatly benefit from well-designed science communication interventions. Additionally, early adolescents are easy to reach as they are all in school, and they are at the nascent stage of worldview construction. Improving scientific literacy in relation to climate change could have immense social and political implications, such as providing all young people with a fundamental understanding of the science of climate change, regardless of the political ideology or social identity, they will develop in the years ahead. Perhaps, if such a literacy programme was properly implemented, we would have a general public that, regardless of worldviews and belief systems, would share a good understanding of the science of climate change as the basis for public and policy deliberations on relevant courses of action. Climate science education of early adolescents offers alternative intervention routes that avoid the worldview-based polarisation on the reality of climate change which we have experienced in recent decades. Future climate science-educated adults could no more deny the phenomena of climate change than they could deny the existence of their large intestines: both are physical phenomena manifest invisibly in our everyday lives.

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The significance of Chapter 3 to the thesis

The research has addressed both research objectives for research question 2. By evaluating the opinions of early adolescents, we address a significant gap in the literature and provide a baseline for opinions in this age group. Early adolescents are concerned about climate change, regardless of their nationality. Since this age group show differences to adult and older adolescent opinions on climate change these findings suggest that worldview is not as influential on this age group as on older adolescents or adults. Furthermore, the concern expressed by early adolescents suggests they will be receptive to efforts to improve their CSL. With concern about climate change so high in this age group, a response from educators and communicators in terms of support, resilience building, and action competence might be a worthwhile endeavour.

Chapter 4:

Toward a Climate Science Literacy Framework: Developing knowledge domains that describe the physical basis of climate science for the 12-13-year age group

4. Toward a Climate Science Literacy Framework: Developing knowledge domains that describe the physical basis of climate science for the 12-13-year age group

The place of Chapter 4 in the thesis

Chapter 4 aims to address research question 3 through research objectives e) and f).

3) What is the current level of CSL in the 12-13-year age group?
    f) Test the level of CSL in the 12-13-year age group.
    g) Investigate how demographic and personal-identity factors affect CSL in the 12-13-year-age group.
    h) Formulate a CSL proto-framework.

Chapter 2 established the potential of early adolescents for knowledge deficit interventions related to Climate Science Literacy (CSL) both with respect to their intellectual development and the potential effect this may have on eventually cultivating a fact-based worldview. Chapter 3 found that early adolescents have strong concerns about climate change and, thus, are likely to be receptive to climate knowledge building interventions

To revisit knowledge deficit as an intervention, Chapter 4 further develops the CSL definition and develops a prototype Climate Science Literacy (CSL) framework for the 12-13-year-age group that can be used to teach CSL. To start with, the USGCRP's definition of CSL was further refined and developed in order to focus on the chemical/physical mechanisms that describe Earth's climate system in equilibrium which is necessary due to anchoring, worldview formation and psychological well-being. A CSL framework was developed based on knowledge domains or learning units which was then tested with using a complementary questionnaire. This comprehensive and highly domain-specific climate science questionnaire covering the physical/chemical mechanisms of Earth's climate system in equilibrium was given to early adolescents in 3 major metropolises in Australia and Austria. The responses were statistically analysed to determine strengths and weaknesses in each knowledge domain and formed the basis of a tested CSL framework. By quantifying the current level of CSL, we can establish a diagnostic value for CSL in this age group and, thereby, address a significant gap in the literature.

Due to absences and errors in completion of the questionnaire, the total number of respondents who took part in the opinion research in Chapter 3 (both as a total and of those who are eligible) and Chapter 4 (both as a total and of those who are eligible) differs from the total number of respondents (both as a total and of those who are eligible).

Abstract

With global action on climate change becoming increasingly urgent and necessary, educators and communicators face a wicked dilemma: although individuals require knowledge about climate science to make informed choices about climate change, individuals and groups with many existing socio-cultural worldviews can react adversely to knowledge-influencing interventions. While this dilemma is observable in adults, recent research suggests that adolescents who have not yet established their worldview may be more receptive to knowledge deficit. The linkages from knowledge to behaviour are uncertain and more tenuous than implied in the classic Knowledge-Attitude-Bebhaviour model, but research suggests domain-specific climate knowledge , as distinct from knowledge of climate change causes and effects, can, at least indirectly, influence attitude and/or behaviour. Our research, therefore, examines the suitability of the early adolescent for climate science literacy (CSL) interventions. To support this objective, we further develop the definition of CSL and devise a CSL Framework for teaching and assessing CSL. The CSL Framework is tested using a prototype questionnaire. We measure pre-existing CSL at 47.3% (n=465) in two schools in Austria (Vienna) and four schools in Australia (2 in Sydney and 2 in Canberra). Performance in selected areas suggests early adolescents have the background or incidental knowledge needed to begin learning climate science in the context of an appropriate supporting curriculum. We find knowledge levels and patterns are shared across borders (culture, language, education system), which allows us to design a prototype CSL curriculum.

4.1. Introduction

> ‘It’s the facts of the matter that matter’
>
> Adam Frank (2017)

As pressure mounts globally to move towards zero emission lifestyles, action to reduce emissions is becoming urgent and necessary (IPCC, 2018). Motivation to support such endeavours, however, remains poor or inadequate in the broader public arena (Gifford, 2011). In spite of efforts to engage and educate individuals on the potential threat of climate change, ambivalence, apathy and even antagonism persist in the general public, impeding effective adaptation and mitigation (Campbell, 2012; Pidgeon, 2012; Poortinga et al., 2011). Although many factors drive this opposition, socio-cultural cognition or 'worldview' is commonly regarded as the most influential and pernicious (Kahan et al., 2011). Worldview, as discussed here, is defined according to Dilthey (quoted in Makkreel, 1975) as an overall perspective on life that sums up what we know about the world, how we evaluate it emotionally, and how we respond to it volitionally' (Makkreel, 1975). It is a perspective that we acquire from our peers, elders, society, politics and culture – and it is very difficult to alter or revise once established (Lewandowsky et al., 2012).

Research in mature audiences has consistently shown that communication efforts to address worldview by education or improving knowledge can polarise viewpoints, entrench an individual's opinion, threaten, alarm or annoy those who are targeted – and often results in counter-productive outcomes (Ojala, 2015b; Schweizer, Davis, & Thompson, 2013; Whitmarsh, 2011). In response to this resistance, there is broad acceptance of socio-cultural worldview as a significant barrier that resists evidence-based arguments (Sarewitz, 2011; Shi et al., 2016). As a result, there is a vast body of research that examines the role and dynamics of worldviews in attitudes toward climate change (e.g. Corner, Markowitz, & Pidgeon, 2014; Fortner, 2001; Hornsey, Harris, Bain, & Fielding, 2016; Kahan, 2015; Weber, 2010). Based on the valuable insights into the complex social dimensions of climate change knowledge and belief that have been gained from these studies, we explore a complementary and promising avenue for circumventing the barriers posed by entrenched worldviews among adults: climate science literacy (CSL) interventions among early adolescents in the school setting.

Recent research suggests at least two unexplored routes around worldview bias that offer considerable promise for contributing to building evidence-based support for climate-friendly endeavours in the broader public arena. Both routes are embedded in the education/schooling context, and as such here we engage with climate communication at its interface with education. The first involves intervening at younger ages (Adelson & Neil, 1966; Harker-Schuch, 2020; Neundorf & Niemi, 2014; Stevenson et al., 2018; Stevenson et al., 2014; Vollebergh et al., 2001), and the second involves the content (both curriculum and pedagogy) of climate science education measures and/or interventions (Azevedo &

Marques, 2017; Clifford & Travis, 2018; M. S. McCaffrey & Buhr, 2008; Shi et al., 2016; Skalík, 2015).

With regard to intervening at younger ages, research indicates that it is likely that worldview is becoming established by the time that most secondary schools introduce climate change into curricula between the ages of 15-17 years (Adelson & Neil, 1966; Bieler et al., 2018; Frappart et al., 2018; Harker-Schuch, 2020; Meehan et al., 2018; Neundorf & Niemi, 2014; Sofiyan et al., 2019; Vollebergh et al., 2001; Whitehouse, 2013; S Wynes & Nicholas, 2017; Seth Wynes & Nicholas, 2019). In an investigation into the growth of political ideas, Adelson and O'Neill (Adelson & Neil, 1966, page 295) show that 'it is only in the later period that youngsters can take into account the long-range effects of political action' and 'there is a gradual increase with age in the use of philosophical principles for making political judgments'. Late adolescence is the 'formative phase' for the establishment of worldview (Neundorf & Niemi, 2014; Vollebergh et al., 2001), which arises, according to Vollebergh (ibid), as a result of growing internalization and stabilisation of attitudes that have been developing from early adolescence.

With regard to content, recent research suggests that climate science education efforts that focus specifically on the physical causes of the climate system may improve concern and reduce worldview bias. For example, Shi et al. (2016, page 759) propose that when knowledge 'is measured in a domain-specific and multidimensional way, knowledge is indeed an important driver of concern about climate change —even when we control for human values'. In a study by Skalík (2015) in the Czech Republic, it was shown that knowledge was positively correlated to an increased sense of personal responsibility. Buhr and Sullivan (2014, page 536) suggest that understanding the 'anthropogenic enhancement of known Earth system processes (e.g., greenhouse effect, carbon cycling, feedbacks) …may perhaps address misunderstandings ..and serve to mediate cultural cognition issues'. With regard to engagement, a knowledge of underlying mechanisms and physical causes might be an essential component in addressing the lack of broad support for climate-friendly endeavours in the public arena because, as Stamm et al. (2000, page 219) describe 'when causes are not well understood, it is clearly difficult to devise effective solutions to a problem'.

Drawing together these two intervention routes (age of interventions and climate science education), is the effect of the anchoring heuristic (‘focalism’) which is when the brain ‘anchors’ the first pieces of information as a departure point for subsequent choices and judgements (Colvin et al., 2020; Furnham & Boo, 2011). Accordingly, it is more difficult to change minds after misinformation has been seated than it is to provide correct information in the first instance (Colvin et al., 2020). This points to the promise of evidence-based climate science literacy (CSL) interventions when students are establishing their broad understandings of climate change in early adolescence. With worldview already exerting an influence in upper secondary and establishing itself throughout adulthood (Harker-Schuch, 2020; Lawson et al., 2019), a younger adolescent group (12-13 years old) offers an under-explored opportunity for interventions that aim to improve CSL ultimately contributing to establishing broad support for climate-friendly endeavours in the public arena. In this article, we explore these two avenues for circumventing barriers to engagement with climate change and, based on empirical research, we propose a preliminary framework for future climate change communication efforts in the educational realm.

4.1.1. Early adolescence – an ideal, but poorly-researched, age group in need of a climate science curriculum framework

Early adolescence is a time of significant physiological, social and intellectual development (Jensen & Nutt, 2015). The early adolescent embarks on a journey that will transition them from child to early adult. These early adolescent transitions include significant physiological changes that cause major changes to the white matter in their brains i.e. the 2nd critical phase of development, (Jensen & Nutt, 2015), which, in turn, accelerates their intellectual development (ibid) and promotes the development of self-determination as they progress through puberty (Field et al., 1997). The changes in early adolescence are markedly different than at later and earlier stages (Harker-Schuch, 2020) and are evident in changes to abstract thinking, logical reasoning, relational processing, episodic and prospective memory (Blakemore et al., 2010; Dumontheil, 2014; Rosso et al., 2004). In addition to cognitive changes, early adolescents experience changes in self-determination, social allegiance

(Piaget, 1972) and social shifts as they switch their source of authority from elders and parents to peers and socially-significant others (Burnett & Blakemore, 2009).

These changes occurring in early adolescence, though confronting, may offer unexplored opportunities and benefits for climate science communication and education interventions. Of particular relevance to climate science education is the second critical phase of intellectual development which begins at ~11-12 years of age and heralds the commencement of abstract-reasoning skills (Piaget, 1972), higher-order thinking and the ability of the individual to conceptualise complex ideas, tasks, and networks (Case, 1985). Prior to the start of this intellectual development, the child typically lacks the neural development to undertake or perform the intellectual processes necessary to understand complex issues such as climate science (Harker-Schuch, 2020; Jensen, 2015; Jensen & Nutt, 2015). Ensuring that scientific information is compatible with cognitive ability is a must for educational appropriateness that may, also, drive societal change (Liu et al., 2014). A recent longitudinal study by Otto et al. (2019) into both behaviour and attitude in children and young people – according to Otto (ibid, page 1), the only study of its kind – shows that environmental behaviour and attitude 'starts consolidating from age 10 onwards' which suggests that interventions that leverage knowledge to promote engagement are likely to be more successful in early adolescence than at other ages.

Climate change is a very serious concern for this age group (Harker-Schuch et al., 2020; Ojala, 2012a). Since sociocultural worldviews typically mirror the worldviews of significant others and the community in which they live, observed differences in opinions about climate change between early adolescents and their respective adult population, suggest that worldview bias has less influence over younger adolescents (Corner et al., 2015; Stevenson et al., 2014; Vollebergh et al., 2001). Hestness et al. (2016) investigated the relationship between worldview and early adolescent ideas about climate change consequences and impacts (n=39; 11-12-years), finding that, although they were influenced by media within and beyond their formal learning environments, discussions on the topic of climate change between parents and respondents were infrequent, which suggests that early adolescents are unlikely to be heavily influenced by their parents. Our own research in Austria and Australia (Harker-Schuch et al., 2020) found that 12-13-year-olds are considerably more worried about climate change

(~87%) than their respective adult populations (63-71%). As well as supporting the premise that it is unlikely that this age group has developed a socio-cultural worldview, there is an imperative to respond to their concern. This response needs to occur before the added pressures of adolescence threaten their emotional and psychological well-being and, in addition, before emotional influences overwhelm the potential for a rational response (Maughan et al., 2013).

Research on adolescents' understanding of climate science has been limited, and that on early adolescents, even more so. When research does include early adolescence, findings often fail to focus on specific age groups or quantify knowledge signals (Marcinkowski et al., 2011). In addition, the use of inconsistent measures for assessing and reporting levels of knowledge on climate change and the lack of an agreed educational framework for CSL make comparisons among studies problematic.

A United Nations Children's Fund (UNICEF) study from 2011 in Montenegro investigating ‘children and climate change’ concluded that CSL was poor although respondents see climate change as a ‘very serious’ global problem, but only 14-17 year-old students were included (UNICEF & UNDP, 2011). Likewise, Corner et al. (2015) report that, for the broad swathe of 12-25 year old youths, ‘there remains much uncertainty around basic underlying scientific concepts among young people... confusing damage to the ozone layer with climate change; or making inaccurate causal links between short-term weather and long-term climate change’, but no value is given for this uncertainty or reported confusion. Although this paper offers many useful guidelines towards a climate science pedagogy, there is no insight into CSL rates amongst young people. A more quantitative study of older adolescents (16-17 years; n=188) from 2011 found a value of 48.5% for overall climate science literacy (causes and consequences) measured against a challenging knowledge survey (Harker-Schuch & Bugge-Henriksen, 2013). While this figure provides a baseline to which early adolescents may be compared, there is no information on this age groups’ knowledge strengths and weaknesses across the different dimensions of climate change. Bodzin (2014) examined the effectiveness of a geospatial curriculum in the US on CSL in 8th grade students (13-15-years, n=956) and, though showing a CSL pre-test score of 40.8% as well as nuances in knowledge strengths and weaknesses (differentiating between particular aspects of climate science for selected aspects of cause- and consequence-based climate science), climate science as a complete and comprehensive topic was not considered. A different approach was taken by Lombardi (2013). In an effort to gauge the 'plausibility' of certain climate phenomena (rather than a baseline of CSL), Lombardi (2013) asked 12-13-year old students (n=268) to rate particular climate-related events between 'greatly implausible' and 'highly implausible' as a measure of their 'truthfulness'. Their results show that instruction 'promoting critical evaluation and plausibility reappraisal may facilitate sustained conceptual change' (ibid). While gains for two of the six items were statistically significant, the overall gain for these two items was 2% and there is a risk – due to the effect of the 'anchoring' heuristic, which tells us that we are disproportionately influenced by the first piece of information we receive so that it becomes the 'anchor' for successive decisions (Tversky & Kahneman, 1974) – that asking young people about the plausibility of climate-related events may promote misconceptions about climate change if these questions are the first exposure these students have to these concepts.

More importantly, the lack of adequate research in exploring domain-specific CSL for this age group deprives us of ready material or resources we could adapt to either obtain useful findings, such as a baseline of CSL as recommended by Marcinkowski et al.(2011), or develop necessary CSL material for this age group. McCaffrey et al. (2008), report that 'a review of five decades of science education relating to climate in general and climate change in particular reveals that basic climate science has not been well addressed in national and state education standards or science education curricula'. As recently as 2017, Colliver (2017) found that the numbers of resources available to teachers, as well as their accessibility, is having a detrimental effect on CSL in the classroom.

To accurately assess CSL and effectively teach climate science, a knowledge framework that encompasses the entire domain of climate science is needed. Such information is essential as, without it, it is impossible to accurately assess students, or know where the content differences or disconnects are. Furthermore, without this information, we are unable to approach the design or construction of a curriculum and pedagogy. Put simply, we need to know how well (e.g., as a %) individual students understand a domain of climate science (e.g., albedo) and, if they do have some existing knowledge, to what level of detail can they recognise and describe that domain (e.g., ranging from recognising that albedo has a cooling effect to a detailed description of radiation budgets in correlation with albedo).

The lack of an adequately-tested, coherent and comprehensive CSL framework based on tested pedagogical or curriculum-supported material or guidelines was highlighted in the creation of course material by Miléř and Sládek (2011) whose endeavour to develop a CSL programme, although offering some valuable contributions to the formation of such a framework (particularly in relation to the physical science basis), lacked a pedagogical structure or learning design, and was not tested for learning outcomes. More critically, their course did not involve students in its creation or design which is, 'crucial here: no scientific programme should be launched without talking to the people it aims to reach' (Nature Editorial, 2018). Although Miléř and Sládek did not include the students, their strong focus on the physical science basis offers a valuable advancement toward a CSL framework that focuses on understanding the scientific mechanisms and/or processes that underlie the phenomenon of climate change (Clark et al., 2013; Ranney & Clark, 2016; Shi et al., 2016). In a study examining worldview and early adolescent understanding of climate change (Hestness et al., 2019), the research instrument only explored impacts and consequences. These are foreboding concepts for mature individuals (Cunsolo et al., 2018) and caution needs to be exercised when introducing them to children (Ojala, 2012a, 2013) – particularly for those starting puberty when the physiological changes of adolescence make them vulnerable to clinical anxiety, depression and other psychological imbalances (Eaves et al., 2003; Maughan et al., 2013; Reardon et al., 2009). As argued by Colliver (2017), 'there is a need for a more holistic, pedagogically relevant and integrated approach to teaching and learning that addresses the science of climate change and its component parts in a way that is developmentally appropriate for a range of students across a range of age and year levels'. With regard to global education standards, there is also a need for an approach that requires students to explain climate phenomena scientifically, as described by Azevedo and Marques and outlined in the Organisation for Economic Co-operation and Developments (OECD) Programme for International Student Assessment (PISA Science Framework) (Azevedo & Marques, 2017; OECD/PISA, 2013).

4.2. Objectives and aims

The aims of this paper are to assess early adolescents' pre-existing CSL and develop a prototype CSL curriculum that can be used in schools. To this end, we further develop the definition for Climate Science Literacy (CSL), translate the CSL definition into a CSL Framework that we used to design a CSL curriculum, test the Framework and assess early adolescents' pre-existing CSL using a prototype CSL questionnaire, and devise a CSL curriculum suitable for use in schools. The response results from the questionnaire are ordered (least to most difficult) to derive a taxonomy for intended learning outcomes, as described by Biggs and Collis (1982). We assessed the level of pre-existing CSL of 12-13-year-olds in six schools in three cities in central urban areas in Austria and Australia. This allowed us to examine whether there are differences in performance among the different countries and schools. Two countries are included since there is a need for a more ‘holistic, pedagogically relevant approach to teaching’ climate change (Colliver, 2017, page 73). The influence of gender and student subject preference are also investigated. Gender differences in attitudes and concern about climate change are well established in the literature (McCright, 2010; McCright & Dunlap, 2011a; Lorraine Whitmarsh, 2011), and since this research investigates knowledge, the influence of a student’s subject preference on their understanding of climate science is a logical inclusion.

The quantitative portion of this study explores the following hypotheses:

- H1: CSL at the KD level in the early adolescent age group is different to the level of CSL at the KD level in the older adolescent age group *(H0: There is no difference in the CSL at the KD level between the early and the older adolescent age group)*
- H2: There is a difference in knowledge levels between each knowledge domain *(H0: There are no differences in knowledge levels among the knowledge domains)*
- H3: Demographic and personal-identity factors do not affect the performance in knowledge domains in the 12-13-year age group *(H0: Demographic and personal-identity factors do affect the performance in knowledge domains in the 12-13-year age group)*

4.3. Developing a prototype Climate Science Literacy framework

4.3.1. *Climate science literacy (CSL) – a definition for compulsory education*

In order to assess climate science literacy and ensure that efforts to improve climate science understanding in the public education arena are coherent, meaningful, and effective, we need to define CSL (Azevedo & Marques, 2017; Milér & Sládek, 2011). To begin with, we explore existing definitions for climate literacy broadly, and as distinct from a division of CSL as a specific knowledge base that is bounded to the physical and chemical mechanical processes that underpin our climate system, built upon their scientific disciplinary foundations. A widely used - and critiqued - definition of climate science literacy was developed by the US Global Change Research Program (USGCRP) and the National Oceanic and Atmospheric Administration (NOAA) through a series of workshops with contributions predominantly from US experts (Arndt & LaDue, 2008; Beaudoin, 2002; Harrington, 2008; Johnson et al., 2008; McCaffrey & Buhr, 2008; Niepold et al., 2008; Shafer, 2008; Uherek & Schüpbach, 2008). The USGCRP/NOAA's (2009) Climate Literacy: The Essential Principle of Climate Science proposes that climate science literacy 'is an understanding of your influence on the climate and climate's influence on you and society' and a 'climate-literate person understands the essential principles of Earth's climate system'. This definition is useful in that it encapsulates the complexity of climate change, drawing in interactions between human actions and the climate system (as with CSL guidelines proposed by Benchmarks for Science Literacy, 2009; The UNESCO Climate Change Initiative, 2010; Azevedo & Marques, 2017) and is regarded as 'the single most authoritative effort to define climate literacy' (Bedford, 2016, page 189). However, although the USGCRP/NOAA's definition has been widely adopted, it has been acknowledged 'the field is still taking shape and even the definition of climate literacy has not been uniformly established' (Clifford & Travis, 2018, page 2) and that climate literacy 'is a brand-new term and its meaning [in context with the USGCR's definition] has not been defined and agreed upon worldwide' (Milér & Sládek, 2011, page 151).

For the purposes of this research we propose a related, but specific, definition for Climate Science Literacy that is scoped to the physical processes that are fundamental to, and underpin, the mechanics of climate change that can be utilised in the classroom. In this way, we are centring the physical processes of climate change, and – distinct from broader climate literacy – scoping out the complex, dynamic and oftentimes emotive dimension of human influence on the climate system within a knowledge deficit context. A definition that focuses on climate science literacy (CSL) for the classroom, specifically, is needed – particularly if it is to be used outside the realm of politics (Kannan, 2019) and includes essential pedagogical considerations such as anchoring and worldview bias. In other words, the definition of CSL for the classroom needs to encompass the scientific processes, phenomena, and knowledge domains of climate science. This need has been identified by scholars who have examined the appropriateness of extant CL frameworks. In a review exploring the definition and conceptualisation of CL in the literature Azevedo and Marques' (2017) found that there were no papers that offered a climate literacy definition that included the condition for students 'to explain phenomena scientifically', in spite of the requirement for this in the PISA Science Framework (OECD/PISA, 2013). As the mechanics of climate change are fundamentally a science issue, and therefore ought to be positioned within science education, and 'if science education', according to Shepardson et al. (2011, page 482), 'is to promote a citizenry that is knowledgeable about global warming and climate change, it is essential to determine what students' conceptions are about the greenhouse effect, global warming, and climate change in order to plan curriculum and design instruction that builds on these conceptions'. In summary, we note the important, but often obscured, distinction between broad climate science literacy that engages with not only the scientific mechanisms of climate change but also impacts, future projections, social-political responses, and personal responsibility, and climate science literacy (CSL) for the classroom within in the PISA Science Framework, that is positioned specifically within science education and examines the physical/chemical mechanisms of climate change at the exclusion of complex social-political factors. We propose, therefore, that CSL for the classroom is '*a systematic and integrated understanding of how the natural climate system works, including drivers of natural variation, and the roles of feedback systems and anthropogenic emissions in driving climate change*'.

This research[11] supports Article 12 of the Paris Agreement that acknowledges the role of education as an important means to achieve the ambitious goals set by the United Nations Organisation (UNO) Climate Conference of the Parties (COP) and the United Nation Development Programme's (UNDP) Sustainable Development Goals (SDGs) 4: Quality Education; 5: Gender Equality; 11: Sustainable Cities and Infrastructure; and, 13: Climate Action.

4.3.2. *Including pedagogical design*

In developing a CSL framework for early adolescents, we must also consider pedagogical appropriateness. In particular this includes the protection of this age group from material or content that could be perceived as alarming or threatening. According to Ojala (2012b), 'many young people feel that the world may end in their lifetime' and 'learning about global problems can trigger feelings of worry, helplessness and hopelessness' in early young people. Recent research suggests that climate science should be initially introduced as a natural, mechanistic science (Ranney & Clark, 2016) – with a particular focus on causes rather than consequences (Clark et al., 2013; Mittenzwei et al., 2019; Shi et al., 2016) – as this provides students with the tools and skills to approach the issue as a mechanical, process-oriented problem and, according to Wolf and Moser (2011, page 551), understanding causes 'lays an initial foundation for directing people to the right kinds of mitigative actions'. Alongside this, and the interests of the students, Häussler & Hoffmann (2000) propose that students 'are interested in physics in the context of its practical applications, its potential to explain natural phenomena, or in the context of chances and risks which lie in physics-based technologies'. Based on these findings, CSL learning objectives for this age group should focus on the first component of the expanded CSL definition i.e. 'a systematic and integrated understanding of how the natural climate system works' and leave the remaining topics i.e. drivers of natural variation, the roles of feedback systems and anthropogenic emissions in driving climate change, until later years. In this way, not only do we approach climate communication and climate education on the physical science and causes 'ground-

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[11] In consideration of limits to journal space, alignment and support of the Sustainable Development Goals (SDGs) and Article 12 are inferred. For further clarification on the SDGs, please visit: https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals

floor', we provide context for engagement and an intellectual foundation on which stronger intellectual understanding as well as future mitigative or adaptive responses may take hold.

4.3.3. *Designing a curriculum framework: constructing knowledge domains*

Climate science, like any natural science subject, occupies specific, physical realms where certain phenomena take place. These physical domains describe the main scientific fields, i.e. physics, chemistry, biology etc., and are structured in our perception, according to Dewey (1960), as an 'organised experience'. This system of categorisation is further carried into education and allows educators to organise information into subjects, topics and 'knowledge domains'. For example, when preparing curricula for education, as observed by Bloom, 'most teachers begin by dividing the concepts and skills that they want students to learn into smaller learning units' (Guskey, 2015). These learning units, or 'knowledge domains', provide a framework to assess students easily, diagnose learning issues and prescribe corrective measures (Guskey, 2015). In addition, they provide a clear, coherent boundary around what a learner is expected to understand within a set time frame and, when adjusted to classroom practice, a limited curriculum that can be tested and graded and extend into the larger curriculum. We, therefore, define specific knowledge domains (KDs) as having clear, coherent boundaries around what a learner is expected to understand relative to their age group that form, when ordered by level of difficulty, the learning scaffold or framework of that scientific field or subject.

To develop a draft CSL framework, we deconstructed the entire climate science topic into three groups: 1. Natural climate system in equilibrium, 2. Natural variability/instability/feedbacks and 3. Anthropogenic impacts, evidence, mitigation and adaptation (Table 4.1, and described in detail below). These groups were then further deconstructed into 9 subgroups characterised by domain-specificity and then sorted by spatial scale. Since effective learning requires us to understand the causes before the consequences (Ojala, 2012a; Shi et al., 2016; Stamm et al., 2000) as well as considerations related to the emotional well-being of students (see previous section), the first four knowledge domains are based on the deconstructed causes and physical components (and respective spatial scales) within natural variability of the physical science basis (Table 4.1. Knowledge domains: see KD1-KD4). In other words, the first four knowledge domains scientifically describe how climate functions naturally without the input of anthropogenic emissions and adheres to the first part of the revised CSL definition that ‘climate science literacy is a systematic and integrated understanding of how the natural climate system works’. The following two knowledge domains (Table 4.1 Knowledge domains: see KD5-KD7) relate to natural variability, instability and feedbacks, and correspond to the CSL definition for ‘including drivers of natural variation, and the roles of feedback systems’. The remaining knowledge domains describe anthropogenic impacts and their consequences, evidence of climate change, mitigation and adaptation (Table 4.1. Knowledge domains: see KD5-KD9) and completes the requirements of the CSL definition: ‘anthropogenic emissions in driving climate change’. Since we cannot a priori define the relative learning progressions or levels of complexity within and amongst these knowledge domains to construct a suitable curriculum framework we term this stage of the framework the ‘preliminary’ curriculum framework. These levels of complexity are particularly important for teaching climate change as they ‘describe the increasingly sophisticated knowledge of core concepts that are, for example, needed for a better understanding of socio-scientific issues’ (Mittenzwei et al., 2019). To propose a ‘tested’ curriculum framework requires exploring how students perform in these knowledge domains, which we commence in this paper.

The content of the learning material (curriculum) was derived from a synthesis of the evidentiary basis of Earth’s climate system and the underlying mechanisms/processes that permit liquid water at Earth’s surface (Group 1: The Natural climate System in equilibrium), the natural drivers of climate change (Group 2: Natural variability/instability/feedbacks) and the role that human emissions play in climate change (Group 3. Anthropogenic impacts, evidence, mitigation and adaptation). Lectures and learning materials (online discussions, quizzes) were created and used in schools/universities at the primary, secondary and tertiary level in Austrian and Danish high schools and universities (I.H.S). The teaching experience ensured the content was comprehensive, age-appropriate and linked to the required curriculum and, when used in practice, could be used to make trans- and inter-disciplinary links between each knowledge domains as well as domain-to-domain links. While it may be argued that this approach may seem ‘cold’ in the sense that it is being ‘driven solely by logic and scientific findings’ (Pintrich, Marx, & Boyle, 1993, page 170), knowledge domains also allow us to construct ‘scenes’ upon which narratives and conceptual understanding can be constructed – segueing along the inter- and trans-disciplinary connections between each knowledge domain. This approach, according to Kaiser and Fuhrer (2003) allows the different forms of knowledge to work together in a convergent manner, such that the various threads of knowledge can be woven together into a whole.

As the scientific basis for each of the knowledge domains will differ, given the breath of disciplines that underpin these KDs, it is to be expected that some KDs are more challenging than others. When the knowledge domains are then sorted into their level of difficulty for the climate science subject (and become the 'tested' CSL framework), they form a proto-narrative which may assist in the development of pedagogies, curriculum design and assessment rubrics. Critically, since CSL should be tailored to the ability of the learner (Milér & Sládek, 2011), the sorted levels of difficulty provide a sign-posted map for learning/competence progression which allows the learner to start at 'square one' and gradually improve competence and understanding over time (Brabrand & Dahl, 2009). This is additionally important because, according to McNeal et al. (2014, page 210), learners 'require an ability to engage in systems thinking to understand climate change'. By starting off with simple constructs, learners can build up a more-complex mental model of the system and integrate incoming ideas with mental models they have already constructed.

Furthermore, since natural science topics correspond to physical domains, they translate well into learning narratives, curriculum creation and pedagogical design which can assist learners in explaining climate phenomena scientifically, as outlined in the PISA science framework (OECD/PISA, 2013).

4.3.4. The knowledge domains

Here we outline in detail the content included across the Knowledge Domains (KDs) in this research. The first four knowledge domains, which describe the natural climate system in equilibrium (Table 4.1. Knowledge domains: see KD1 to KD4), are arranged from largest to smallest spatial scale based on the phenomena encompassed. The first knowledge domain (10^{10} to 10^{7} meters (m)) relates to the comparison of Earth to other rocky planets in our solar system, the presence of liquid water and the place of Earth within that system (KD1). The second knowledge domain (10^{5} to 10^{7} m) describes the properties of, and/or phenomena, in the Earth's troposphere, stratosphere, mesosphere, thermosphere and exosphere (KD2). The third knowledge domain (10^4 m) explains the role of albedo in regulating Earth's Global Mean Surface Temperature (GMST) and the interaction of radiation (solar and infrared) with greenhouse gases (KD3). The fourth knowledge domain (10^{-10} m) illustrates the molecular characteristics, structure, concentration/abundance, global warming potential, overall warming effect, and the reaction of Greenhouse Gases (GHG) to infrared radiation in order to generate heat (KD4).

Two additional knowledge domains are then added when we include natural drivers of climate variability, feedbacks and climate instability (Table 4.1. Knowledge domains: see KD5 and KD6). The fifth knowledge domain relates to the natural drivers of climate variability including Milankovitch cycles, carbon cycle, solar irradiance, volcanoes, to name but a few (KD5). The sixth knowledge domain describes the influence of positive and negative feedbacks in the climate system and how system instability (loss of equilibrium) reinforces instability and amplifies risk and uncertainty (KD6).

The remaining knowledge domains comprise amplified or anthropogenic influences and evidence thereof, the consequences of these influences to the natural variability of the climate system and the solutions, engagement and social transitions that are necessary to achieve emission reduction and climate stability (Table 4.1. Knowledge domains: see KD7 to KD9). The seventh knowledge domain encompasses the influence of humans on the climate system (e.g., industry, business-as-usual, political, economic, social and cultural systems, decision theory, psychology, public health, education, and communication) and the essential role humans play in emissions increase (KD7). The eighth knowledge domain investigates the collection of proxy and empirical evidence that have contributed to our current understanding of past and present climate change (KD8). The final knowledge domain examines pathways and solutions for emission reduction including technological solutions (renewable, clean and nuclear energy), mitigation and adaptation strategies and strategies (at the individual and societal level) for engagement, action competence and pathways to zero-emission lifestyles (KD9).

Table 4.1: Overview of the preliminary curriculum framework and associated knowledge domains – note: arranged in order of spatial scale, i.e. untested but including early adolescent pedagogical design

	KD code	KD title	KD – domain description	Scientific field
Natural climate system in equilibrium	KD1	Earth and water in the Solar System	Earth and its comparison to other rocky planets in our solar system, the presence of liquid water and the place of Earth within that system	Astrophysics
	KD2	Earth's atmosphere	The effect of gravity on Earth's atmosphere and the characteristics, properties, and/or phenomena in the troposphere, stratosphere, mesosphere, thermosphere and exosphere	Atmospheric chemistry and physics
	KD3	Albedo	the role of albedo in regulating Earth's global mean surface temperature (GMST) and the influence of radiation (solar and infrared) on greenhouse gases; cryosphere including ice sheet variation	Physics: thermodynamics
	KD4	Greenhouse gases as molecules	Described the molecular characteristics, structure, concentration/abundance, global warming potential, overall warming effect, and the reaction of Greenhouse Gases (GHG) to infrared radiation in order to generate heat	Chemistry, Physics
Natural variability/ instability/ feedbacks	KD5*	Natural drivers of Climate variability	Milankovitch cycles; carbon cycle; solar irradiance; volcanoes; ocean currents; tectonic activity; alterations in albedo; greenhouse gases abundance; ocean and terrestrial uptake of CO_2; vegetation coverage; meteorite impacts	Astrophysics, earth science,
	KD6*	System feedbacks and instabilities	Climate-changing feedback systems with a focus on evaporation of sea water as well as the physical science basis of positive and negative feedbacks and system instability (loss of equilibrium)	Physics, Chemistry
Anthropogenic impacts, evidence, mitigation and adaptation	KD7*	Anthropogenic emissions	Anthropogenic emissions and the effect on climate stability – including consequences such as sea level, global surface temperature, effect on climate feedback systems	Economics, politics, social sciences, physics, chemistry, thermodynamics
	KD8*	Evidence of climate change	Proxy and empirical evidence of climate change as well as the evidence of our influence on climate change	Geology, Geography, Physics, Chemistry, Biology, Palaeontology, Paleoclimatology
	KD9*	Climate solutions	Anthropogenic mitigation of, and adaptation to, greenhouse gas emissions; including technological, economic and political instruments	Technology, social science, politics, economics

*Not included in this research

4.4. Methods

To achieve these aims, a questionnaire was created based on a previous survey that was conducted in high schools in Austria and Denmark in 2011 (Harker-Schuch & Bugge-Henriksen, 2013). This questionnaire was administered as part of a larger research project examining the role of serious-gaming interventions to improve CSL in the 12 to 13-year-age group and undertaken within the scheduled science class time (45-50 minutes). All requirements from the regulating authorities were met. The research was conducted in accord with ANU ethics protocol 2015/583.

4.4.1. *Schools and students*

The research catchment criteria were selected as being within a 10 km radius of the central business district and being categorised as an inner-city public high school. Since the research was subject to approval from the residing school director and the supporting staff, willingness to participate decided which schools would be involved. With these requirements, 6 high schools, two each in Vienna (Austria), and Sydney and Canberra (Australia) agreed to participate in this research – coded as VHS 1 and 2, SHS 1 and 2 and CHS 1 and 2, respectively. All schools had a state-regulated curriculum and taught in the native tongue of their respective nationalities, i.e., English in Australia and German in Austria). Vienna, Austria, and Sydney and Canberra, Australia, were included in the study because (a) the lead researcher had access to Vienna high schools based on prior research with them (Harker-Schuch & Bugge-Henriksen, 2013), (b) the Australian government funded the study, and (c) the Sydney and Canberra high schools had established relations with the Australian National University and existing research relationships.

The students were all in the first year of secondary school and were 12-13 years of age. In total, 901 students took part in the CSL survey with 465 (n=212, 45.6%) females, (n=246, 52.9%) males, and other (n=7, 1.5%) – being eligible for final inclusion and analysis. Inclusion depended on parental and student approval, participation in the study and valid responses to the questionnaire. It is worth noting, also, that while nearly all permission notes for the Austrian students were returned, more than half refused permission. For Australia, nearly all returned forms gave permission but up to half of all potential participants did not return notes at all. A more detailed breakdown cannot be reported due to privacy concerns. Whether this was in lieu of a refusal, lost or misplaced permission notes, lower parental engagement, a social norm in Australia, low support from the participating science teacher or a multitude of other reasons; we can only speculate.

Due to privacy laws, we are not able to provide precise demographic information that would make identification of the participants or their schools possible. However, some useful background information can be provided (Australian Bureau of Statistics: 2016 Census QuickStats, 2016; Stadt Wien - Statistisches Jahrbuch Der Stadt Wien 2017, 2017) that offers both context and assists in interpreting and discussing the findings without conflicting with privacy law requirements. From a district perspective, Sydney (27.6/ha) and Canberra (15.9/ha) have a lower population density than in Vienna (176/ha) and a lower proportion of adults with minimum-requirement education ~16 years. The jurisdictions for both participating Vienna high schools (VHS1 and VHS2) as well as a participating Canberra high school (CHS2) all had far higher non-mandatory secondary levels of education (~18 years). The jurisdictions for both participating Canberra schools (CHS1 and CHS2) and one of the Sydney high schools (SHS1) all had considerably higher tertiary levels of education (Bachelor or above). The catchment for CHS1 had the lowest level of unemployment. The participating Canberra high schools also had higher percentages of participants born in the country than Sydney or Vienna and have lower net migration. In VHS2, it was reported by the director that the school had a very high number of new immigrants as a result of the higher-than-usual migration influx to Europe that increased incoming refugees 7-fold in Vienna from approximately 12,000 in 2008 to 88,000 in 2015 (European Commission: EUROSTAT, 2018) which, in their opinion, was the cause of the high rate of permission refusal at their school.

4.4.2. Questionnaire

Based on a previous climate science survey used to investigate CSL in 16-17-year olds (Harker-Schuch & Bugge-Henriksen, 2013), this questionnaire (Appendix V) was adapted for the early adolescent age group to further explore knowledge related to the physical climate science basis (mechanism and processes that describe the natural climate system in equilibrium) and to extract a detailed overview of CSL relative to that age group.

In total, there were 19 science questions that encompassed the natural climate system in equilibrium basis of climate science delineated into KDs 1-4. While the most significant aspects of natural climate system were covered, questions on the drivers of natural climate variability and feedbacks were not included (See Table 4.1, KD5 and KD6, respectively), in order to anchor the physical/chemical mechanisms that describe Earth's climate system in equilibrium and to fit the scientific content to the cognitive level of the candidate age group. As discussed previously, aspects related to anthropogenic emissions (KD7), evidence of climate change (KD8) and climate solutions (KD9), which complete the climate science topic, were not included as they were also considered beyond the intellectual and emotional scope of this age group and may induce unwelcome emotional responses. Since KD5 introduces and teaches feedbacks, we may assume that an understanding in the basic processes (without instability/variability) is necessary before introducing effects that alter equilibrium. For KD6 to KD9, research in young people regarding their emotions about climate change, as was discussed previously, strongly suggests that teaching the impacts of climate change needs to be at a time when they are emotionally ready to manage them. Establishing a solid scientific understanding of the physical science basis of the natural climate system in equilibrium provides an intellectual foundation upon which solutions, innovations, and critical thinking may be anchored – in a similar way that 'grounding' works to overcome anxiety.

Within each of the areas listed above the questions were scaled into anticipated levels of complexity (later to be restructured depending on student performance) to determine how well each respondent understood the subject according to the Structure of Observed Learning Outcomes (SOLO) taxonomy of Biggs and Collis (1982) and to prepare domain-specific learning objectives (LOs). The SOLO taxonomy is a model or taxonomy that classifies a student's learning outcomes into three groups (surface knowledge, deep knowledge and conceptual knowledge). These three groups are shared across 5 levels of complexity: pre-structural, uni-structural, multi-structural, relational and extended abstract. By positioning the questions and answers on these 5 levels of complexity, we are able to obtain a highly-nuanced overview of where students' strengths and weaknesses lie as well as position their existing knowledge within a level of complexity. This is useful for both teachers and learners. For example, it allows teachers to establish prior knowledge, construct LOs, create effective lessons plans (those that start at the basic level for that topic and become increasingly difficult), targeted assessment with specific feedback on a student's performance, and to improve their teaching where shared knowledge gaps prevail. From a student perspective, the SOLO taxonomy provides students with LO which allow them to self-regulate, coordinate their learning, and easily identify their knowledge strengths and weaknesses as they progress through the material. The levels of complexity also provide a structure for critical thinking insofar that level 4 of the taxonomy links to other knowledge domains and represents 'systems thinking', which is a requirement for understanding climate science (McNeal et al., 2014). An example of the SOLO taxonomy for KD3 (Albedo) and the associated LO shows (Table 4.2) the structure of four of the five levels of complexity excluding 'pre-structural' as this level represents the start of the learning journey) and the order of increasing level of difficulty.

In order to gain insight into the spread of prior knowledge across the KDs, on many questions we elected to adopt an answer design that allowed for differing levels of 'correctness' on a single question, rather than a binary correct/incorrect response. Accordingly, the answers for some multiple-choice had multiple correct answers (four out of eight, arranged randomly) (see Appendix V) while other questions with 5 possible answers were scaled (arranged randomly). The scales answers were designed upon the 'plausibility of distractors' as described by the OECD assessment guide, 'Measuring Student Knowledge and Skills: A New Framework for Assessment, 1999, in order for respondents to demonstrate their understanding of increasing complexity. Most answers offered a score of 0%, 25%, 50%, 75%, 100% with two questions at the pre-structural level (SOLO Taxonomy level 1) offering only a right or wrong outcome. In this way we were better able to determine how well a certain aspect of climate science were understood (i.e., beyond a correct/incorrect binary). The careful construction of this questionnaire allows us to extract proficiency signals from each student's responses – and to compare KDs with one another. While the questionnaire was intended to be an intellectual challenge for the students, we attempted to alleviate survey fatigue by also including visual and drag-and-drop questions.

Table 4.2: SOLO Taxonomy (ST) and associated learning objectives (LO) example for Albedo

	ST Level 1 **(Unistructural)**	**ST Level 2** **(Multistructural)**	**ST Level 3** **(Relational)**	**ST Level 4** **(Extended abstract)**
Learning objectives:	1) Identify the warming effect of solar radiation on a dark or light surface 2) Describe regions with high albedo	Describe albedo and how it is expressed as a scale	Compare and contrast the interaction of radiation (solar and infrared) with greenhouse gases	Express albedo as a scale on Earth's energy system as an influence on warming

Low difficulty → High difficulty

Increasing level of complexity

In a parallel study involving older adolescents in Australia and Norway (16-18 years; n=99), the same questionnaire was used to determine CSL and knowledge strengths and weaknesses; Harker-Schuch and Watson (2019) reported a CSL score of 51.1% (Table 4.3) in the older age group for the same KDs and showed that knowledge strengths and weaknesses are shared across countries. These findings from prior research provide us with a value to which we can compare the early adolescents in the present study and evaluate the robustness of the findings.

Table 4.3: Descriptive values for each knowledge domain (sum of multiple questions within that KD) and overall CSL for older adolescents (mean value for 19 questions); 95% CI; data derived from KDs 1-4, Harker-Schuch & Watson (2019)

		Earth and water in the Solar System: **KD1 Mean (95% CI)**	**Earth's Atmosphere:** **KD2 Mean (95% CI)**	**Albedo:** **KD3 Mean (95% CI)**	**GHG's as molecules:** **KD4 Mean (95% CI)**
Older adolescents	**Individual question scores for each KD**	62.4 (58.1-66.7)	25.3 (20.1-30.43)	49.2 (42.9-55.6)	42.7 (35.3-50.1)
		55.3 (51.3-59.3)	38.8 (31.2-46.3)	56.3 (46.6-56.5)	54.6 (47.8-61.3)
		51.3 (48.0-54.6)	62.9 (59.1-66.7)	45.2 (38.3-52.1)	66.4 (62.8-70.0)
		68.9 (64.8-73.1)	20.9 (18.5-23.3)	56.8 (49.4-64.2)	47.5 (40.5-54.5)
		66.7 (63.0-70.4)		64.4 (57.3-71.5)	51.0 (47.1-54.9)
	Mean KD score (KD CSL level):	60.9 (58.9-62.9)	36.6 (33.6-39.5)	54.4 (50.9-58.0)	52.42 (49.7-54.9)
	Upper secondary Climate Science Literacy (CSL):			**51.1**	

4.5. Analysis

Climate science literacy (CSL) was obtained by combining the score(s) of each question, divided by the number of participants (*n* =465) and then summing these results for all questions in each knowledge domain and dividing by the number of questions in each knowledge domain. The overall CSL was then the sum of each knowledge domain score divided by the number of knowledge domains.

4.5.1. Statistical methods

To investigate differences in each overall knowledge domain score, we conducted linear regression (IBM SPSS statistics 23.0) between each of the groups: 'KD1', 'KD2', 'KD3' and 'KD4' as well as for school ('School'), gender ('Gender'), and subject preference ('Sub_Pref'). A t-test was conducted for differences between each country ('Country').

The overarching analysis approach, therefore, consisted of the following stages:

1. Descriptive values for overall CSL as defined by the knowledge domains (KDs).
2. Independent t-test was conducted to determine the significance of differences between countries.
3. Oneway ANOVA was conducted to determine differences between each KD.
4. Oneway ANOVA was conducted to determine the differences, respectively, between schools, genders, and subject preferences for each KD.

4.6. Results

4.6.1. Descriptive values for overall climate science literacy as defined by the KDs

Descriptive values are presented to provide an overview of CSL in the 12-13-year age group, as defined by the KD learning units. Data are presented as mean + 95% confidence interval (CI). The mean KD score in each column (Table 4.4) corresponds to the mean value of each KD as derived from the 19 climate science questions: 5 for KD1: 'Earth and water in the Solar System', KD3: 'Albedo' and KD4: 'GHGs as molecules'; 4 for KD2: 'Earth's atmosphere' and represents the CSL level for each KD (KD CSL level). Our analysis indicates that KD climate science literacy (KD CSL) is 47.3% (n = 465) in the 12-13-year age group as a mean of the specific knowledge domains (KDs). There were no outliers and the data was normally distributed with skewness of -.172, (SE=.057) and kurtosis of -.594 (SE=.113), respectively, but there was heterogeneity of variances ($p = <.001$) as assessed by Levene's Test of Homogeneity of Variance ($p = <.001$) when all domains were compared to one another.

Table 4.4: Descriptive values for each knowledge domain (sum of multiple questions within that KD) and overall climate science literacy for early adolescents in the 12-13-year age group; 95% CI

		Earth and water in the Solar System:	**Earth's Atmosphere:**	**Albedo:**	**GHGs as molecules:**
		KD1 Mean (95% CI)	**KD2 Mean (95% CI)**	**KD3 Mean (95% CI)**	**KD4 Mean (95% CI)**
Early adolescents	**Individual question scores for each KD**	63.0 (61.2-64.9)	26.3 (24.1-28.4)	33.0 (30.8-35.2)	39.3 (36.5-42.6)
		57.3 (55.6-59.1)	43.8 (40.4-47.1)	49.7 (45.1-54.2)	46.2 (43.1-49.3)
		52.6 (50.8-54.5)	28.9 (27.7-29.5)	47.4 (44.2-50.6)	66.8 (64.9-68.7)
		66.4 (64.7-68.1)	22.9 (21.7-24.1)	48.5 (45.3-51.7)	48.8 (45.6-52.0)
		65.7 (64.0-67.4)		58.3 (55.2-61.4)	51.3 (49.6-52.9)
	Mean KD score (KD CSL level):	61.0 (60.0-62.0)	30.4 (29.3-31.6)	47.4 (45.9-48.9)	50.5 (49.3-51.6)
	Early adolescent Climate Science Literacy (CSL):				**47.3**

4.6.2. *Differences between early and older adolescence*

When we compare early adolescents ($n = 465$, CSL = 47.3%) to older adolescents ($n = 99$, CSL = 51.1%) using the independent t-test for independent samples (Table 4.5), we find statistically significant differences for CSL at the KD level between these two age groups for KD2: 'Earth's atmosphere' (early adolescents: Mean=30.40, SD=13.0; older adolescents: Mean=36.55, SD=13.8) and KD3: 'Albedo' (early adolescents: Mean=47.37, SD=16.4; older adolescents: Mean=54.44, SD=17.9) but no statistically significant differences between KD1: 'Earth and water in the Solar System (early adolescents: Mean=61.01, SD=10.7; older adolescents: Mean=60.91, SD=10.2) and KD4: 'Greenhouse gases as molecules' (early adolescents: Mean=50.47, SD=12.9; older adolescents: Mean=52.42, SD=13.4) when equal variance is not assumed.

We, therefore, partially reject the null hypothesis (H1) that there is no similarity between early and older adolescents in CSL at the KD level.

Table 4.5: Comparison of CSL at the KD level between early adolescents and older adolescents

	Early adolescents		**Older adolescents**				
	Mean	**SD**	**Mean**	**SD**	**Mean Diff**	**t**	**p**
KD1	61.0	10.68	60.9	10.161	-0.1	0.09	ns
KD2	30.4	13.032	36.6	14.846	6.14	-3.813	<.001***
KD3	47.4	16.404	54.4	17.87	7.07	-3.626	<.001***
KD4	50.5	12.873	52.4	13.446	1.95	-1.321	ns

***$p < .001$, **$p < .01$

4.6.3. *Differences between countries*

Differences between countries were analysed using the Independent t-test for paired samples. There was no significant difference between countries (Table 4.6) when equal variance is not assumed for three of the four KDs: KD2, KD3, and KD4. In KD1: ‘Earth and water in the solar system’ Australian students scored higher (Mean=61.61, SD=10.83) than students in Austria (Mean=58.27, SD=9.55) (p=.009).

Table 4.6: Comparisons of mean KD scores. Country: mean for all schools in that country

	Austria (mean=46.27)		**Australia (mean=47.55)**		***Mean Diff***	***t***	***p***
	Mean	**SD**	**Mean**	**SD**			
KD1	58.3	9.55	61.6	10.83	-3.34	-2.829	.009*
KD2	31.9	14.09	30.1	12.78	1.87	1.123	ns
KD3	44.9	18.16	47.9	15.96	-3.04	0.050	ns
KD4	50.0	14.79	50.6	12.43	-0.58	-0.333	ns

**$p < .01$

4.6.4. *Differences between knowledge domains*

Differences between KDs were analysed using Oneway ANOVA. Results from the Welch ANOVA (Welch, 1947) were used to look for significant differences in the population due to the heterogeneity of variance. Welch ANOVA showed there were statistically significant differences between the KD scores (Table 4.7), Welch's F (3, 1021.342) = 515.734, $p < .001$. Results from the Games-Howell post hoc analysis were used to define where the differences lay; revealing statistically significant differences between all KD Scores: KD1: ‘Earth and water in the Solar System’ (Mean=61.01, SD=17.3), KD2: ‘Earth’s atmosphere’ (Mean=30.40, SD=13.0), KD3: ‘Albedo’ (Mean=47.37, SD=16.4) and KD4: 'GHGs as molecules' (Mean=50.47, SD=12.9) therefore rejecting the null hypothesis (H2) that there are no differences among knowledge domains.

Table 4.7: Differences between KDs

	KD1		KD2		KD3		KD4	
	Mean Diff	**SE**	**Mean Diff**	**SE**	**Mean Diff**	**SE**	**Mean Diff**	**SE**
KD (score)								
KD1 (61.01)	-	-	-30.6***	.781	-13.6***	.908	-10.5***	.776
KD2 (30.40)	30.6***	.781	-	-	17.0***	.971	20.1***	.849
KD3 (47.37)	13.6***	.908	-17.0***	.971	-	-	3.1**	.967
KD4 (50.47)	10.5***	.776	-20.1***	.849	-3.1**	.967	-	-

****p* < .001, ***p* < .01

4.6.5. Comparison between Knowledge Domains for school, gender and subject preference

Oneway ANOVA analysis of KDs was conducted to determine differences in KDs as a function of school, gender and subject preference. Levene's test for homogeneity of variance indicated there was equal variance within each KD. The analysis indicated there were differences in mean in relation to school, gender, and subject preference in KD1: 'Earth and water in the Solar System' and KD2: 'Earth's atmosphere' but no effect of these variables in KD3: 'Albedo' and KD4: 'GHG's as molecules'.

For KD1: 'Earth and water in the Solar System' there were no differences for gender and subject preference. There was, however, an effect of school (Figure 4.1) with both CHS1 (Mean=62.90, SD=10.979) and CHS2 (Mean=64.01, SD=11.875) performing significantly better at α = .001 than VHS1 (Mean=56.10, SD=9.013) and SHS1 (Mean=59.80, SD=9.982). CHS1 and CHS2 also indicated a significantly higher results than SHS2 (Mean=60.0, SD=9.825).

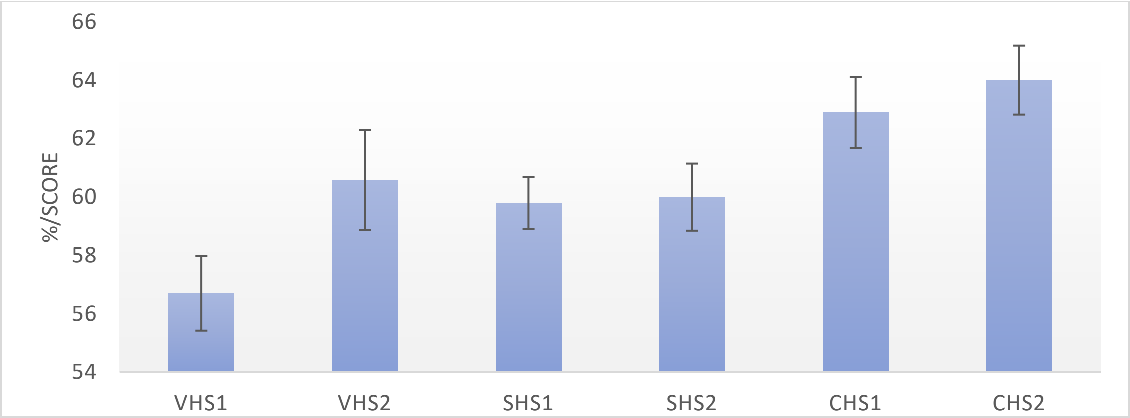

Figure 4.1:School scores in KD1. y-axis showing range 54-66% for clarity. Whiskers are 95% CI.

For KD2: ‘Earth’s atmosphere’, gender and subject preference showed statistically significant differences with males (Mean=32.06, SD=13.784) scoring significantly higher than females (Mean=28.60, SD=11.895) (p =.013) (Figure 4.2) and students interested in science (Mean=36.06, SD=16.360, p = 0.024) and social science (Mean=39.90, SD=16.204, p=0.020) (Figure 4.3) scoring significantly higher than students in other subjects. There was no effect of school on performance. We, therefore, partially reject the null hypothesis (H3) that demographic and personal-identity factors do affect the performance in knowledge domains in the 12-13-year age group.

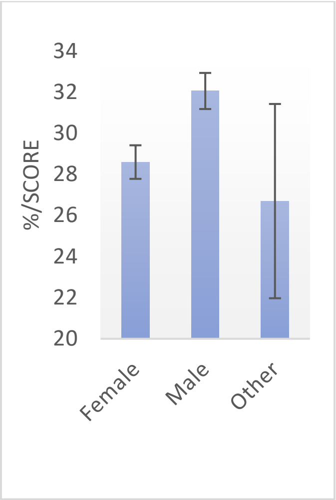

Figure 4.2: Effect of Gender on KD2 score. y-axis range between 20-35% for clarity

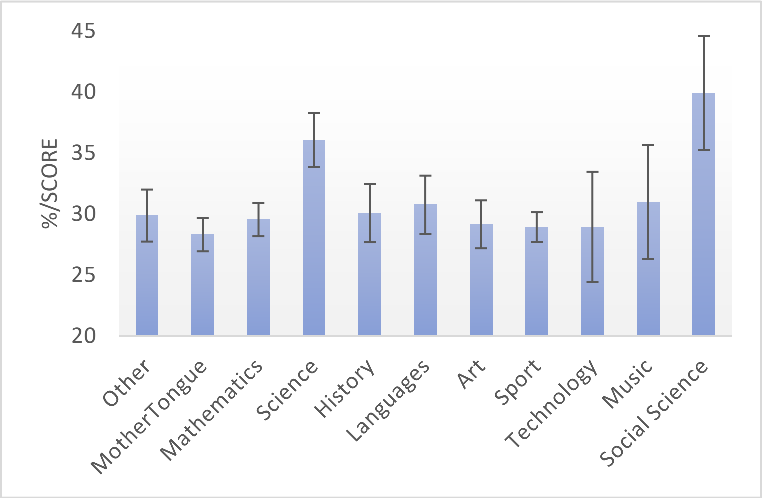

Figure 4.3: Effect of Subject Preference on KD2 score. y-axis range between 20-45% for clarity.

4.7. Discussion

This study explored the climate science literacy of 12-13-year olds as a starting point for knowledge deficit interventions. We quantified how well 12-13-year olds understand the physical basis of climate science and where the specific knowledge strengths and weaknesses lay as a base on which to construct a tested CSL framework.

Overall, we find that Climate Science Literacy (CSL), measured as a mean of specific knowledge domains as suggested by Shi et al. (2016), is 47.3% in the 12-13-year age group in inner urban areas in Austria and Australia, when our questionnaire is used as a measurement tool. This result describes the CSL of this age group without any specifically-designed CSL knowledge intervention.

In comparison to a study of upper secondary students using the same survey questionnaire (Harker-Schuch & Watson, 2020), we find overall CSL to be similar between lower (47.3%) and upper secondary (51.1%) in spite of the likelihood that older adolescents may have had longer exposure to such concepts. Our results also indicate that there are differences between the knowledge domains and, similarly to the findings of Harker-Schuch and Watson (2019), some knowledge domains are better understood than others. Other studies exploring overall CSL in older age groups also report similar findings. For example, a CSL score of 48.5% was reported for an empirical study in 16-17 year olds in Austria and Denmark (Harker-Schuch & Bugge-Henriksen, 2013) and a CSL score of 40.8% was reported for an empirical study in 13-15-year olds in the US (Bodzin & Fu, 2013). Without a standard for assessing CSL or an established CSL framework, however, these findings provide context but are not comparable. When we compare performance at the KD level between early and later adolescence (Table 4.5), we find mixed results. For those KDs where both groups performed well (KD1: ‘Earth and water in the Solar System’ and KD4: ‘Greenhouse gases as molecules’), we find no differences in CSL at the KD level between both groups. For the KDs where knowledge is less well understood (KD2: ‘Earth’s atmosphere’ and KD3: ‘Albedo’), we find small, but significant differences, in CSL at the KD level between early and later adolescents. In spite of the differences in KD2 and KD3 between early and older adolescents, there are commonalities in these results that indicate shared strengths and weaknesses i.e. similar levels of increasing complexity, which suggests that CSL does not greatly improve from the age when students are first able to cognitively process the material to the period when they are on the verge of their emergence into society. This finding suggests that current efforts to improve CSL in the secondary school system may not be effecting any great change at all – which is particularly worrisome when the earlier age group already show significant concern about this issue.

The knowledge domains have been constructed to be largely independent of each other, i.e., KD2 does not depend on KD1 and can be taught separately, they build toward the knowledge domain ‘sum’ of climate science. When we order the KDs from those that appear to be easiest to understand to those that are most difficult based on the tested results, a progressive learning CSL framework based on Biggs and Collis’ ‘cumulative construction’ takes shape that aids knowledge development (Biggs &

Collis, 1982). By ordering the KDs based on complexity, we provide a basis for competence Learning/progression; that is, students begin the topic at a level which is easier to understand or master (relative to their intellectual abilities) and constructively complete the topic by gradually increasing the levels of difficulty (Brabrand & Dahl, 2009).

In short, we propose that, when teaching the physical science basis of climate science (as recommended by Clark et al., 2013; Mittenzwei et al., 2019; Ranney & Clark, 2016), teachers should start with the ‘Earth and water in the Solar System’, followed consecutively by ‘GHGs as molecules’, ‘Albedo’ and, finally, ‘Earth’s atmosphere’. We further propose that the physical science basis should be introduced when students enter lower secondary school in order to minimise the influence of worldview bias and assist these learners in establishing a fact-based foundation on which to construct informed climate change attitudes.

We also undertook several analyses that interrogate associated dimensions of CSL delivery, including comparisons between demographic variables. In light of the very strong knowledge commonalities between the two country groups, education efforts could benefit from these shared starting points. The knowledge commonalities suggest that, for these countries at least, knowledge deficits persist across culture, language and geography. Testing these findings with further research is a necessary next step. While this result is compelling for the creation of a global CSL framework, replication of this study in other socio-cultural/-economic/-political systems is vital to elucidating the validity and dynamics of such an endeavour.

When we evaluate the results of the influences on the different knowledge domains, we see influences of country, school, gender, and subject preferences – but only on two of the four KDs (KD1 and KD2) and no factor significantly influences more than one KDs. Since there are no consistent patterns across all KDs, there is little value in discussing these influences in greater detail.

Although we would have expected an influence of survey fatigue on the results of the climate science questionnaire, due to both the difficulty of the questionnaire and the large number of questions, we found scores improved as students progressed through the questions – particularly in the last section of the questionnaire. Arguably, there may be an inherent bias in the research instrument that made some KDs easier to understand than others, i.e. the questions themselves may have subconsciously been designed to be easier to understand than others. However, both the nuance of the answers (i.e. scaling) and the SOLO structure of the questions mitigate this effect. With each question, we obtained very specific responses which minimize questionnaire design bias and, in conjunction with this, each KD is sorted according to a level of complexity. In this way, we are better able to harmonise the relative value of each KD.

4.7.1. The tested climate science literacy (CSL) framework

Based on the results of this study, we propose a tested CSL framework (see Appendix VII for full framework) for 12-13-year olds that is structured on examined 'level of complexity' results, according to Biggs and Collis (1982). KD1: 'Earth and water in the Solar System' with a KD CSL mean score of 61.01, remains as the first (easiest) KD and becomes KDI: 'Earth and water in the Solar System'. KD4: 'GHGs as molecules' with a KD CSL mean score of 50.47 is ranked second and becomes KDII: 'GHGs as molecules'. KD3:'Albedo', with a KD CSL mean score of 47.37, remains as the third KD and becomes KDIII: 'Albedo'. KD2: 'Earth's atmosphere' with a CSL mean score of 30.41, is ranked fourth becomes the KDIV: 'Earth's atmosphere'. While our results indicate there are statistically significantly differences in knowledge levels among all KDs, the new KDII (50.47%) and KDIII (47.37%) could be swapped with one another due to the similarity of their scores. The new ordering of the KDs ensures that students are presented with the easiest material at the beginning and can then tackle the more complex and intellectually-demanding material as they progress through secondary school. While the new sequencing may present some narrative challenges, we suggest that these KDs are taught individually, and staggered over time, so that a solid, integrated understanding of climate science can be cultivated which reinforced the 'practice and drill' mechanism for learning (Lim et al., 2012). At the time of submission (March, 2020), four individual 3D interactive games corresponding to the 4 KDs are in production which all have a shared story-arc with a strong focus on inter-disciplinarily, priming material i.e. content that prepares a learner for upcoming KDs, and alignment with curriculum standards e.g. Earth and water in the Solar System is a topic that is typically taught in early adolescence.

These findings largely reflect the results from the parallel study in upper secondary and demonstrate a similar arrangement of KDs (Harker-Schuch & Watson, 2020) with the exception (and, again, similar scores) that KDII (52.42%) and KDIII (54.44%) swap positions in the framework for upper secondary.

This CSL framework provides teachers, pedagogues and those concerned with learning design for climate science communication and education a clear guideline and plan on what to teach and when. Not only does this framework deliver intellectually appropriate material to the relevant learner, it provides a foundation on which to test, design and structure CSL frameworks for all learners. With regard to the more detailed CSL definition that we propose, this CSL framework delivers the first part of CSL for the classroom, i.e. ‘a systematic and integrated understanding of how the natural climate system works, which forms the foundation for further knowledge development in older age groups; specifically, 'drivers of natural variation, the role of feedback systems and anthropogenic emissions in driving climate change'.

4.7.2. Limitations and considerations

As with all studies, there are several limitations to note. The first relates to heterogeneity of sampling in that, while the schools were located in inner urban centres, the sample of students may not be indicative of the general population and may not, therefore, be a representative sample. As highlighted by the demographic data, there are differences between these schools. However, while demographic differences exist in many urban communities, we may expect that there are larger, shared commonalities.

Conversely, the second factor relates to homogeneity of sampling in that the participation of the schools themselves and agreement from parents may affect responses (selection bias) as they belong to inner-city, urban centres and the participation of the school requires that science teaching staff and parents respond favourably to the research project. This response may be an example of echo chambers (Lewandowsky et al., 2012). Students are frequently influenced by their teachers’ worldviews and, with the role of worldview so pernicious, further research is warranted for this age group and in a broader socio-political context. As highlighted by Busch, permission to conduct research in climate change education is often difficult (Busch et al., 2019), and the loss of the students who did not take part cannot be overlooked. Without their participation, we cannot know if their refusal to join the project reflected their beliefs about climate change or other factors. Understanding this age group will require the input of all participants – a circumstance that is, in the practice of early adolescent research, devilishly difficult to achieve.

The third factor relates to the difficulty of the questionnaire which, from a student perspective, is complex, strict and (quite likely) highly advanced for that age group. It was, however, necessary to test student performance in all KDs spanning the physical science basis of climate science to obtain a thorough overview of their knowledge strengths and weaknesses (upper and lower knowledge thresholds) in order to establish a CSL baseline. Future research will elaborate on these findings and further explore the definition of CSL as a function of knowledge, attitude and engagement – expanding the sample to include other demographics outside inner urban settings.

Finally, the construction of the research instrument may affect overall findings insofar that it is the most comprehensive to date to explore knowledge related to the entire realm of the physical climate science basis (mechanism and processes that describe the natural climate system in equilibrium) in the early adolescent age group and, therefore, lacks precedent. For example, there may be gaps in the KDs due to data collection time constraints or omission of important material in the questionnaire. Since CSL efforts should aim to improve CSL throughout secondary school, the KDs should be separated and expanded upon with further research testing key competencies in the early adolescent age group (with revised KDs and revised research instrument) and further investigation in how CSL and revised KDs are understood in older age groups, also. Further revision, testing and service of this instrument will provide more context and additional testing of its validity.

While this age group demonstrates a solid understanding of some aspects of climate science i.e., Earth and water in the Solar System, they may lack key competences in other aspects of climate science including knowledge related to energy budgets, carbon and energy sources and sinks, radiation transfer, and the statistical benefits of spatial and temporal averages. However, this age group is not expected to grasp all the material necessary to understand Earth's climate system in equilibrium but to slowly build their knowledge and competencies as they progress through mandatory secondary school. This research offers a starting topic and structure for CSL upon which further learning can take place. Since this group starts learning about Earth in the Solar System from the age of 10 in Australia and are asked to 'recognize that there is a regularity in the arrangement of climatic phenomena on Earth' by the age of 10 in Austria, we may expect that they are cognitively ready to begin instruction in KD1 by the time they begin secondary school. KD1 will prepare them to tackle greenhouse gases as molecules in KD2 within the following 6 to 12 months which will prepare students to investigate albedo in KD3 and so on. Investigating the KDs separately, including more detailed content in both the questionnaire and CSL, and validating the content of the research instrument should be assessed in future work. Finally, while we have proposed a revision to the climate science portion of the USGCRP/NOAA definition of climate literacy, we expect this to be expanded and critiqued further. Defining CSL is non-trivial and warrants an international effort that informs the construction of the definition both from experts and practitioners, as well as from those for whom it will be employed, i.e., via testing of its aims and learning outcomes. In the spirit of scientific rigour and debate, we must be willing and open to revisions of this kind in order to find effective means for communication and public education.

Our research has identified the need for a structured approach to developing CSL among early adolescents. In order to evaluate existing knowledge across four key knowledge domains concerning the natural climate system, we designed a questionnaire to measure knowledge about key concepts across the domains. While our research cannot be used to argue a numerical measure of objective knowledge on climate science, it does offer a tool for designing and evaluating CSL interventions in the schooling context. Critically, it has demonstrated those CSL knowledge domains on which early adolescents have the strongest and weakest a priori knowledge, allowing us to structure curriculum such that students engage first with those knowledge domains they are most likely to master before extending into the knowledge domains that will prove more challenging.

4.8. Conclusion

Alongside the mounting pressure to reduce greenhouse gas emissions and the re-discovery of education as an essential player in motivating individuals to engage with climate change, the need to find an effective audience, vehicle and methodology for knowledge deficit interventions is more pressing now than ever before. While early adolescents hold great promise as a potential audience, a CSL framework could hold enormous potential as a mass communication methodology and vehicle. Firstly, the high concern for climate change in the early adolescent age group may translate more rapidly into action– and the willingness to understand the underlying physical cause is more likely to be present as these individuals have not yet established their worldview. Secondly, this age group shows a strong capacity to understand the underlying mechanisms and processes that form the physical science basis of climate science. Thirdly, similarities between countries indicate that this age group share a similar intellectual threshold that appears to transcend culture, language and geography; permitting the creation of a framework that could be implemented globally if these findings are replicated in the future. Lastly, the differences in the four knowledge domains appear to offer a promising scaffold on which to structure a CSL framework; forming clear, coherent boundaries around what a learner is expected to understand and a curriculum that can be tested and graded and embedded into larger, national curricula.

For those concerned with motivating the global audience to constructively address emission reduction, an effective strategy that reaches the global mass is the holy grail of climate communication. A framework, for example, that can be translated across language and culture, but matched to the intellectual capacity of an individual to comprehend and evaluate the information, could alter the climate science education and communication practice and theory landscape. With regard to 12-13 year olds, the potential is even greater as it opens an opportunity for mass communication that, heretofore, has been hindered by the barriers of worldview and wickedness (Harker-Schuch, 2020). In addition, with 12-13-year olds required to attend school in nearly all parts of the world, creating a framework designed to sit within existing national curriculum requirements would ensure that every individual, passing through the compulsory public education system, would be given instruction in the physical science basis of climate science. The extraordinary advantage of reaching early adolescents is their lack of existing worldview, which provides the opportunity for educators to assist these learners in developing an informed and fact-based worldview about climate change. The potential of early adolescents to be ‘game changers’ in this shift back to CSL is an exciting development for educators and communicators – not only as a candidate for interventions but to rejuvenate the legitimacy of climate science.

The significance of Chapter 4 to the thesis

Chapter 4 answered the research question and objectives and found that CSL in the 12-13-year-age group, though low, was similar to other studies that had also investigated literacy in adolescence (14-17-year-olds in Montenegro; 16-17-year-olds in Vienna and Copenhagen; and 13-15-year-olds in the northeast region of the US). More pertinently, this research shows there are show strong similarities in both Austria and Australia with regard to specific knowledge domains in this age group. By identifying these knowledge domains, it is possible to test the prototype CSL framework for early adolescents in these two countries. These knowledge domains may provide a pathway to improve understanding of CSL prior to worldview development, particularly when introduced as phenomena that can be described by well-understood climate system mechanisms and processes.

Chapter 5:

CO2peration – Structuring a 3D interactive digital game to improve climate literacy in the 12-13-year-old age group

5. CO2peration – Structuring a 3D interactive digital game to improve climate literacy in the 12-13-year-old age group

The place of Chapter 5 in the thesis

Chapter 5 aims to address research questions 4 and 5 through research objectives i), j), k) and l).

4) Can the interactive 3D game, CO2peration, improve CSL in the 12-13-year age group?
    i) Examine the knowledge development in CSL of 12-13-year olds from playing the game
    j) Discuss the potential of the CO2peration game as a valid climate communication and climate education vehicle
5) Is the CSL framework a valid instrument to teach climate science in the early adolescent age group?
    k) Test how each KD (knowledge domain) performs in relation to its respective prior score
    l) Discuss the validity of the CSL framework for use in CSL in early adolescence

Chapter 2 proposed that early adolescents might be an ideal group for communication and education interventions when it comes to climate change outreach and engagement. Their concerns about climate change were explored in Chapter 3 both to establish a baseline of opinions in this age group and to assess whether they were receptive to knowledge deficit interventions. A CSL framework was then developed and tested in the 12-13-year-age group in Chapter 4. This (pre-)test also established the level of pre-existing CSL in this age group, demonstrating that there are commonalities in specific knowledge domains that are shared across Austria and Australia. In Chapter 5 the CSL framework was tested further by embedding key parts of it in a 3D interactive game that teaches the physical climate science basis (mechanism and processes that describe the natural climate system in equilibrium) and then testing the adolescent players' knowledge development with the same climate science questionnaire that had been used to measure CSL prior to this intervention. I first examine the knowledge development of early adolescents using the interactive 3D game and then test how each KD performs in relation to the respective prior score. I then discuss the potential of the CO2peration game as a valid climate communication and climate education vehicle and then the validity of the framework for use in teaching CSL in early adolescence.

Due to absences and errors in completion of the questionnaire, the total number of respondents who took part in the opinion research in Chapter 4 (both as a total and of those who are eligible) and Chapter 5 (both as a total and of those who are eligible) differs from the total number of respondents (both as a total and of those who are eligible). Therefore, the results from the pre-test will be different between Chapter 4 and Chapter 5 as only those who participated in both questionnaires are reported in Chapter 5.

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CO2peration – Structuring a 3D interactive digital game to improve climate literacy in the 12-13-year-old age group

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ABSTRACT

Preparing students for their future and qualifying them to enter public life is the essential role of the public-school system. As such, an understanding of climate science ought to be an essential – and significant – component of that preparation. This research proposes a novel pathway to teach climate science via a 3D interactive digital game and examines the potential of 12–13-year olds as a prepatent group for climate science interventions. After playing a proof-of-concept climate science game that covers the physical causes and mechanisms of climate change, 401 students in Austria and Australia were tested with a climate literacy questionnaire. Our results indicate that climate literacy can be improved in this age group via the digital game. In addition, we found further evidence of established climate science 'knowledge domains' in this age group that form a natural 'increased levels of complexity' scaffold that can be used to design curricula such as that in the digital game. These four 'knowledge domains' are (in brief): Earth in the solar system; gravity and its effect on the atmosphere; albedo and solar radiation, and; greenhouse gases and their warming potential.

1. Introduction

> In the end, we will protect only what we love. We will love only what we understand. We will understand only what we are taught - Baba Dioum (1968).

Climate change is, arguably, the greatest existential threat we are facing today – and the one threat that each individual can do something about (Goswami, 2016; Ripple et al., 2017). It threatens our economic and social stability (Barnett & Adger, 2007), food security (Conforti, 2011), water resources (Kiparsky, Milman, & Vicuña, 2012) and – ultimately – our survival (Ojala, 2012b). This threat to our species encompasses most other species – and brings with it ethical (Baer, 2000), moral (Reese, 2016), and philosophical (Nash, 1989) dilemmas. Understanding what climate change is, and how it will affect us, plays a vital role in our future mitigation and adaptation decisions and actions. Complicating efforts to undertake meaningful action is a discourse that has been polarised by socio-cultural worldviews (i.e., opinions/attitudes) which shape how individuals and groups come to understand climate change (Colvin, Witt, & Lacey, 2015; Kahan, Jenkins-Smith, & Braman, 2011; Unsworth & Fielding, 2014), and ultimately shape their

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acceptance (or otherwise) of the need for mitigation and adaptation actions.

Education has been identified as a valid intervention (Guy, Yoshihisa, Walker, & O'Neill, 2014); especially for young people who have less established worldviews and a lower level of denialism (Harker-Schuch, 2019; Clark, Ranney, & Felipe, 2013; Corner et al., 2015), and knowledge has been shown to increase concern about climate change (Clark et al., 2013; Shi, Visschers, & Siegrist, 2015; Shi, Visschers, Siegrist, & Arvai, 2016). A study of a national sample of adult Australians in 2014 (n = 335) (Guy, Yoshihisa, Walker, & O'Neill, 2014) showed that 'specific' climate science knowledge strengthens the acceptance of the reality of climate change, and reduces denial in those who have strong individualistic identities. Shi et al. (2015) (Switzerland, n = 1065) refined this further by showing that causal knowledge of climate change is significantly correlated to concern about climate change. For adolescents in particular (11–15 years), Stevenson, Peterson, Bondell, Moore, and Carrier (2014) (n = 387) found that knowledge about climate change correlated with increased concern about climate change in individuals with both communistic and individualistic identities with a stronger positive relationship among individualists than in communistic groups. With climate literacy so poor in the broader public arena (Clark et al., 2013), significant progress might be made if we improve climate literacy in early adolescence.

In response to these new findings and to provide further insight into the climate science education arena, we explore a promising pathway: the use of a proof-of-concept 3D interactive digital game to teach climate science in the first year of secondary school (12–13 years) (Harker-Schuch, 2019).

1.1. *The climate science education problem*

Climate change is not well taught in public secondary school (Harker-Schuch & Watson, 2019) as it is often disjointed, incoherent and/or tagged-on to other science topics, not sufficiently included in the curricula at all (Church & Skelton, 2010; Corner et al., 2015; Hess & Collins, 2018; Shepardson, Niyogi, Choi, & Charusombat, 2010) and many teachers are not adequately familiar with the theoretical foundations that underpin it (Plutzer, Hannah, et al., 2016; Porter, Weaver, & Raptis, 2012(Plutzer, Mccaffrey, et al., 2016)).

In addition, the impacts and consequences of climate change (particularly those related to an amplified greenhouse effect) are usually the main focus when teaching this phenomenon; eschewing the mechanisms and processes that form the basis of climate change (Clark et al., 2013; Shi et al., 2016). Clearly, teaching the consequences and the impacts of climate change are necessary if students are to be sufficiently prepared to address these issues, but knowledge of the system itself is required, as well. Understanding climate science and the natural greenhouse effect is, according to Porter et al. (2012), '*a starting point when discussing the role of the atmosphere in the Earth system*'. By initially approaching climate science education as a mechanistic, process-oriented problem, we are laying '*an initial foundation for directing people to the right kinds of mitigative actions*' (Wolf & Moser, 2011). Not only does this approach provide clear guidelines toward how we engage with and respond to climate change, capacity- and resilience-building are fostered by improving understanding, preparedness and innovation (Fath, Dean, & Katzmair, 2015). Ojala (2012a) proposes that meaning-focused coping may offer '*the ability to reverse one's perspective, and see not only threats but also opportunities* [that] *could buffer the excessive worry that problem-focused coping may otherwise evoke*. Without an understanding of the climate system, it may be hard for individuals to imagine where opportunities may arise: improving knowledge may, therefore, improve opportunities and – by default – resilience (Bell, Lindenfeld, Speers, Teisl, & Leahy, 2013; Fath et al., 2015).

The relationship between knowledge attitude and behaviour is a messy one (Potter & Oster, 2008; Sturgis & Allum, 2004) but it is vital to note the lack of clear climate literacy guidelines or the presence of a tested and accepted curriculum in the public education system (Azevedo & Marques, 2017; Milér & Sládek, 2011). Despite NOAA offering the 'Essential Principles of Climate Literacy' NOAA (2009) which was developed through workshops and collaboration/discussions, this framework was not tested on students, did not include other inputs from students (Nature Editorial, 2018) and lacks climate-specific pedagogical considerations including framing, worldview influences, and structured learning outcomes. Similarly, the Erasmus + Climate Literacy project has also not been tested on students, lacks a pedagogical design and focuses, almost exclusively, on the impacts and consequences of climate change (EU Erasmus+Climate Literacy Project, 2015).

1.2. *Potential solutions, remedies and considerations*

The education route to improve climate literacy is clearly not an easy one. Recent research, however, is offering some valuable new leads to pursue in relation to *when, what and how* we introduce climate science into the classroom. Climate change is typically taught in upper secondary (Australian Curriculum - Senior secondary climate change, 2015; Bieler, Haluza-Delay, Dale, & Mckenzie, 2018; Whitehouse, 2019; Wynes & Nicholas, 2017) and, although older students are closer to entering society and could effect societal change sooner, they already have established opinions and can demonstrate the same worldview bias (and inability to revise their existing opinions) as adults do (Corner et al., 2015; Stevenson et al., 2014; Vollebergh, Iedema, & Raaijmakers, 2001). New findings in intellectual development (Jensen & Nutt, 2015) indicate climate science could be introduced at the beginning of high school before students have formed their socio-cultural worldviews (Harker-Schuch, 2019). Many aspects can be understood at this earlier age, and teaching climate science when the human brain is learning to undertake 'higher order executive function' allows an intellectual scaffold to be built which would form the basis for introducing more complex aspects of climate science at a later age (Harker-Schuch, 2019; Harker-Schuch, Colvin, Lade, & Mills, 2019; Case, 1985; Jensen & Nutt, 2015; McBeth, Hungerford, Marcinkowski, Volk, & Meyers, 2011; Stevenson et al., 2014; Harker-Schuch et al., 2019).

Earlier introduction of climate science may help to address the high levels of concern about climate change found in early (Harker-Schuch, Mills, Lade, & Colvin, 2019) and later adolescents (Harker-Schuch & Bugge-Henriksen, 2013) by helping them develop 'meaning-focused' coping strategies that, according to Ojala (2012a) '*evoke positive feelings that can work as buffers hindering negative emotions from turning into low well-being*'. There is too little research being done on this age group (Nature Editorial, 2018) (Wray-Lake, Flanagan, & Osgood, 2010), but 12-13-year olds show enormous potential as change agents.

As outlined by Shi et al. (2015), causal knowledge (that is, knowledge related to what causes climate change) '*significantly increased concern about climate change and willingness to* support *climate-friendly policies*'. Further, '*mechanistic information*' about the physical drivers of climate change, according to Clark et al. (2013), is essential for knowledge development and '*highly germane science information can clearly change the public's understandings and opinions*'.

When considering 'how' to make climate science relevant to learners and to ensure that we deliver the appropriate content to the target audience (i.e., the pedagogy), we need to include: the relevant frame of climate change (Stevenson et al., 2014); the emotions and interests of students (Corner et al., 2015; Nature Editorial, 2018) the right material, tools and vehicles to deliver the content (Schroth, Angel, Sheppard, & Dulic, 2014); an efficient way to grade and monitor students; and to ensure that the materials are developed to achieve the highest learning outcomes in the most cost-effective way (Guskey, 2015).

The development of materials, tools and vehicles needs to be able to tackle the complexity and breadth of climate science as a subject (Schroth et al., 2014). Climate change takes place at temporal and spatial scales that range from stellar to molecular. The linked systems of processes, mechanisms, and feedbacks are complicated and manifold. Understanding these systems depends on tools and materials that allow for both the individual systems and their linkages to be conceptualised (Schroth et al., 2014). In this paper, we discuss the use of an interactive 3D digital game to teach the mechanistic and domain-specific processes that underlie climate science.

1.3. 3D interactive games to teach 'domain-specific' climate science to 12-13-year olds

Games are, according to Wu and Lee (2015, p413) '*natural tools for climate change education and engagement*' which provide '"*designed experiences*" *where players can learn through doing and being, rather than absorbing information from readings and traditional lecture formats*'. In addition to the arguments presented by Wu & Lee that 'first-hand' experience offered by games is the better teacher due to the 'emotional pathway' games offer, the brain also prefers visual 3D visual information over all other sensory input (Sheppard, 2005; Wu & Lee, 2015); up to 70% of the human brain is dedicated to optical information. As a species, we obtain and retain more information that is visually delivered than from any other sense (Sheppard, 2005). This fact, perhaps more than any other, is why games show such overwhelming success as learning tools (Ma, Fradinho, Jannicke, & Hauge, 2014) This benefit is enhanced when the game is a 3D, interactive exploration of a topic (Cai, 2013; Su & Cheng, 2013) designed on state-of-the-art pedagogical frameworks and curriculum (Erhel & Jamet, 2013; Lamb, Annetta, Firestone, & Etopio, 2018); particularly one that incorporates narratives as an essential pedagogical tool (Hazel, 2008; Moezzi, Janda, & Rotmann, 2017).

Learning outcomes using 3D interactive games have been shown to be consistently higher than with the use of conventional tools (textbooks, lectures, videos) and are known to improve executive function (Homer, Plass, Raffaele, Ober, & Ali, 2018; Jing, Yue, & Murugesan, 2015). However, while Wu and Lee (2015) investigated the usefulness of many climate change games – both digital and non-digital formats – the research primarily examined governance and '*preparation for future action*' as '*very few contain information about the mechanisms and processes believed to cause anthropogenic climate change*'. As highlighted by Wu and Lee (2015) investigations into games that deliver 'domain-specific' content and teach causes of climate change are scarce, if not entirely absent, in the literature.

From a pedagogical perspective, digital games offer teachers unparalleled support and tools that cannot be matched in existing materials (Davidson & Goldberg, 2009; Shute, Ventura, Bauer, & Zapata-Rivera, 2009; Tyner, 1998; Wu & Lee, 2015). Grading (Loh, Dirk, & Sheng, 2015; Moreno-ger, Burgos, & Torrente, 2009), preparation for classes, learning materials and user information are all found in the game analytics and back end of a properly-designed digital game (Aldrich, 2009). These tasks (grading, testing and performance-qualifying) take up a large portion of a teacher's working life (Lee, 2003; Shute et al., 2009) which could be better spent tailoring teacher-support to student needs or any number of teacher-dependent tasks. Digital games and learning environments also offer other features that are, in a normal classroom, time-intensive or costly (Bellotti, Kapralos, Lee, Moreno-Ger, & Berta, 2013; Lester et al., 2014, 2013; Southgate, Budd, & Smith, 2017) – such as pre-testing, tailored-learning and long-term performance monitoring. In addition, teachers do not need to be intimately familiar with the topic in order to teach it – the theoretical foundations of any subject are the essential content of the game. When well-designed, a game curriculum provides the framework for the entire topic: learning outcomes, narratives (McQuiggan, Rowe, Lee, & Lester, 2008), story-arcs, and linked multidimensional relationships both within sub-topics and/or with other meta-related or inter-disciplinary, topics.

Climate science digital games could be a paradigm shift in climate science education and communication (Twining, 2009) – and, ultimately, engagement. Creating 3D, interactive models of a specific domain allows the learner to observe, conceptualise, and manipulate the process more meaningfully than in a lecture (Adamson, Chen, Kackley, & Micheal, 2017; Bodzin & Fu, 2013; McElhaney, Chang, Chiu, & Linn, 2015), with diagrams (Sheppard, 2005) or text-dependent explanations. For example, the ice-loss negative feedback system as a function of atmospheric warming with the option to alter variables (e.g., concentration of greenhouse gases, albedo scale, Earth's energy budget) to observe different outcomes.

3D games also allow us to culturally identify with something and develop local associations, without the emotional baggage – circumventing the paradoxical task of making it relevant without making it paralysing or polarising (Sheppard et al., 2011). For building awareness, Sheppard et al. recommend that climate change be 'linked to things that people can identify with and which they care about' but caution must be exercised in order not to overwhelm those we target (Sheppard et al., 2011). Research has shown that virtual interactive 3D visualisations can offer the same benefits as real worlds but provide a distance when those worlds are uncomfortable and threatening. Researchers in the UK employed virtual reality for the treatment of acrophobia (fear of heights) with a success rate of 70% (Freeman et al., 2018) and the Endeavour Foundation in Australia are using virtual reality to help those with an intellectual disability overcome social and public anxiety (Renault, 2018). While these treatments employ VR technology, which is both interactive and immersive, similar findings are reported for only interactive 3D visualisations. For example, researchers in Spain reduced phobia-related anxiety in individuals with 'small animal phobia' via the use of 3D visualisations (Ma et al., 2014). An earlier study, employing an existing 3D game framework, demonstrated a reduction in arachnophobia in 11 subjects who reported this phobia since early childhood – to the extent that 'many participants were able to touch the live spider with a pencil' (Bouchard, Côté, St-Jacques, Robillard, & Renaud, 2006).

Table 1

Order of KDs as a result of tested outcomes by X et al. (2018) – based on the SOLO Taxonomy (Biggs & Collis, 1982). CL = climate literacy; LO = learning objective. * not included in the present study. Question scores are the average % correct out of 100.

KD order	Name of KD	Question score	ST level	SOLO Taxonomy (ST) Learning objective (LO)
KD1 KD CL level: 61.01	Earth in the Solar System	66.40	1	Identify the range of the circumstellar habitable zone a.k.a Goldilocks Zone
		65.70	1	Name the zone around our Sun that can support liquid water at its surface
		63.01	2	List the distinguishing features of planetary atmosphere that accommodate life, and liquid/gaseous water at their surface
		57.31	3	Explain the role of atmospheric pressure on the climates of the rocky planets in our solar system
		52.63	4	Reflect on the atmospheric composition and abundance of greenhouse gases on the rocky planets in our solar system
KD2 KD CL level: 50.47	GHGs as molecules	66.77	1	Identify an image of a Greenhouse gas
		51.29	2	Describe the factors that increase the global warming potential of a greenhouse gas
		48.76	2	Describe how greenhouse gases react to infrared radiation and contribute to atmospheric warming
		46.24	3	Distinguish a greenhouse gas from a non-greenhouse gas in the atmosphere
		39.30	4	Reflect on the effect of greenhouse gases as a percentage of Earth's atmosphere
KD3 KD CL level: 47.37	Albedo	58.28	1	Identify the warming effect of solar radiation on a dark surface
		49.68	1	Describe regions with high albedo
		48.49	2	Describe albedo and how it is expressed as a scale
		47.42	3	Compare and contrast the interaction between greenhouse gases and shortwave and longwave radiation
		32.99	4	Express albedo as a scale on Earth's energy system as influence on warming
KD4 KD CL level: 30.41	Earth's Atmosphere	43.78	1	Identify the effect that causes layering of Earth's atmosphere and sort the layers into the percentage of gases found in each layer
		28.87	2	Describe the gaseous composition of Earth's atmosphere as a sum of percentages
		26.28	3	Classify the atmospheric layers in the order they present in our atmosphere
		22.92	4	Reflect on what properties in the atmosphere define the events/phenomena/technology that occur in the different layers
KD5*	Natural drivers of climate change	Untested	1	List the main drivers of natural global climate cooling
				List the main drivers of natural global climate warming
			2	Describe the movement and effect of the respective Milankovitch Cycles (eccentricity, axial tilt and precession) on Earth's temperature over millennia
			3	Classify the natural drivers of abrupt climate change and the associated potential for warming
			3	Explain the effect of terrestrial and ocean uptake of CO_2 on Earth's energy budget
			4	Reflect on the role of the Holocene on anthropological development and progress
KD6*	Feedbacks and climate instability	Untested	1	Name a positive feedback and a negative feedback system and their functions on system stability
			2	List five main feedbacks (positive and negative) that play a significant role in Earth's climate and current loss of climate stability
			3	Explain the role of Albedo on Earth's global mean surface temperature (GMST)
			4	Reflect on the abundance of water at the Earth's surface and the effect of warming temperatures in relation to Earth's global mean surface temperature (GMST)
KD7*	Anthropogenic emissions and their consequences	Untested	1	Name the known impacts of climate change on Earth's natural system, human health and human infrastructure
			2	List three significant direct anthropogenic drivers of climate change
			3	Explain the effect of direct and indirect anthropogenic drivers of climate change on system equilibrium
			4	Reflect on the role of anthropogenic emissions on the anticipated impacts and consequences of climate change as a measure of risk and threat
KD8*	Climate solutions	Untested	1	List the main known clean and renewable energy solutions
			2	Name the most viable renewable energy option(s) for your region with justification
			3	Describe the terms 'carbon neutral' 'regenerative/cradle-to-cradle design', 'life-cycle assessment', 'dematerialisation', 'planetary boundaries', 'steady-state economy'
			3	Compare different individual emission reduction strategies for action competence against reduction potential
			4	Reflect on your action competence and your personal emission-reduction journey

1.4. Developing CO2peration – a 3D interactive climate science game

Science is a '*systematic enterprise of gathering knowledge about the universe and organizing and condensing that knowledge into testable laws and theories*' (American Physical Society, 1999). The scope of each scientific realm (e.g., geology, biology, or astronomy) is defined by physical boundaries, phenomena, temporal/spatial scales, and/or associated theory. Educators use this same method to organise information into specific knowledge domains. As observed by Bloom, '*most teachers begin by dividing the concepts and skills that they want students to learn into smaller learning units*' (Guskey, 2015). These learning units, or knowledge domains, are necessary as they allow teachers to assess students easily, diagnose learning issues and prescribe corrective measures (Guskey, 2015). More importantly, they define what a learner is expected to understand and a limited curriculum that can be tested and graded and embedded into a larger curriculum. Since some phenomena and/or theories are common to multiple realms, learning transitions between one topic and another can be facilitated by these shared phenomena and theories. Teachers employ these shared phenomena/theories to construct learning narratives, curricula and pedagogies.

As with other natural sciences, climate science translates well into learning units. These learning units or 'domain-specific knowledge' have clear, coherent boundaries that can be taught in one grade or age group (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019). We previously found 8 knowledge domains (KD) that encompass all aspects of climate science (Table 1)(Harker-Schuch et al., 2019). These KDs were used to guide the design and development of CO2peration, an interactive climate science game. Only KDs 1–4 were tested in this research. KD5 (natural drivers of climate change), which includes the Milankovitch Cycles, the effects of volcanoes and tectonic activity, and oceanic and terrestrial uptake of CO_2, was not included due to its anticipated difficulty for the early adolescent age group and the difficulty of creating quality 3D interactive content within the budget for the overall game. KD6 (feedbacks and climate instability) and KD7 (anthropogenic emissions and their consequences), which relate to consequences and impacts, were excluded to avoid distress in the early adolescent age group but should be included in older age groups (Ojala, 2012a). KD8 (climate solutions), which includes renewable energy options, emission reduction, behavioural change and action competence, i.e. having the belief that we, as individuals, can effect change and take action to reduce emissions, was not included due to the limited class time allocated for this study and the desire to focus on climate causes as a starting point. Based on previous testing of the first four KDs, X et al. (2018) sorted the KDs in the order of highest score performance to lowest score performance, i.e., from easiest to hardest, and recommended that they should be introduced into the classroom in this order.

Within each KD, questions were sorted based on this pre-testing from highest score to lowest score (i.e., levels of complexity) These formed the essential learning objectives (LO) and structured 'levels of complexity' for Biggs and Collis (1982) Structured Observed Learning Outcomes, a.k.a the SOLO Taxonomy. The proof-of-concept portable (executable) CO2peration game was developed in order to obtain a 'starting point' and to provide a basis for more rigorous testing at a later stage: this will allow us to see what aspects improve and what don't (particularly in relation to knowledge) and test the validity of the approach.

1.4.1. The CO2peration learning narrative

The knowledge domains and learning objectives for climate science were translated into a narrative that formed the foundation for the curriculum and pedagogy. The storyline within each KD begins at an easy level then graduates to increasingly difficult levels. Although the term 'story' might seem more fitting, the term 'narrative' denotes a more 'formal, non-fiction form' of discourse (Moezzi et al., 2017) as we would expect in a science curricula. Narratives are an important tool in correcting misinformation as they are context-dependent which, in turn, assists in memory retention (Dahlstrom, 2014; Lewandowsky, Ecker, Seifert, Schwarz, & Cook, 2012).

The narrative for CO2peration follows the journey of a photon as it visits the Rocky Planets in search of answers as to why Earth has liquid water on its surface. After working with friendly orbital space probes (i.e., Messenger, Magellan, Viking I & II, etc.) to collect data (e.g., composition of planet/surface temperature samples/diameter of planet), the photon begins modelling the molecules that it finds along the way. After reaching Mars, the photon returns to Earth where it explores the role of albedo on Earth's global mean surface temperature (GMST); observing the effect from the Exosphere and then testing it in an atmospheric-tank simulation (altering all relevant variables to observe outcomes). Earth's atmosphere is then investigated by the photon to understand the role that each of Earth's atmospheric layers has in allowing us to understand climate phenomena (e.g., research on the International Space Station in the Thermosphere/data from orbital satellites in the Exosphere) and the role each layer plays in the protection and maintenance of life (e.g., burning-up of meteors in the Mesosphere/weather in the troposphere/ozone in the stratosphere) and other atmospheric phenomena (e.g. auroras). Both game versions were played in the native language of instruction (English in Australia and German in Austria) and the game contents were translated by a certified English-German translator.

1.4.2. Educational design

There are several different types of software applications for education, skill-development and training, and according to Annetta (2010), it is '*important to distinguish between serious games, serious educational games (SEGs), simulations, and virtual worlds … SEGs juxtapose serious games by targeting K–20 content knowledge. They allow teachers and students to connect real-world scenarios with common school content, thus answering the age-old question, "Why do I need to know this?*". The CO2peration game has been designed as an SEG – the content of the game is structured on a proposed curriculum (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019) with the intended learning outcomes given in Table 1, which are focused on the causes of climate change. CO2peration aims thereby to help students understand the climate system.

Annetta (2010) present a framework for serious education game design (SEGD) that is a nested model comprising six elements: (1) identity; (2) immersion; (3) interactivity; (4) increasing complexity; (5) informed teaching; and (6) instruction. CO2peration meets some but not all these criteria. For the first stage (1), ‘identity’, CO2peration’s photon avatar partly aligns with Annetta’s SEGD. The photon is gender-neutral, ensuring gender bias will not influence players’ activity, engagement or outcomes (Annetta, 2010; Ivory, 2006). However, while we recognise that players, tend to build a stronger community of learning when they are given a choice of avatar (Annetta, 2010), budget constraints prevented us from incorporating this feature into the prototype of CO2peration used for this research. Furthermore, its use as an avatar emphasizes the significant role that solar radiation plays in a planet’s energy budget. For immersion (2), the narrative for CO2peration was created in order to promote ‘flow’ (Csikszentmihalyi, 1997) and, while most of the criteria for flow were met in the design and testing (successful completion of activity, immersion into activity, clear activity goals, fast feedback, deep concentration in the activity), more autonomy needs to be given to the player in order that self-awareness disappears and a player’s sense of elapsed time loses its pace. Interactivity (3) in the game was kept to a minimum (interactions with nonplayer characters or music or sound) partly due to constraints within the proof-of-concept project and partly due to concerns about the potential for introducing distractions that may interfere with the learning objectives, concerns about noise levels in class, and unnecessary cognitive ‘noise’ and congestion (Annetta, 2010). CO2peration aligns most strongly with the element of increasing complexity (4). By designing the game based on the KDs in Table 1 and the SOLO taxonomy (Biggs & Collis, 1982), we embedded an evolution of difficulty both within the game itself (it gradually becomes more complex) and in the anticipated learning outcomes (Table 1). For a proof-of-concept game, we argue that this is the essential first step in game design from the perspective of the game script developer and game designer. Although Annetta has structured the SEGD in nested stages, their approach appears to take the player’s viewpoint rather than that of the SEG script developer or game designer. For informed teaching (5), the results of this research have been fed back into refining the game’s design. Lastly, the instructional element (6) is met in CO2peration as the player can play at their own pace within a learning environment that is highly visual and enjoyable where they are ‘in a state of mental disequilibrium, all of which facilitate learning (Annetta, 2010; Piaget, 1972). With the prior testing of students, we have established a baseline upon which we can create the desired mental disequilibrium within the defined KDs.

Consistent with Annetta (2010) framework and the CO2peration learning narrative, an experiential learning environment was created using 3D animations. These were based on real-life models and scientific findings/data whenever possible. The space probes, for example, were designed on modelling data from Magellan, Messenger, and Mars Global Surveyor. The planets were textured based on topography data from NASA (NASA EOSDIS, 2018; NOAA): Mercury topography data via the Messenger mission: (Denevi et al., 2018; Hawkins et al., 2007; Solomon et al., 2001); Venus topography data via the Magellan mission: (Rappaport, 1997; Rappaport, Konopliv, Kucinskas, & Ford, 1999); Earth topography data via USGS Earth Resources Observation and Science (EROS) Center, (2018); and Mars topography data via the Mars Global Surveyor mission (Smith et al., 2001).

As a student progresses through the learning narrative, their avatar visits each of the Rocky planets. When the avatar visits Earth, it is taken initially to the student’s geographical location. Players in Sydney and Canberra zoomed down through the atmosphere to the East coast of Australia and players in Vienna zoomed down over middle Europe. This was done to help frame climate change as real, proximal and present, as described by Scannell and Gifford (2013). This place-based association and local/regional closeness helps strengthen an awareness of the reality of climate change (Sheppard et al., 2011) within an abstract, safe, virtual space.

A student’s progression through KD3, the albedo knowledge domain (Fig. 1), illustrates the educational design for CO2peration. In this section, the player is tasked with investigating how albedo regulates temperature on Earth. Before commencing this section, the

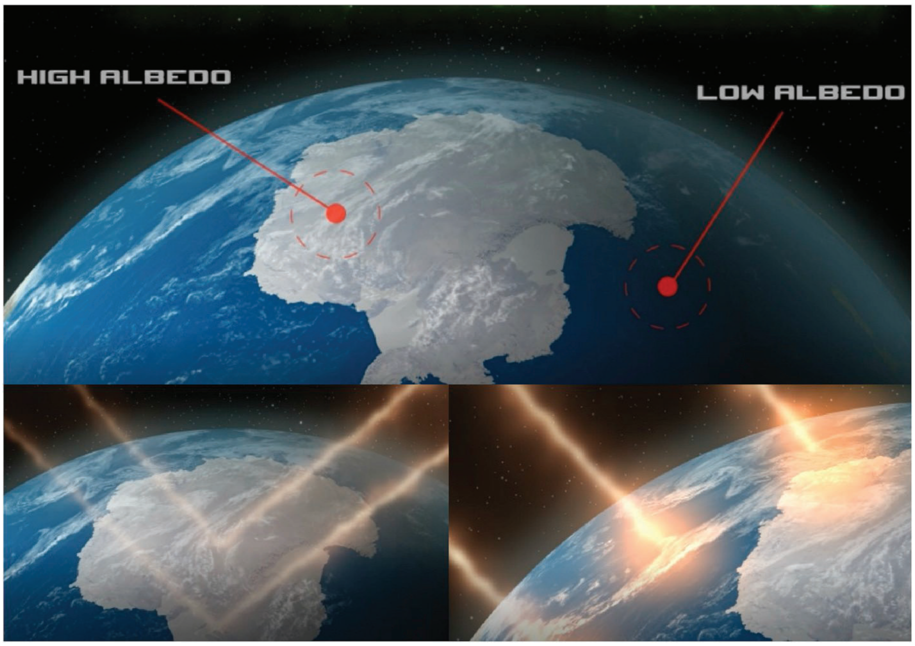

Fig. 1. Depiction of albedo in the proof-of-concept CO2peration game.

player must complete a quiz that tests the knowledge gains from the previous sections (KD1: Earth in the Solar System; KD2: Greenhouse gases as molecules). This quiz repeats the earlier material from KD1 (slightly altered to test understanding) and tests the new material from KD2. This 'drill and practice' (Lim, Tang, & Kor, 2012), ensures students are prepared for the next level of complexity and encourages them to retain the information and knowledge they recently acquired – especially any that relates to the upcoming section. This approach also provides '*formative assessment*' (assessment that provides unmarked evaluation) and '*rapid feedback … early in the evaluation process*' (Dobson, 2008). Similarly to recreational gaming, if a student fails the quiz, they are returned to the start of the previous section and must repeat the section and pass the quiz before they are able to progress. At the end of KD3, players are given a quiz regarding the new material (albedo section) as well as material from previous sections to improve knowledge and memory.

This study was a proof-of-concept that used an alpha prototype of CO2peration to explore and assess the efficacy and learning outcomes achieved from the viewpoints of players, educators, and developers. The prototype described in this article included a series of 3D animations interspersed with quizzes and short activities (molecular modeller) followed by a 3D lab sequence where players could adjust variables in a climate-controlled tank to recreate climate systems representative of Earth, Venus and Mars – as well as to alter the variables arbitrarily for fun – and a 'greenhouse gas molecule maker' where players could build and test greenhouse gas molecules (water, carbon dioxide and methane). Since the game was an experimental alpha-version of CO2peration, high learning outcomes were not anticipated. The aims for this study were to gain feedback on the design of CO2peration and to test and refine the prototype pedagogical and curriculum framework.

2. Objectives and hypothesis

The main objective of this study is to explore the use of a 3D interactive digital game to teach climate science in the first year of secondary school (12–13 years) and to test the prototype pedagogical and curriculum framework (climate literacy framework) (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019) on which the CO2peration game is based. We investigate, therefore, changes in the level of climate literacy of 12 to 13-year-olds regarding their understanding of climate science after playing a 3D interactive digital game 'CO2peration'. Following on from a previous study that explored how prior climate science knowledge (PRIOR) can be broken down into knowledge domains (KD), this study examines how those KDs perform after (POST) the intervention of a 3D interactive game, and the association between the previous performance in the KDs (PRIOR) and the performance in the follow up performance in the KDs (POST). We further investigate the influence of school and gender on the results between PRIOR and POST KDs.

The hypotheses of our study can be summarised as follows:

H1. Climate literacy will improve in the 12-13-year-age group with the use of a 3D interactive digital game to teach climate science. (H0: There will be no improvement in climate literacy in the 12-13-year-age group with the use of a 3D interactive digital game to teach climate science.)

H2. Climate literacy in each knowledge domain will improve in the 12-13-year-age group with the use of a 3D interactive digital game to teach climate science (H0: There will be no improvement in the knowledge domains in the 12-13-year-age group with the use of a 3D interactive digital game to teach climate science).

H3. There is an association between the POST and PRIOR results for individual student scores (H0: There is no association between the POST and PRIOR results in the knowledge domains).

Additional statistical analyses were done to assess the role of additional information, confounding factors or other variables.

3. Methods

As part of a larger research project investigating the use of digital tools to teach climate science in the early adolescent age group (Australian National University ethics protocol number, 2015/583), climate literacy was quantified using a climate science questionnaire based on a previous research instrument created by the one of the authors (X) used to investigate opinion and knowledge in the 16-17-year age group (Harker-Schuch & Bugge-Henriksen, 2013).

All permissions were acquired from the relevant authorities (ethics department of the Australian National University, departments of education in their relevant jurisdiction, school directors, teachers) and signed consent forms were obtained from participating students and their parents. All students present on the days of testing participated in the project but those without parental permission were deleted from the record. All data were collected anonymously to prevent misuse of personal information and any anonymised data collected from students without consent forms were stringently removed from the database.

3.1. Schools and students

Two schools in each of Vienna (Austria) and Canberra and Sydney (Australia) took part in the research coded as VHS1 and 2, CHS 1 and 2, SHS 1 and 2, respectively. The research catchment was within 10 km of the central business district in each city due to the high urban density of inner-city populations. Alongside the classification of the school as an inner-city public high school, willingness of the school to participate determined the inclusion of the school in the research. All schools provided instruction in the native language (German in Austria and English in Australia) and followed the state-mandated curriculum. The three class periods reserved for this research were during the planned science class time and lasted between 45 and 50 min each. The students were given a climate science questionnaire (PRIOR) in the first science class and then, 7–14 days later, played the CO2peration game in the second science class. They were then given the same climate science questionnaire 7–14 days after the CO2peration to determine how much information they had retained. No students had been provided with any lessons in climate science at their school prior to the start of the research project.

The participants were all in the first year of high school and between 12 and 13 years of age. Of the 965 students who played the 3D interactive digital game and then completed the science question, 401 students (186–46.4% females, 209–52.1% males, 6–1.5% other) were eligible for final inclusion in the study and analysis. Eligibility depended on valid responses to both questionnaires and signed parental and student permission. Further demographic information can be found in Appendix I.

3.2. *Questionnaire*

The questionnaire for this study was based on an existing questionnaire but was adapted to investigate only cause-based climate science and to extract a detailed overview of climate literacy. Following revision, the present questionnaire involved 19 climate science questions (Appendix II) that encompassed the physical science basis of climate change and, according to the outcome of the previous climate literacy research, was separated into four knowledge domains (KDs, Table 1) (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019). Each of the KDs are ordered and sub-ordered according to the SOLO taxonomy, their tested level of complexity and learning objectives (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019; Biggs & Collis, 1982). The questionnaire was then adapted for the younger age group for use in the prior research project in the early adolescent age group (Harker-Schuch et al., 2019) for readability, phrasing, conceptual comprehension (e.g. while radiation does not bounce, it is frequently used when explaining climate change to younger audiences as they are unlikely to have knowledge about Earth's energy budgets, of concepts in physics such as emission, radiation and absorption, etc.). The questionnaire was translated by a certified English-German translator and proof-read by another certified English-German translator. The final questionnaire was tested on four 12-year-olds for readability, time management, academic level and understanding.

Although the questionnaire was intended to be intellectually extending for the students in order to test the thresholds of their understanding, we endeavoured to minimise the influence of survey fatigue by offering a variety of question types. These included visual questions, drag-and-drop, multiple choice, and four-answers-in-one. As well as reflecting the levels of increasing complexity as described by Biggs and Collis (1982), we were able to construct a questionnaire that was very specific to climate science which, according to Shi et al. (2016), is a requisite to adequately measure climate literacy (Harker-Schuch et al., 2019; Harker-Schuch & Watson, 2019). This specificity was further refined in the scale of complexity in the answers to the more-complicated questions. For example, in the single-answer multiple choice questions, the score of each of the five answers (arranged randomly) scaled from 0% to 100% (0%-25%-50%-75%–100%). Other questions had four answers to one question (with 8 answer options) which allowed us to determine how well the system of a certain aspect of climate science was understood (i.e., beyond a correct/incorrect binary). The careful construction of this questionnaire allows us to extract proficiency signals from the student's responses – and to compare KDs with one another and PRIOR and POST results.

3.3. *Statistical analysis*

To investigate differences between the PRIOR and POST results (PRIOR_SCORE & POST_SCORE) and differences in knowledge domains (e.g., for Knowledge Domain 1: PRIOR_KD1 & POST_KD1) as a measure for climate literacy we conducted a series of paired-samples T-tests and a spearman correlation (IBM Statistics 23.0).

The overall analysis approach:

1. Paired-samples T-test for differences between PRIOR and POST question scores.
2. Paired-samples T-test between PRIOR and POST knowledge domains (KDs).
3 Spearman correlation for association between knowledge domains (KDs).

To investigate the role of confounding factors (school, country, gender) on the performance/improvement and to compare the influence of recreational game play on score, we conducted a series of linear regression analyses (IBM Statistics 23.0).

Additional statistical analysis:

1. Linear regression to assess the relationship between performance on the PRIOR questionnaire, school, country and gender on the results of the POST questionnaire (performance).
2. Linear regression to assess the relationship between PRIOR, school, country, and gender and the change in score (improvement).
3. One-way ANOVA to compare the influence of recreational digital game playing on score differences.

4. **Results**

4.1. *Main statistical analysis results*

The results of this analysis indicate that students performed better on POST than PRIOR testing on some questions in the climate science questionnaire (Fig. 2). That is, on most questions, there was an improvement in participants' climate science knowledge as measured a week following completion of the game.

T-test results indicate a significant difference in the scores between PRIOR questionnaire scores (M = 48.45, SD = 7.97) and POST questionnaire scores (M = 53.61, SD = 11.13); t (400) = −9.75, $p < .001$. On average, climate literacy improved by 5.16% after playing the climate science game 'CO2peration'. Overall, we see an improvement in climate literacy between the questionnaires that can be explained, at least in part, by the treatment of the CO2peration game. Subsequent paired T-test results show significant differences between PRIOR and POST results (Table 2) in each knowledge domain. Improved performance in POST (cf. PRIOR) was observed for all KDs: KD1 1.78% (p = .004); KD2 4.34% (p < .001); (KD3 8.86%) (p < .001); and KD4 5.79%) (p < .001). Therefore, we reject the null hypotheses (H1 and H2) that there will be no improvement in climate literacy generally or in each of the KDs in the 12-13-year-age group with the use of a 3D interactive digital game to teach climate science.

Correlations between PRIOR and POST scores for individual students within each KD were also statistically significant (Table 2), showing correlation between PRIOR and POST scores within each KD, with overall scores averaged across all KDs (KD1, KD3, KD4: p < .001; KD2: p = .003). Therefore, while scores generally improved from PRIOR to POST, the POST results follow the same knowledge weaknesses and strengths within each KD. This demonstrates that the existing knowledge the students had was maintained when we do the follow up; thereby rejecting the null hypothesis (H3) that there is no correlation between the POST and PRIOR results within each KD.

In order to assess for the role of confounding factors, other variables or additional information, further statistical analyses were performed.

4.2. Additional statistical analysis results

To identify whether there was an influence on POST performance due to PRIOR performance, gender, country, and school, a series of regression analyses were conducted, with POST performance as the dependent variable. As such we tested 4 (H4): There is no difference in POST performance due to PRIOR performance, gender, country, and school (H0: There is a difference in POST performance due to PRIOR performance, gender, country, and school). These analyses (Table 3) yielded no significant differences in gender and country (gender p = .27; country p = .744) but some significant differences compared with PRIOR to POST scores, and school. Results from the regression analysis between schools showed that CHS1 (M = 50.24, SD = 9.429) had a POST score significantly different to (lower than) the mean across all schools (mean total = 53.63; mean diff = 3.39; p = 0 0.023). Overall, the model looking at the impacts of schools is not significant, however, as no other schools differed significantly, CHS1 has a p value of < .023 and can be considered borderline when viewed in context with the adjusted R^2value of 0.014 which indicates the effect size is very small. We, therefore, partially reject the null hypothesis (H4) that there is a difference between POST performance due to PRIOR performance, gender, country, and school.

To assess the influence of PRIOR score, gender, country, and school on *improvement* between PRIOR and POST scores, a further series of regression analyses of the change in score were conducted. This we tested as hypothesis 5 (H5): There is no difference in improvement between PRIOR performance and POST performance due to PRIOR score, gender, country, and school (H0: There is a difference in improvement between PRIOR performance and POST performance due to PRIOR score, gender, country, and school). These analyses (Table 4) yielded no significant differences in gender and country (gender p = .690; country p = .067) but significant differences between PRIOR scores, and school, on change in score. Results from the regression analyses confirm the statistically significant influence of PRIOR scores on improvement (p < .001). The analyses also show a statically significant influence of CHS1 (M = 6.12, SD = 10.710) on improvement (i.e. CHS1 students improved substantially less than those at other schools between PRIOR and POST, reflecting the findings of H4).

To determine if differences in score were affected by the time students played computer games recreationally (time spent playing

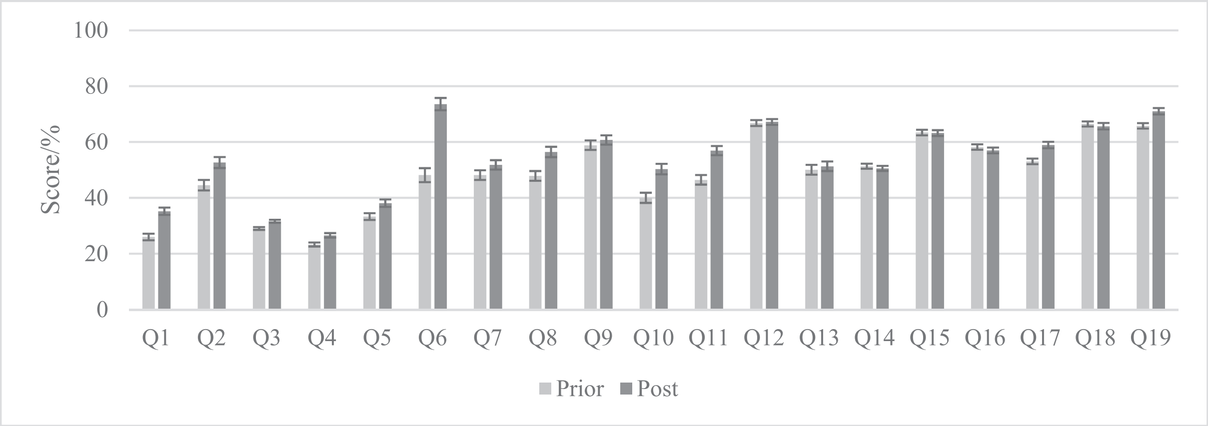

Fig. 2. Comparison of PRIOR to POST results for each question in the climate science questionnaire.

Table 2

Descriptive statistics, *t*-test results and PRIOR-POST correlations in each KD for PRIOR and POST results between all Knowledge Domains (KD1-KD4).

	PRIOR		POST		n	95% CI for Mean Difference	t	Correlation	df
	M	SD	M	SD				r	
KD1	61.37	10.62	63.16	13.45	401	−2.98, −0.59	−2.93**	.509**	400
KD2	50.92	12.98	55.26	15.12	401	−6.15, −2.53	−4.72***	.147**	400
KD3	47.26	16.53	56.13	18.57	401	−11.04, −6.69	−8.01***	.206***	400
KD4	30.67	13.41	36.46	16.08	401	−7.48, −4.10	−6.73***	.329***	400

***$p < .001$ **$p < .01$* $p < .05$.

Table 3

Summary of multiple regression analyses for performance: influence of prior score, school and gender on post scores (PRIOR scores were included for clarity).

Variable	Linear model adjusted R^2	Linear model significance (p-value)	Regression coefficient (B)	Standard error of the coefficient (SE_B)	Significance test of the difference between the coefficient and zero (p-value)
PRIOR performance	**0.177**	<.001***			
Constant			25.012	3.110	–
PRIOR_Score			0.590	0.063	<.001***
Gender	**0.002**	**.27**			
Constant (Male predicted in the model)			54.141	.769	–
Female			-.933	1.121	.405
Other			−6.795	4.603	.141
Country	**0.000**	**.744**			
Constant (Austria predicted in the model)			53.974	1.253	–
Australia			-.457	1.398	.744
School	**0.014**	**.061***			
Constant (SHS1 predicted in the model)			54.196	1.099	–
SHS2			−0.853	1.733	.623
CHS1			−3.961	1.741	.023**
CHS2			1.215	1.621	.454
VHS1			1.083	1.937	.576
VHS2			−2.244	2.268	.323

***p < .001, **p < .01. Note: Regression analyses were conducted separately for each of the variables of interest. Analysis results are displayed for each regression model (bold) and for each predictor within the models (not bold). Multiple regression models built in one predictor for each model, this is noted in the table.

per day in minutes), a one-way ANOVA was conducted. As such we developed hypothesis 6 (H6): There is a difference in POST performance due to the influence of recreational digital game use (H0: There is no difference in POST performance due to the influence of recreational digital game use). Levene's test for homogeneity of variance indicated there was equal variance between each time group (separated by 30-min intervals per day from '0 min' to 'more than 3 h'). The one-way ANOVA analysis indicated there were significant differences between groups ($p = .044$), though with a relatively high significance level of $\alpha = 0.05$, this can be considered a borderline result. To examine this question further, post-ANOVA pair-wise comparisons using Bonferroni's correction were conducted, though there were no statistically significant differences in these post-hoc tests. Although the ANOVA yielded a statistically significant result ($p = .044$), given this was very close to the 0.05 threshold and the post-hoc tests were all non-significant, we therefore fail to reject the null hypothesis (H6) that there is no difference in POST performance due to the influence of recreational digital game use. This indicates whether students are more or less accustomed to playing computer games has no significant bearing on their performance.

5. Discussion

This study explored the use of a proof-of-concept digital game as a vehicle for climate literacy interventions and to investigate the use of knowledge domains to measure climate literacy. In doing so, we tested the prototype curriculum and pedagogical framework and gained feedback on the educational design of the game. We found that the CO2peration game improved climate literacy in one class lesson by 5.16 percentage points. For those KDs where prior knowledge was high (e.g., KD1) the improvement was lower (1.78%) as can be expected when existing knowledge about a specific area was good (PRIOR overall = 61.37%). Equally, for the KDs where prior knowledge was lower and the potential to improve was greater (e.g., KD4; PRIOR overall = 30.67), higher outcomes (5.78%) were also recorded. In addition, results show that there is an association between PRIOR KDs and POST KDs showing that the same knowledge strengths and weaknesses recorded in the respective PRIOR score results persist in the respective POST score results,

Table 4
Summary of multiple regression analyses for improvement: influence of prior score, school and gender on change in score.

Variable	Linear model adjusted R^2	Linear model significance (p-value)	Regression coefficient (B)	Standard error of the coefficient (SE_B)	Significance test of the difference between the coefficient and zero (p-value)
PRIOR performance	**.092**	**<.001*****			
Constant			25.030	3.119	–
PRIOR_Score			-.410	.064	<.001***
Gender	**-.005**	**.912**			
Constant (Male predicted in the model)			4.986	.737	–
Female			.428	1.074	.690
Other			-.486	4.410	.912
Country	**.006**	**.067**			
Constant (Austria predicted in the model)			7.139	1.192	–
Australia			−2.444	1.300	.067
School	**0.032**	**.003****			
Constant (SHS1 predicted in the model)			6.307	1.040	–
SHS2			1.616	1.640	.325
CHS1			−5.814	1.647	. <.001***
CHS2			-.226	1.534	.883
VHS1			1.172	1.833	.523
VHS2			.306	2.146	.887

***p < .001, **p < .01. Note: Regression analyses were conducted separately for each of the variables of interest. Analysis results are displayed for each regression model (bold) and for each predictor within the models (not bold). Multiple regression models built in one predictor for each model, this is noted in the table.

suggesting that the ordering of topics, as defined by the PRIOR results, is sound. For example, KD1 PRIOR is associated with KD1 POST, KD2 PRIOR is associated with KD2 POST, and so on. Results also showed that, overall, little differences exist between country, school and gender, with the exception of CHS1, who performed and improved statistically less well (3.39% lower than the mean difference) than the total study sample (i.e., all schools together). Regarding the large increase in the KD3 score, we observed that the interactive animation that described albedo was particularly successful. We propose that this increase can be explained by to the simple mechanistic and narrative visual required to portray this phenomenon. Further testing of this approach will help illuminate the role of simple mechanistic and narrative approaches to improve learning outcomes both in climate literacy and other topics that require systemic concepts to be understood.

While POST scores were correlated to PRIOR scores, it is necessary to acknowledge that there were only small increases in performance for some questions and no or negligible improvement for others. For questions that had very high scores, such as Q9, Q12, Q15, and Q18 (and, to some extent Q16), we can expect that improvements in the score might be harder to achieve (even show slightly lower scores) at higher levels of literacy. For questions that were at the highest SOLO taxonomy level, such as Q9, Q14, and Q15, we may expect lower success rates as these are the ‘extended abstract’ and typically represent the highest achievement. However, not all lower performance scores at the individual question level can be explained by the pedagogical or curriculum model. In these cases, the failure of the game to adequately teach these LOs, or a shortcoming in the research instrument to measure performance, or a poorly-scaled level of complexity may have either separately - or in combination – contributed to the lower or negligible performance.

Our results support previous research recommendation for the use of visualisations and game-based interventions (Sheppard, 2005; Wibeck, Neset, & Linnér, 2013; Wu & Lee, 2015) to improve climate literacy. In addition, our results support earlier findings (Harker-Schuch et al., 2019) showing that the ordering of KDs is repeated in this study of the 12–13 year age group. These knowledge domains provide a scaffold on which to construct narratives and structured learning objectives and form a natural scale of difficulty (or ‘levels of complexity’ as described by Biggs and Collis (1982)). For example, because 12-13-year olds are familiar with most of the material in KD1: ‘Earth in the Solar System’, a climate literacy programme should start with this topic. This allows a foundation of mastery to be established (Bloom, 1968), i.e., giving the student the material they find the easiest to understand gives them the sense that they can manage the tasks and achieve the learning objectives (Guskey, 2015). Mastery is an essential motivator in engaging with a topic and achieving intended learning objectives (Biggs & Collis, 1982) and allows us to create levels of complexity (Biggs & Collis, 1982; Hattie, 2008; Piaget, 1972). Once KD1 has been mastered, we can tether KD2: ‘GHGs as molecules’ to the knowledge they have acquired in KD1. Once KD2 has been mastered, we can connect KD3: ‘Albedo’ to the knowledge gained from KD1 and KD2. When students have completed KD3, they can start KD4: ‘Earth’s atmosphere’ and tether this KD to the earlier KDs. By determining the KD with which early adolescents are most proficient and ordering the subsequent KDs into their respective levels of complexity, we can develop tools and educational materials that foster understanding and effectively target a learner’s needs and capabilities. In doing so, they will complete a full course on the physical basis of natural variation in climate.

Based on these findings we can now construct a framework for learning objectives (LO), according to the SOLO (Structured and observed learning outcomes) taxonomy from Biggs and Collis (1982). By categorising the questions in each KD (Fig. 3) according to observed learning outcomes (high score to low score), we can develop a taxonomy with increasing complexity for each KD.

When ordered according to KD and LO, the climate literacy framework follows a similar arrangement as those described from the order of KDs as a result of tested outcomes (Table 1). While the proposed climate literacy framework is not infallible, we provide a solid structure that offers teachers a clear framework for all aspects of cause-based climate science that is ordered by the difficulty of the KDs and, within that difficulty, the order of learning objectives (LO) as described by the SOLO Taxonomy. For teachers, this framework performs three services. The first is a climate science curriculum of what should be taught and in what order. The second is a clear overview of climate literacy for teachers less familiar with the physical causes and mechanisms that underpin the climate science phenomena. The third is a grading and assessment rubric that progresses through a student's learning journey; allowing both the learner and the teacher to maintain an audit of improvement and knowledge development.

Regarding the influence of recreational game play on performance, there is no signal in our findings that frequent digital game play affects score performance. Analysis of the time spent playing computer games each day revealed that, while the performance of students who play games a little (0–30 min) is consistent with those who play somewhat moderately (30–60 min), longer time intervals reveal staggered performance for each subsequent 30-min time interval. For example, those students who play for 150–180 min outperformed all other groups and those who play longer than 3 h scored less than all other groups. Therefore, determining a finding from these results is difficult without either refining the type of games that are played, the devices that are used for play and/or the effect of recreational play on serious game performance.

In summary, by giving early adolescents a thorough background in the physical science basis that underpins climate science, we may help ensure worldview development is founded on fact and informed decision-making. Aside from the importance this approach has to worldview, climate literacy also lays a solid intellectual foundation in climate science which will provide students with the tools and understanding they'll need to address this problem. By establishing climate change in the realm of science, we provide a base for meaning-focused coping which will help individuals perceive climate change as a solvable and mitigatable problem. In this way, we can prepare them to be intellectually, psychologically and emotionally equipped to deal with climate change, which is the least we can do in view of the uncertain and tumultuous future we leave for them.

5.1. Considerations and limitations

There are several factors to note. The first is that, we cannot hope to align knowledge with attitude as knowledge is known to be poor (Corner et al., 2015), even when attitudes are high (Clark et al., 2013; Hayhoe, 2013). Although increased climate literacy does correlate with increased concern, the disparity between the two is often large. The second factor is the complexity of the questionnaire which, from a student perspective, is very explicit, detailed and (most probably) quite advanced for that age group. Since it covers most of the climate science topic, it is not cognitively possible for students to learn all the material in the knowledge domains in one science lesson of ~45 min. Without an existing measure of climate literacy in this age group in relation to cause-based climate science knowledge, it was necessary to test student performance in all cause-based KDs to obtain a thorough overview of where their knowledge strengths and weaknesses were (upper and lower knowledge thresholds). Third, the time allocated to playing the game was not longer than one class period of 45–50 min – which is less time allocated to a topic than in the regular classroom (Plutzer, Hannah, et al., 2016). Canhoto and Murphy, 2016, argues that, for deep learning to take place, experiential learning should take place over more than one class period, provide a positive-feedback mechanism (e.g. first-lesson data outcomes forming the basis for subsequent inquiry) as well as a reflective justification of inquiry outcomes. Given these limitations, we feel the 5.16% improvement demonstrates the value of this approach to building climate literacy and anticipate the potential for more substantial gains should the approach be implemented more expansively across several lessons or a term's curriculum.

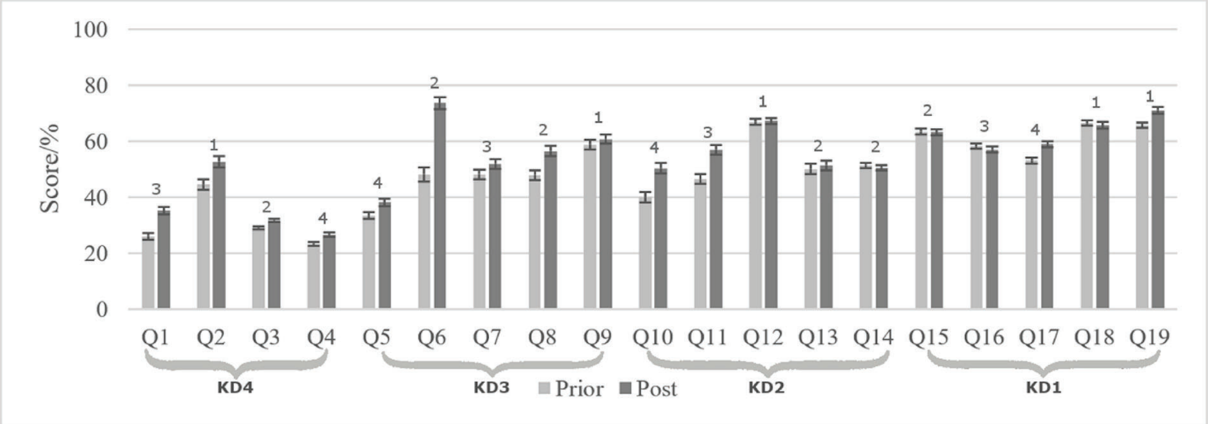

Fig. 3. Order of KDs sorted according to the SOLO Taxonomy as per the observed learning outcomes. Note: values above each column (1–4) denote the order of the Learning Objectives (LO) – scaled from 1 representing the highest scores to 4 representing the lowest (see Appendix III).

Finally, it is necessary to note that there were disruptions at the schools that may have had an impact on the results (due to privacy concerns, it is not appropriate to specify which school had these disruptions). For example, there was a death at one school the day before we post-tested and, in another school, an alarm was activated during a post-test session at the start of the class which triggered an evacuation. After consultation with the teachers, it was agreed to continue with the research as scheduled with provisions made for the students to seek support or counselling if they so required. Lastly, our game was an alpha version proof-of-concept (prototype), not a polished game product. The lower quality of such a game would have implications in learning outcomes and engagement – to what degree will only be elucidated when the beta game is complete and tested.

Regarding limitations, other factors than the gameplay may have contributed to the observed changes in knowledge. For example, the research itself (PRIOR questionnaire, participation in the project) may have primed the students to be more aware of climate-science information as well as other potential influences. While other potential influences include television, the internet, and social media, the study reported no significant differences in the knowledge gains between schools which would suggest that the influences were similar for all groups in Austria and Australia. A lack of prior research on the role of SEGs in climate literacy may have limited the theoretical foundation of this research and, while aspects of gaming culture have been examined, there is a need for a thorough exploration of the potential of SEGs in climate education; particularly in relation to behavioural change. The participation of the schools may influence overall outcomes (selection bias) as they belong to inner-city, urban centres and the inclusion of the school depended on science teaching staff and parents responding favourably to the research project. Favourable attitudes in teachers towards climate change are often transmitted to students and, for this reason, further study in this age group and in a broader socio-political context would be recommended. Without a control group to determine whether the same knowledge gains can be achieved without a game, we cannot presume that knowledge improvement is the result of the game intervention over other instructional methods. While this was not the focus of the study (as described, this was a proof-of-concept' that will form the basis for more rigorous testing in the future), further research into serious educational gaming and climate literacy should include a no-treatment sample and more in-depth research could focus on each KD with respect to different treatments (e.g. no-treatment, conventional learning tools, serious educational game). Finally, we may expect bias in the construction of the research instrument and game (terms/language/culture) that may affect the overall findings.

In addition to these disruptions, there are other, smaller issues that take place when employing digital tools in a classroom. As outlined by Gotkas et al. (2013), there were ICT-related impediments such as lack of hardware, lack of time, lack of technical support; this study experienced similar hurdles with low bandwidth, too few computers or notebooks for participants, and a lack of supporting software (especially when playing the game). Further problems involved issues with game play (some sections did not play on some devices but ran well on others) and functionality complications, i.e., students had to manually stop the game in order to read all the text on the screen. All students, however, were able to play the game and demonstrated a good familiarity with computers. Aside from many not knowing their necessary ID code and/or password to log on there were no observed issues from a research perspective.

6. Conclusion

In this study, we outlined the rationale for developing climate literacy among 12-13-year olds via the school system and tested the prototype climate literacy framework. In addition, we demonstrated why a 3D interactive game is a promising vehicle for improving climate literacy, described the development of an alpha version of such a game, and analysed the impact of deploying this game in classrooms in Australia and Austria. We observed an increase in climate literacy following students' completion of the game. Most notably, these findings demonstrate that early adolescents do understand important concepts related to climate change and they are capable of improving their understanding of climate science which supports previous recommendations to introduce climate science earlier into the secondary curricula.

Our findings indicate that climate science can be taught – and should be taught – as a cause-based natural science in early adolescence. We recommend that the consequences of anthropogenic climate change should only be introduced when students have a solid understanding of the underlying physical causes of climate science in order to prevent opinion-polarisation, action-paralysis, anxiety and to prepare our youth to enter public life with the intellectual tools and skills needed to respond to climate change.

For climate literacy, 3D interactive digital games offer enormous potential as an effective mass communication tool. Visualising climate change helps learners interpret complex information in a meaningful and comprehendible way; visually and dynamically representing processes and mechanisms that may be impossible to explore in real life, e.g., atmospheres on Venus or atomic interactions of greenhouse gas molecules.

To this end, ongoing research should focus on developing a complete framework for teaching climate science and further investigate '*whether the use of games can result in long-term, observable changes in behaviour regarding climate change*' (Wu, Lee, Chang, & Liang, 2013) and if such interventions will be enough – and timely enough – to adequately prepare our youth for tomorrow.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compedu.2019.103705.

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The significance of Chapter 5 to the thesis

This Chapter has answered research questions 4 and 5 and found that as well as improving CSL, the signals of the knowledge domains persisted in both the prior and post climate science questionnaire and across countries, demonstrating the endurance of knowledge strengths and weaknesses in this age group. These knowledge strengths and weaknesses allow development of a more-nuanced structure in the CSL framework that forms a schematic for implementation, narratives, assessment and learning objectives (LOs).

Our findings show that teaching climate science as a natural science that describes the natural climate system in equilibrium is not only possible but, based on findings in previous chapters, would be a very sound pedagogical practice. Of relevance to educators are the ability of this age group to understand many aspects of climate science and the shared knowledge domains that prevail in spite of socio-political or socio-cultural differences. This implies climate science can be taught from early adolescence as a fact-based physical science. Establishing this early foundation for climate science before socio-cultural worldview has been fully developed may eventually lead to a more fact-based worldview.

The research presented in Chapter 5 also shows that the knowledge domains persist – the same strengths and weaknesses in the prior questionnaire are evident in the post questionnaire; further validating the findings in Chapter 4. The knowledge gains from the 3D interactive game were statistically significant in all knowledge domains, which strongly aligns with recommendations in the literature that 3D interactive digital tools should be deployed to teach climate science. After excluding questions with student scores close to or below those expected from random guesses (Table below), it is important to note that the knowledge gains were driven by improvements on five of the 19 questions (Q1, Q2, Q6, Q8, and Q11) with improvement predominantly occurring at the unistructural and multistructural levels (SOLO Taxonomy Levels 1 and 2)

Finally, since Chapter 4 is currently under review and the findings related to Chapter 5 that form the framework for CSL are developed from the same research instrument, peer review for Chapter 4 has highlighted the need to provide further discussion on the random probability of the respondents' scores i.e. by guessing or randomly selecting a choice. Therefore, when we analyse the questions behind each KD (Table 5.5) (for further detail see Appendix VII), there are several points that require further consideration. The first relates to the probability score within each KD level. Using the tested CSL framework from this chapter which adjusted the KDs according to complexity (Appendix VI), the post-test scores in KD1 are higher for all questions (Q15, Q16, Q17, Q18, Q19) than the calculated probability of 50%. The post-test scores for KD2 are high for one question (Q12), but comparable to, or lower, than the calculated probability for all questions of 50% for the other four questions (Q10, Q11, Q13, Q14). The post-test scores for KD3 are high for three questions (Q5, Q6, Q9) but lower than the calculated probability for two questions (Q7, Q8). Four tested scores for KD4 (Q1, Q2, Q4) are higher than the calculated probability and one (Q3) is lower than the calculated probability.

Table 5.5: Probability score for random guessing for each question at each KD level within the tested CSL framework from this chapter which have adjusted the KDs according to complexity (Appendix VI) and showing pre-test scores for comparison. Ordered by SOLO taxonomy and then KD level (see Appendix VI).

KD (App VI) Post-test	**KD (Ch 4)** Pre-test	**Question (App V)**	**Pre-test % correct**	**Post-test % correct**	**Random Guess Score**
1	**2**	19	65.77	71.01	50
		18	66.46	65.65	50
		16	58.17	56.98	50
		15	63.4	63.22	50
		17	53.05	58.92	50
2	**3**	11	46.45	56.92	50
		12	66.77	67.21	50
		10	40.02	50.31	50
		13	50.06	51.31	50
		14	51.31	50.56	50
3	**4**	6	48.13	73.57	25
		8	47.88	56.42	50
		9	58.85	60.72	50
		7	48.13	51.81	50
		5	33.32	38.1	50
4	**1**	2	44.54	52.67	20
		1	25.99	35.21	20
		3	29.07	31.61	50
		4	23.32	26.58	10

* These have been revised after the post-test to include improvement (or lack of) at the question level and in comparison to other questions in the KD

For KD1, these findings provide some insight into the intellectual ability of this age group and offers further evidence, since the scores are higher than the expected values from random guessing, that this age group may be cognitively ready for CSL interventions. For KD2 and KD3, the variability in the overall performance is difficult to assess. While random guessing may be the explanation, other factors could also exert an influence. For example, with KD2 it is possible that the respondents may have some incidental knowledge and, at a higher level of difficulty, will only slightly improve. There is, however, no clear pattern in the responses that offer any clear indication of student behaviour aside from a general improvement at the KD level. This finding may also reflect a measure of survey fatigue as this section of the questionnaire was reached approximately 20 minutes after they started, and we might expect respondents to lose concentration and resort to random guessing when completing a questionnaire at this level of difficulty. For KD3, the low performance in pre- and post-test for Q5 and the high post-test scores for Q6 and Q9 offer some evidence that respondents did not randomly guess although a more detailed statistical assessment is required. However, Q7 and Q8 both sit close to the score of random guessing. In KD4, the higher scores for Q1 and Q2 and the lower scores for Q3 in comparison to the expected scores for random guessing suggest these results represent the true pre- and post-knowledge of these students but, again, a more detailed statistical assessment is required.

Increasing resolution to the question level, there are variable improvements across the questions that need to be discussed (see Fig 2 in Chapter 5 manuscript). While some showed considerable improvement, others had little or no improvement and post-test scores on some questions were lower than on the pre-test. Questions 14 (-0.75%), 15 (-0.18%), 16 (-1.19%) and 18 (-0.81%) all performed less well than in the pre-test. Since three of these questions were all within the highest performing knowledge domain (KD1) and were the easiest for the students to understand, this may be explained, at least in part, by the fact that knowledge gain increases become smaller as performance increases. A reduced performance can also arise as we transform information into understanding at higher levels of complexity, even within a single idea, concept, or piece of knowledge. Aside from Q14 in KD2 which represents the highest level of complexity in that knowledge domain, all other questions showed an improvement in performance. Questions 3 (2.54%), 4 (3.26%), 5 (4.78%), 7 (3.68%), 9 (1.87%), 12

(0.56%) and 13 (1.25%) all showed only slight or modest improvement (defined here as any improvement greater than the pre-test but less than 5%). Questions 1 (9.22%), 2 (8.13%), 8 (8.54%), 17 (5.87%) and 19 (5.24%) all showed good improvement (defined here as any improvement in comparison to the pre-test score that is over 5% and less than 10%). Questions 6 (25.44%), 10 (10.29%) and 11 (10.47%) all showed considerable improvement (defined here as any improvement in comparison to the pre-test that is more than 10%). These results support the view that, with more room for knowledge to develop in KDs that are less well understood, students may be more likely to increase their knowledge. It is important to keep in mind that this was one class period of 45-60 minutes and, with more time, greater knowledge gains might be achieved as students myelinate the knowledge through practice and drill, ongoing exposure and increasing competency.

We cannot, however, discount the possibility that a significant number of students did randomly guess or that a significant number of students may not have had appropriate knowledge to attempt to answer the questions where the mean score was close to that expected from random guessing. Further research in this arena would provide context for these findings and inform further development of the CSL framework for early adolescents in a classroom environment.

Reflecting on when these topics are included in the curriculum (see Section 1.5.3; Table 1.4) the performance in KD1 (Earth and in the Solar System) can be explained by the presence of similar themes or topics in the respective national curricula (Australia: The Earth is part of a system of planets orbiting around a star (the sun); Austria: Erfassen, dass es auf der Erde eine Regelhaftigkeit in der Anordnung klimatischer Erscheinungen gibt). For KD2 (Greenhouse Gases), the topic is not covered until later in secondary school in both Australia and Austria. For KD3 (Albedo), some themes and topics are covered in both the Australian and Austrian curricula (Australia: Light from a source forms shadows and can be absorbed, reflected and refracted; Austria: modellartig verschiedene Formen des Wärmetransportes und wichtige Folgerungen erklären können; Wärmeleitung, Wärmeströmung, Wärmestrahlung). For KD4 (Earth's atmosphere), both the Australian and Austrian curricula include aspects of this topic (Australia: Solids, liquids and gases have different observable properties and behave in different ways; Austria: Einsichten in globale und lokale Wettervorgänge und

Klimaerscheinungen gewinnen (Jahreszeit, Wasserkreislauf auf der Erde, Meeresströmungen, Windsysteme)). This will not mean that domain-specific aspects of the physical/chemical mechansims that describe Earth's climate system in equilibrium will be explicitly taught. Nor does the presence of these topics suggest that students should have knowledge of these topics. Rather, it provides an opportunity for embedding climate science into the curricula in both countries.

Finally, the CSL framework has not been developed solely for early adolescence. Rather, it provides a starting point for introducing the different KDs. With both Australian and Austrian curricula teaching KD1 (Earth in the Solar System), this could be an obvious place to start. How the remaining KDs can be embedded into later secondary education and how older students perform in them will be the task of future research.

Addendum regarding game development and choice of player options, format, and game features.

Since this project was a research endeavour, certain choices were taken with regard to game development to facilitate the research and stay within budget. For example, single-player was chosen due to the socio-cultural nature of the subject and to obtain individual-level data. With regard to socio-cultural influences, when a player is competing against a fellow student, their experience of the game may reinforce their attitude to the content of the game or the material presented in the game and increase polarisation of the issue, i.e., beating another player may positively reinforce a player's attitude to climate science while losing may reinforce a player's anthropocentrism as discussed in Section 1.3.2.9). As well as avoiding polarisation of the climate issue, single-player encourages a player to experience the scientific method as a personal journey of discovery as new concepts and experiences challenge or reinforce existing concepts. Since the content of the game is the same for all players and players must achieve the learning objectives (LOs) in order to progress in the game, individuals are more likely to learn as a group and share similar understanding and knowledge. Furthermore, although multi-player could also have been used to build teams whereby students explore the topic together, it would have prevented collection of individual performance data which was necessary for this research project. In a school setting, which focuses on individual performance and testing, single-player aligns better to public education norms. Research into whether higher learning outcomes and stronger social cohesion can be achieved through multi-player teams toward climate friendly attitudes and behaviour would be a welcome development for climate education.

It is difficult to distinguish between games and simulations, particularly for SEGs, as representations of real-world systems, such as those used in simulations, are frequently used in educational games (De Freitas, 2006). For CO2peration, the aim was to include real-world environments where possible and incorporate the system-oriented processes inherent in simulation-based interactions as outlined by Gredler where the basis is 'a dynamic set of relationships among several variables that reflect authentic causal or relational processes' (2004, page 573). For example, the exploration of Earth’s atmosphere took place within an atmospheric tank simulation which the player could adjust to simulate Earth’s atmosphere by changing the concentrations of atmospheric gases and albedo. However, due to both budget and class-time constraints, the interaction was guided which did not allow students to explore these environments freely and thus fully ‘experience the effects of one’s decisions’ as would be found in a simulation (ibid). Another significant difference is that games provide competition (Gredler, 2004) and fun (Alsawaier, 2018) which relaxes players and motivates players, which ‘enables a learner to take things in more easily, and motivation enables them to put forth effort without resentment’ (Prensky, 2002). The game elements in CO2peration were the quizzes that allowed students to progress and the ‘quest’ of the photon to discover why Earth has liquid water at its surface. However, rewards such as points, skins, leader-boards, badges, and other encouragement were not included in the game due to budget constraints. These are known to improve both enjoyment and learning outcomes (Alsawaier, 2018) and further research should be undertaken to explore this effect on both player engagement and learning outcomes.

Chapter 6:

Conclusions

6. Conclusions

This thesis extends the limited previous research on the potential effectiveness of interventions that seek to induce more climate-friendly attitudes by building climate science knowledge in early adolescents. This age range was selected for study based on a critical review of their intellectual capacity, general physical science knowledge, undeveloped socio-cultural worldview, and previous research on the influences of worldview. Using an international, integrative, and multiple-method approach that drew on theory from the climate communication and climate education domains, this thesis then surveyed the opinions of early adolescents (12-13 year olds) in Austria and Australia on climate change, tested their pre-existing understanding of the physical science that describes the natural climate in equilibrium, and examined the potential for climate science education to improve climate science literacy (CSL) through the application of a 3D interactive climate science game. A previous definition of CSL was analysed and extended and a framework for teaching climate science was tested. I now describe the main findings that the thesis developed.

6.1. Main findings

The key outcomes for the respective research questions are presented below.

Research question 1

What are the characteristics of early adolescents that make them a suitable age-group for climate science communication and education?

The review of previous research in Chapter 1 showed that there are significant complications in interpreting past studies on the relationships amongst socio-cultural worldview, general knowledge, climate-specific science knowledge, and reasoning skills due to definitional and methodological differences between studies. Past research shows that general knowledge and reasoning skills are frequently trumped by socio-cultural worldview, but that climate-specific science knowledge can override worldview. Because socio-cultural worldview can impede efforts to induce more climate-friendly attitudes and behaviour, socio-cultural worldview interventions and climate knowledge building interventions have been perceived as zero-sum pathways for climate communication. I have proposed in Chapter 2 that climate knowledge building interventions may be effective for early adolescents, based on the characteristics of that age group.

Key outcome 1a: Early adolescents may be a highly suitable age group for climate science knowledge deficit interventions as they have begun the second critical stage of intellectual development, have sufficient general physical science knowledge to begin understanding some basic climate science concepts, are beginning more intense exposure in the standard public school curriculum to material closely related to climate science, and have not fully developed their socio-cultural worldviews.

Key outcome 1b: Early adolescents are highly accessible in the compulsory public-school setting and have great potential to effect long-term change due to their social position and age.

Research question 2

What opinions do early adolescents maintain with regard to climate change (their worry about climate change, their opinion on who is responsible, and whether or not climate change is happening now)?

Understanding how this age group perceive climate change and the priority they accord it is an important consideration toward improving climate literacy. Antipathy or apathy toward the topic of climate change would make knowledge deficit interventions difficult to implement and would have challenged the premise on which the overall planned research approach was based. Due to a lack of existing data on opinions in this age group, the study presented in Chapter 3 collected and analysed the opinion data for this age group. The adolescent opinion data also were compared and contrasted with the most relevant adult opinion data available to place the results into a broader context.

Key outcome 2a: Overall, 12-13-year olds are concerned about climate change (88.5%) and believe it is caused by humans (82.5%) and is happening now (85.2%), suggesting strong climate-friendly sensitivities. This concern indicates they are aware of climate change as an issue and may be receptive to climate knowledge deficit intervention.

Key outcome 2b: The opinions of early adolescents on the three dimensions i.e. their concern about climate change, that it is caused by humans, and is happening now, are all highly correlated. For example, when early adolescents are worried about climate change, they are also likely to think climate change is caused by humans and is happening now. These findings suggest that when we know that climate change is a concern for individuals, at least in this age group and in these countries, we can assume those individuals will also think it is anthropogenic in origin and is happening now. This finding is useful as it helps to understand the increasing youth activism such as the recent #FridaysForFuture movement and the potential role that youth play in public policy development both within their families and the broader public arena.

Key outcome 2c: Early adolescents are more concerned about climate change (Austria: 85%, Australia: 89%) than their respective or proxy adult population (Austria: 71%, Australia: 63%). Since the effect of worldview is known to be more elastic in this age group and the influence of parents is apparently less than one may expect according to cultural cognition theory and worldview bias i.e. parents do not appear to be transmitting their attitudes and beliefs about climate change to their offspring, there may be significant value in revisiting the knowledge deficit model as a means of informing early adolescent opinions and attitudes.

Research question 3

What is the current level of climate science literacy (CSL) in the 12-13-year age group?

Intervening to build climate knowledge requires a CSL framework and determining current climate science knowledge. This research established a prior (or incidental) knowledge base and then constructed and tested a CSL framework for this age group. To test this framework, early adolescents were given a climate science questionnaire comprised of 19 questions related to the physical climate science basis (mechanism and processes that describe the natural climate system in equilibrium) and the results analysed to assess the students' pre-existing climate knowledge within defined domains.

Key outcome 3a: CSL as elicited in the developed instrument in the early adolescent age group is 47%, which is comparable to results for older adolescents surveyed using an almost identical questionnaire in prior research. The similarity across ages indicates that CSL does not appear to improve throughout the secondary education period but neither improvements that have been made recently in teaching climate science in secondary school nor any impacts from increasing student interest in climate change in recent years would have been captured.

Key outcome 3b: Knowledge strengths and weaknesses can be compartmentalised into specific knowledge domains with clear, coherent boundaries around what should be taught and when. Within each knowledge domain, the levels of complexity (those that are easiest to learn gradually increasing to those that are hardest to learn) were also ordered from easiest to most difficult. These knowledge domains form a learning scaffold for curriculum-based CSL for understanding the physical climate science that describes the natural climate system in equilibrium. This scaffold introduces a tested CSL framework for early adolescents that describes the physical science basis of the natural climate system in equilibrium.

Key outcome 3c: Although the detailed results suggest students were not randomly guessing, their overall performance (47%) is roughly consistent with what would be expected from random guessing. Performance in the knowledge domains "Earth and water in the Solar System" and "Earth's atmosphere," was above the random guess level for almost all questions. In addition, substantial improvements were seen for many of the SOLO Taxonomy Level 1 and 2 questions after playing the interactive 3D game, CO2peration. Together, these suggest early adolescents may be ready for age-appropriate climate science knowledge deficit interventions, but further study is required to confirm.

Research question 4

Can the interactive 3D game, CO2peration, improve climate science literacy (CSL) in the 12-13-year age group?

Chapter 5 built on the preceding research by investigating the use of an interactive game to improve CSL in the early adolescent age group. The research analysed the improvement in performance of early adolescents after playing a digital 3D, interactive science game. While knowledge deficit interventions are known to improve knowledge, a structured and tested CSL framework has not been incorporated into previous studies. Chapter 5 addressed these gaps by presenting and analysing the comparative results obtained from administering the 19-question climate science questionnaire before and after the adolescents played CO2peration.

Key outcome 4a: CSL may be able to be improved with a digital, 3D interactive game that teaches the physical science basis of the natural climate system in equilibrium. Substantial improvements were seen for five of the 19 questions, particularly for many of the SOLO Taxonomy Level 1 and 2 questions.

Key outcome 4b: The relative performance within the knowledge domains and observed learning outcomes as determined from the pre-intervention results in Key Outcome 3b were observed again in the post-intervention results. These findings show that the same knowledge deficit patterns that were observed in the pre-test were also present in the post-test, and test performance improved overall.

Key outcome 4c: Interventions that exploit visual information technology, such as 3D interactive games, offer potential for improving CSL and may assist learners in conceptualising and contextualising climate change. Using dynamic visualisations may be a particularly useful tool to represent dynamic processes and mechanisms that are difficult to describe in text and/or impossible to explore in real life.

6.2. Major Contributions

Contribution 1: The thesis has argued that early adolescents may be an important group for climate communication efforts. This study simultaneously examined this age group in consideration of their concerns, their intellectual to learn climate science, and their social capacity to effect change.

Contribution 2: This research provides evidence that interpretations commonly expressed in the climate communication literature of knowledge deficit need to be revisited, particularly in relation to worldview and cultural cognition theory.

Contribution 3: This study broadens the body of public opinion research by including the previously overlooked, and under-researched, opinions in the 12-13-year age group. This advances knowledge on the spectrum of opinion over time and at different ages, includes a broader swathe of the population, and offers important data on worldview development.

Contribution 4: As educators and communicators continue to struggle with the mass communication barriers associated with climate change, this study shows that there are potential opportunities for improving CSL in the compulsory education system.

Contribution 5: This study demonstrates the potential contribution that 3D interactive digital science games can make to improving CSL in the compulsory education system. Actual effectiveness will depend on how they are integrated, used, and supported.

Contribution 6: The CSL framework was designed for early adolescent education based on tested learning outcomes and knowledge domains from research on CSL in 12-13-year olds. To the author's knowledge, this is the first tested CSL framework that includes climate communication theory and the analysis of prior and post results across important demographic factors. The CSL framework is also the first framework that provides a rationale for teaching the physical basis of climate change (mechanisms and processes that describe the natural climate system in equilibrium) as the departure point for further development of CL.

Contribution 7: This thesis proposes a strategy towards cultivating a fact-based world view on climate change in early adolescents by providing them first with the scientific facts that ensure they are sufficiently conversant with the mechanisms and processes of the physical basis of climate science.

6.3. Challenges and limitations

This thesis faced challenges and limitation including 1) a limited number of schools, participants and countries; 2) a lack of prior data on CSL and opinion in the early adolescent age group; 3) limitations within the research instrument; 4) limitations to the time period for data collection ; 5) challenges in including a full exploration of CSL; 6) limitations due to class teaching time and availability of the class for this research; 7) access to schools and students and the socio-political associations and perceptions of climate change; 8) cultural and other bias; 9) the absence of a control group; 10) the

CSL framework as a prototype; 11) budget and financial limitations; and 12) the lack of input from the students regarding the game experience.

It is acknowledged that the selection of Austria and Australia may not be a representative sample (1) of all 12-13-year olds and, while the sample number of the research was robust for a project of this size, a larger (number of respondents and participating schools), more diverse and geographically scattered sample would provide greater insight into both CSL and opinion in the early adolescent age group. The locations of the schools in inner, urban areas of major cities are likely to affect the findings i.e., worldview influence, and studies that include regional, rural and/or remote locations would provide further context for research in this domain.

Due to a lack of prior data in the 12-13-year age group in relation to CSL and opinions (2), it was not possible to obtain a meaningful comparison on attitudes and knowledge about climate change and science in this age group.

In conjunction with a lack of prior data on this age group, a tried and tested questionnaire on the domain-specific, physical science basis of climate change (that which describes the mechanisms and processes of the natural climate system in equilibrium) was also lacking (3). The research instrument that was employed was adapted from an earlier study investigating CSL in 16-17-year olds and, while the original research instrument provided a strong connection to CSL, the questionnaire had to be amended to encompass only knowledge related to the physical-chemical mechanisms of climate science as well as important pedagogical factors (e.g., climate communication theory, the SOLO taxonomy). Since the physical/chemical mechanisms of Earth's climate system in equilibrium do not include variability (see Table 4.1) natural aspects contributing to the natural state of Earth's climate were not included. No single instrument can capture all the aspects of CSL and there may be benefit to alternative approaches. Since this research intended to establish a baseline of CSL in the early adolescent age group, a quantitative approach was deemed the most suitable. Structuring the research instrument to include all aspects of the physical-chemical mechanisms to describe the climate system in equilibrium is challenging and some aspects may have been omitted or overlooked. Furthermore, in order to consider the influence of random guessing, different styles of questions covering the same, or similar content, should be trialled to better understand the degree to which students might randomly guess answers. With regard to the completeness of the CSL framework (see the limitation of CSL as a prototype; (10) below), there is also a limitation on whether the research instrument fulfils the task of capturing all relevant portions of the CSL framework. Without an antecedent research instrument or CSL framework, it is difficult to resolve this challenge. In light of the fragmentation of climate education in the compulsory school system, a lack of a climate science literacy definition for education (particularly for teaching the physical/chemical mechanism that describe Earth's climate in equilibrium), ongoing discussion about knowledge deficit interventions, and the lack of a precedent, further testing of the research instrument is recommended.

Naturally, like most 3-year doctoral research projects, there were time limitations in relation to data collection (4) which defined both the scope and the boundaries of this study. One aspect that deserves further investigation is a longitudinal study on the influence of the improved CSL on the subsequent attitudes and opinions of participants in relation to climate change and their ability to retain the knowledge, particularly in comparison to the retention of other science knowledge. This study did not follow up on opinions in the POST questionnaire as previous research indicates that opinion development and revision may take longer than the period in which this research took place (Harker-Schuch & Bugge-Henriksen, 2013). There is also a lack of literature on the effect of specific climate change knowledge deficit interventions. Further investigation would provide context for the results found in this study and provide context on the effect of knowledge deficit interventions on climate-friendly attitude and behaviour and how well students are able to retain knowledge. A longer-term longitudinal study could also assess the degree to which improved early adolescent CSL impacts later adolescent worldview.

The time limit also prohibited a full exploration of all aspects of CSL (5). There will be sub-domains that may have not received the same attention or consideration as other sub-domains. At the time of thesis completion, I was not aware of any sub-domains within the physical-chemical mechanisms of Earth's climate system in equilibrium that were not covered, at least in part, by the first four KDs. This does not mean that there are none, and further elucidation of what constitutes the KDs for the physical-chemical mechanisms of Earth's climate system in equilibrium are recommended.

The teaching scenario was also a challenge (6) as students only had ~1 hour to play the game before testing for knowledge domains 7-14 days later. A better scenario is before and after a longer module as this allows students the opportunity to 'practice and drill' new information and knowledge. However, since research indicates that only 1-2 hours a year is dedicated to climate topics in the classroom (Plutzer, McCaffrey, et al., 2016) and, with the pre- and post-test, this research required teachers to make 3 hours available in their scheduled class time, this was considered a fair arrangement for those involved.

Given this research depended on agreements and permissions from many different groups in a public education setting, an important limitation was access to schools and students (7) and the effect of a household/community worldview bias. School directors, teachers, and parents that support and advocate climate-friendly engagement and activities are more likely to respond to requests for participation in research of this nature than those who deny or challenge climate change. The socio-political associations and perceptions of climate change at the household level have a well-known effect on engagement and denial and we can assume, based on this influence, that data from those students who live in households where climate change is denied are less likely to participate than those who live in households where attitudes toward climate change are ambivalent or accepted.

A further limitation is the selection of countries that participated in the project and the familiarity of terms/language/culture (8). Cultural bias at a broader societal and national level may also play a role in both permission and in student performance. As was discussed in Chapter 4, a high refusal rate at one school was ascribed to an influx of new immigrants at the school. Aside from language barriers, immersion in a new environment may provoke suspicion and anxiety. Vulnerable parents are likely to refuse permission, particularly in the context of a research project.

The absence of a control group (9) is a further limitation in this research as we cannot confirm that the knowledge improvements were produced by the knowledge deficit intervention. While the pre-test provides some control on the performance at the student level between pre- and post-test, the intervention may not be the sole driver of knowledge development. The improvements may have occurred because of an increased awareness triggered by the pre-test and, therefore, primed the respondents to become more attentive to climate-related information during the data collection period. Furthermore, although teachers were asked not to discuss the climate topic until the research was completed, students were free to discuss the topic amongst themselves or at home with their familiar others. However, it is unlikely that large improvements in the post-test are a result of priming or discourse as the results are common across the schools both at the question level and within the KDs. We cannot rule out, however, the influence of other factors and further research would benefit from the use of a control.

The CSL framework as a prototype also presents several limitations (10) as there is no existing framework which attends to the complete physical/chemical mechanisms of the climate system in equilibrium, nor includes climate communication theory – particularly that related to worldview development. The CSL may, therefore, not be a comprehensive summation of all aspects of the physical/chemical mechanisms that describe Earth's climate system in equilibrium. While I have defined CSL (in terms of knowledge related to the physical/chemical mechanisms that describe Earth's climate system in equilibrium), mapped the KDs to this definition and clarified the relationship of the test questions to the KDs, there may be gaps in this design that fail to appropriately or comprehensively test the defined CSL. Further research should test the reliability and validity of this framework over time, both as a measure of CSL in the early adolescent age group and as an instrument for testing CSL in the broader public arena. The limitations presented by the connection between the CSL framework and the research instrument depend also on further testing and refinement of the definition and the research instrument in context with one another.

A further limitation and challenge was the constrained budget for the CO2peration game (11). As a prototype serious educational game, CO2peration had a very low budget of approximately A$30,000. This meant that many common game features, even those employed in recreational games, had not yet been included in order to prioritise scientific content, visualisations, and interactions. From a student perspective, rewards and points are known to improve player enjoyment and learning outcomes and these features may impact the overall performance of climate SEGs. From a teacher perspective, back-end evaluation data on student performance and engagement, such as time spent in different sections of the game or game-play patterns, were also not included in the prototype. These game analytics would be valuable for understanding student knowledge and providing further insight into how and how well students use games to improve their climate science knowledge. It is worth noting that reward and point features have now been added to the latest versions of the climate games with an overall performance improvement of 12% for KD1: ‘Earth, temperature and water in the Solar System’, and 28% for KD2: ‘Greenhouse gases as molecules’ (the only updated KDs tested by student users to date). It is difficult to assign the reward and points system to this improvement, but student enjoyment in this feature was repeatedly observed during alpha testing.

Lastly, due to the complexity and scope of the project, it was decided after the period of data collection not to use the recorded focus group data (12). This decision was made to control the scope and size of the project. As a result, input regarding the game experience was considered secondary to obtaining a baseline of understanding, in spite of the importance of including young people in the design of interventions aimed at them. Furthermore, since the game development had been excluded from the research project, analysis of data from focus groups was tangential to the defined research aims. Nevertheless, student and player experiences are an essential component of both learning and SEGs. The absence of student feedback in this thesis is merely a reflection of research scope limitations and a decision to focus on knowledge interventions.

6.4. Implications and recommendations

This thesis proposes a strategy towards cultivating a fact-based world view on climate change in early adolescents by providing them first with the scientific facts that ensure they are sufficiently conversant with the mechanisms and processes of the physical basis of climate science. With the prospect of revisiting knowledge deficit interventions in relation to CSL there are several implications and recommendations that I have identified in this thesis that may be important for climate education, climate policy and climate communication theory. The first is the need to revisit the interpretation of knowledge deficit in relation to worldview and cultural cognition theory or to resolve the confusion between knowledge deficit as an intervention or knowledge deficit as background or incidental knowledge. This is necessary as there is evidence that knowledge deficit interventions are effective at improving understanding which, in turn, have a positive effect on climate-friendly attitudes and behaviour. The influence of worldview on young people is also not determined and while they may be at early stages of worldview formation, the influence of worldview may already affect knowledge deficit interventions. There are, however, several factors to incorporate in a revisited knowledge deficit intervention model that will impact the effectiveness of CSL efforts aimed at improving climate-friendly attitudes and behaviour. These include 1) the age when knowledge deficit interventions should start; 2) the need to focus on domain-specific knowledge; 3) the need to first teach the physical/chemical mechanisms that describe the climate system in equilibrium before teaching climate change or instability: 4) the importance of including learner's psychological wellbeing and their concern about climate change; and 5) revision of the efforts in compulsory education aimed at CSL knowledge deficit interventions. Lastly, (6) the prototype of the climate science game itself needs to be refined and updated to reflect what has been learned during this research project and for practical use in the classroom.

Due to their age (1), early adolescents may be uniquely positioned for cultivating an informed, fact-based worldview as a result of their intellectual development, the factor of anchoring, and their fledging worldview. Providing CSL in early adolescence allows students to anchor their concepts of climate change in a science narrative upon which further learning can take place. This may assist in developing a stronger fact-based worldview as students grow older and their worldview develops.

CSL knowledge deficit interventions (2) have been shown to be most effective when domain-specific knowledge is taught. The strong evidence supporting knowledge deficit interventions focus on the role of learner understanding of the mechanisms and processes that describe the climate system. Efforts to improve climate-friendly attitudes and behaviour in the compulsory education sector may be improved via knowledge deficit interventions that focus on domain-specific knowledge.

Due to the emotional needs of early adolescents and the anchoring heuristic, introducing the physical science basis of climate change (3) (mechanisms and process that describe the natural climate system in equilibrium) before other aspects (feedbacks, natural variations, anthropogenic influences) might be more intellectually and psychologically beneficial to early adolescents and may reduce negative effects such as polarisation and inaction that have been associated with fear appeals and emotional coping.

There is evidence that the early adolescent age group is particularly vulnerable to psychological burdens and anxiety in the face of a changing climate (4). This concern is something that requires a response from the adult population in some form that will acknowledge their concern and provide them with an avenue to constructively process it, especially as they occur during the fragile and tumultuous years of adolescence. This could be in the form of counselling, emotional-support, capacity-building and knowledge-development. Interventions that avoid confrontations with the potential consequences and impacts of climate change are recommended. Initially framing climate change (as per the CSL framework which introduces the physical/chemical mechanisms of the climate system in equilibrium) as a solvable, 'normal' science problem prior to introducing the post-normal aspects of anthropogenic climate change may empower individuals to engage with climate change more meaningfully and diminish the perception of complexity and global threat. Furthermore, by anchoring the facts related to the 'normal' science of Earth's climate students may be better equipped to psychologically manage the post-normal dimensions of climate change when they encounter them at a later age. The concern shown by early adolescents may also offer climate communicators and educators an opportunity to assist young people in building resilience and self-efficacy – with the well-being and stability of these individuals remaining at the heart of any prospective intervention. Their concern indicates they are overwhelmingly aware of it as an issue and providing them with information, skills, tools and knowledge is a logical next step toward addressing their concerns as well as offering them a chance to engage in emissions reduction and climate-friendly activities.

Efforts in the compulsory education sector need to revise their practice and training of CSL in the classroom (5). Knowledge deficit interventions will not work if the topic remains fragmented, if teachers are not adequately prepared or trained to teach climate change and continue to devote so little time to CSL in the classroom. This study offers a method to improve CSL in the public-school environment that may avoid the risk of worldview bias by teachers, overcome misinformation and confusion from teachers, and ensure that students are provided with fact- and physical science-based CSL to assist them to develop an informed and fact-based opinion about climate change. An effective way to overcome these impediments is the use of 3D interactive digital games that allow 'trusted messengers' (familiar teachers) to deliver the curriculum of climate science without the burden of being a climate expert; permitting teachers to facilitate the process of learning and supporting their students as they navigate this perplexing and complicated task.

Finally, the prototype of the climate science game needs to be adapted and revised (6) to both reflect what has been learned in this research project and in a practical application of the CSL framework and the game in an educational setting. The first recommendation is to add rewards, such as points, leader-boards, badges, or similar, to improve player enjoyment and engagement. The second recommendation is to ensure that there is a focus on 'game' interactions to improve learning performance. Lastly, I would recommend that the game be divided into four distinct games, one for each KD (at least those related to the 'Earth's climate system in equilibrium' until further testing of the CSL framework is completed). The material in each game should be expanded to incorporate more content, including more game interactions and rewards, as well as a more thorough explanation and exploration of the scientific matter. Each game should be played progressively over time to allow the students to maintain a familiarity with the topic and to improve knowledge and competency i.e., via myelination and practice and drill.

6.5. Future research

This research set out to establish a CSL benchmark in the 12-13-year age group and to investigate how a 3D interactive serious educational science game might be employed to improve CSL with the hope that enhanced CSL helps cultivate a fact-based worldview. The structure of this thesis provides a natural guide for future research.

To begin with, further research in the early adolescence age group in relation to CSL and worldview development is a logical first step. Research that secures CSL as the bedrock of opinion development is sorely lacking both in theoretical and applied studies. Further research in this context that includes regional, rural and remote participants in geographically diverse locations may offer us a better understanding of what CSL means at a global scale. The association of concern and climate change as a pathway to engagement needs further examination.

Perhaps the most important direction for future research in opinion and climate change in the early adolescent age group is how we might be able to cultivate a fact-based worldview on climate change through knowledge deficit interventions i.e. revisiting the influence of knowledge deficit. As for emotional and anxiety responses to climate change, one possible future direction may be to foster meaning-focused coping, hope and capacity building as a response to adolescent concern. Furthermore, there is evidence that the focus on opinion needs to serve a more functional and constructive purpose rather than merely as a gauge of attitudes and perceptions; particularly in relation to emotions and hope and over a longer period of time.

Due to time constraints, ethical considerations and the complicated relationship amongst knowledge, attitude, and behaviour, I have not tested for how knowledge may impact attitude nor how this, either in tandem with knowledge or alone, could impact behaviour. There is a need to include the complex, difficult and contested dynamics of the KAB model and the influence of the knowledge and attitude dimensions on behavioural change. Therefore, a longitudinal study that investigates the role and longer-term impacts of knowledge deficit interventions during early adolescence would provide meaningful context for knowledge in relation to attitude and behaviour.

With regard to CSL, future research that examines the physical science and domain-specific knowledge of CSL both as a focus for opinion development and the role of knowledge deficit interventions would provide context for the findings in this study and illuminate the role this kind of knowledge has on worldview development, engagement and self-efficacy. While this study establishes the suitability of early secondary as an ideal starting point for knowledge deficit interventions, the development of a CSL framework that operates throughout mandated secondary school (12-16 years) and covers all aspects of climate science, including feedbacks and anthropogenic influences, is sorely needed. To achieve this, further work is needed to develop the research instrument, the CSL framework, the testing scenario and the definition of CSL. In addition to expanding and refining the KDs, the research instrument should be broken down into component parts and further tested and revised to explore, in greater detail and depth, important components of the physical-chemical mechanisms that describe Earth's climate system in equilibrium.

In relation to 3D interactive digital games that teach climate science, more work needs to be done. Apart from further research into improving CSL through visualisations, a pedagogy for learning in this environment is critical; particularly in teacher-supported learning environments. Accessibility in the public-school system is also a major consideration and future research needs to consider how to embed accessibility in digital games for players with disabilities or provide hardware for less able-bodied players (e.g., Xbox adaptive controller). Also including options for subtitles, for example, may provide access for the hearing-impaired. Sound design can also allow sight-impaired and blind people to play games (voice navigation and musical cues) which may allow them to participate in regular classroom activities.

Including a control group should also be a priority of future research. There are onerous aspects to securing research conditions that, in many ways prevented the inclusion of a control group. These include the barriers to gaining approval which is, in many countries, a six-step process: 1) ethics permission; 2) Department of education approval; 3) school approval i.e. via school director; 4) explicit teacher agreement and participation; 5) parental agreement, and 6) student agreement and participation. Due to these burdens, I prioritised the testing of the intervention with all participants. Future research that is better resourced or has existing research agreements could look at recruiting other schools for counter-factual / control studies.

Future research should further explore the definition of the knowledge domains and investigate how the CSL framework could be expanded in the classroom either through intended instruction or in cross-curricula activities, i.e. aligning them with existing topics or tasks in the national curricula. Since the completion of this research, I have developed a series of serious educational games for CSL in the secondary classroom based on the CSL framework. Consequently, I have refined the KDs for better implementation in the classroom and in response to peer-review and critique from the thesis examiners. Since the aim of this research was to establish a CSL baseline or starting point upon which to establish knowledge deficit interventions over time, one climate science game in a class lesson of 45 minutes is unlikely to improve knowledge or provide the cognitive scaffold necessary to adequately grasp the physical and chemical processes that describe Earth's climate system in equilibrium. Therefore, the CSL framework was revised to now include 5 KDs that cover the physical and chemical processes that describe Earth's climate system in equilibrium by expanding KD1 (Earth and water in the Solar System), KD3 (Albedo), and KD4 (Earth's atmosphere) and adding an additional KD5 topic on the carbon cycle, ocean acidification and biodiversity. No significant revisions were necessary for KD2 (greenhouse gases as molecules). Each KD is taught within a 45-minute lesson and takes an Earth Systems science approach to learning (Finley et al., 2011). That is, since KD1 opens the CSL topic I have added a narrative leitmotiv or 'röd tråd' (from the Swedish meaning 'red thread' which is a narrative tool used in storytelling and professional writing) to conceptualise climate science in context with the learner's relationship to, and perception of, the environment. For example, KD1 (Earth, temperature, and water in the Solar System) posits climate (precipitation and temperature) as the main driver of biodiversity. Since humans, and particularly children, are known to have an affinity for animals, this offers an anchor upon which the CSL topic can be meaningfully fixed. KD5 closes the biodiversity narrative with an exploration of the role of carbon both as a basis for life and as threat to biodiversity and humans. This red thread also helps learners conceptualise the climate system as an interacting, interconnected and dynamic system within and across the KDs.

KD1 (Earth and water in the Solar System) was expanded to explicitly include weather and climate (and how climate is defined and measured) and to prime learners for an expanded exploration of the hydrological cycle in the revised KD4 (Earth's atmosphere). The KD1 (Earth and water in the Solar System) title is now KD1 (Earth, temperature, and water in the Solar System) to highlight temperature as an essential factor for life on Earth, both in relation to liquid water (circumstellar habitable zone) and as an essential driver of weather.

KD3 (Albedo) was revised to explicitly describe and model the greenhouse effect and Earth's planetary budget. Although these concepts were implicitly covered in KD3, examiner feedback suggested there was a need to highlight these concepts and ensure students were aware of radiative budgets and the greenhouse effect model. Please note, while this KD could be titled 'The Greenhouse Effect', this term is frequently criticised as it incorrectly alludes to the physical mechanism of a green- or glass-house. In addition, avoiding 'apocalypse fatigue' is an important consideration so standard terms associated with climate change such as global warming were specifically eschewed. Overly complex-sounding titles, like Earth's energy budget, were also avoided. As a title, albedo is novel and easy to remember. On a side note observed during testing, one student remarked, 'I bet albedo means 'white', like Albus Dumbledore'. In this example, it is likely that the student has few or no preconceptions about albedo, which is important for developing fact-based worldviews in relation to climate change but is ready to frame the term in context with their fledgling socio-cultural identity.

KD4 (Earth's atmosphere) was expanded to include an exploration of the hydrological cycle and build on knowledge from KD1 (Earth, temperature, and water in the Solar System) with a reduced emphasis on the properties of the atmospheric layers above the stratosphere. As well as examiner queries related to the importance of these layers, I felt it was appropriate to keep a focus on the natural elements rather than on human endeavours in keeping with the overall framework focus on the physical and chemical mechanisms in Earth's natural climate system. While the layers are briefly explored, the foci are how the layers are defined (change in temperature), the ozone layer as a different environmental problem and formation of weather in the troposphere. KD4 (Earth's atmosphere) ends with an investigation of the uncertainty in the climate forcing of clouds to 1) reinforce the established climate science evidence; 2) to highlight where some of the scientific uncertainty lies and to connect KD3 (Albedo) with KD4 (Earth's atmosphere).

KD5 (carbon, biodiversity, and climate) was added to respond to examiners' critique that the carbon cycle had not been included and as a segue between the topics on physical and chemical mechanisms in Earth's natural climate system and those related specifically to climate change, such as natural drivers of climate variation, feedbacks, and the human role in climate change. KD5 also explores ocean acidification and highlights this as a related, but distinct, environmental problem arising from fossil fuel emissions. As described, this last KD concludes the physical mechanisms of climate science and connects back to the narrative leitmotiv or 'röd tråd' started in KD1.

There have been other changes to the CSL framework and it has been informally tested repeatedly since it was first constructed for this research, but the main findings remain clear even after these changes have been implemented. Overall, the revised KDs show the same performance signals as the KDs examined in this thesis. This indicates that the order of KDs is useful and provides a meaningful starting point for CSL knowledge deficit interventions.

Finally, as outlined previously, the CSL research instrument that formed the foundation of the CSL framework should be broken down into the component KDs and the questions should be revised and further expanded upon to explore each KD in more detail and depth. As the topics have become more complex and in-depth there is a need for new questions to test the increasing complexity as per the SOLO taxonomy. The revisions that have been made to the research instrument, however, form part of a new research project and these revisions will be reported as the CSL is further tested and the project progresses. It is worth noting that the revision of the research instrument includes topics for the carbon cycle, energy sources and sinks, radiation transfer, and regional and global perspectives on weather and climate, amongst other pertinent topics that describe the physical-chemical mechanisms that describe Earth's climate system in equilibrium.

6.6. Concluding remarks

The research in this thesis examined four important aspects of climate science in the modern public-school classroom in response to an ongoing mass communication problem in relation to climate change. These were 1) the suitability of early adolescents to domain-specific climate science knowledge deficit interventions; 2) their opinions about climate change; 3) the refinement of the CSL definition and the development of a CSL framework that addressed the physical/chemical mechanisms that describe Earth's climate system in equilibrium; and 4) the use of a 3D interactive climate science game to improve CSL in the early adolescent age group. While pre-existing worldview has been a pernicious barrier to communication efforts, this research has highlighted the need to include new groups in communication and education efforts and to revisit the value of knowledge as a motivator towards climate-friendly attitudes and behaviour. As well as this new audience, this thesis offers new methodologies i.e. a CSL framework, and state-of-the-art tools i.e., 3D interactive digital games, which may offer opportunities to improve climate communication.

The task of climate amelioration now lies at the feet of our children. The least we can do is provide them with the intellectual tools they will need to manage that task and further develop their psychological fortitude to face it.

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Appendices

Appendix I – Data sources for opinions of adults

AI.1: Source of opinion polls for adult CONCERN opinion on climate change

	Reference	Question	Answers						
CONCERN: Opinions on whether climate change is a concern or something to worry about	Yale Climate Opinion Maps, 2016	How worried are you about global warming?	Very worried	Somewhat worried	Not very worried Not at all worried				
	Steentjes et al., 2017	How worried, if at all, are you about climate change?	Not al all worried	Not very worried	Fairly worried	Very worried	Extremely worried		
	Pew Research Center, 2017	I'd like your opinion about some possible international concerns for (survey country). Do you think that global climate change is a major threat, a minor threat or not a threat to (survey country)?	Major threat	Minor threat	Not a threat	Don't know/no response			
	Yale Climate Opinion Maps, 2016	There is a controversy over what the countries of the world, including Australia, should do about the problem of global warming. I'm going to read you three statements. Please tell me which statement comes closest to your own point of view:	Global warming is a serious and pressing problem. We should begin taking steps now even if this involves significant costs	The problem of global warming should be addressed, but its effects will be gradual, so we can deal with the problem gradually by taking steps that are low in cost	Until we are sure that global warming is really a problem, we should not take any steps that would have economic costs	Don't know/no response			
	Steentjes et al., 2017	How much do you, personally, care about the issue of global climate change?	A great deal	Some	Not too much	Not at all	No response		
	Pew Research Center, 2016	As I read each one, please tell me if you personally worry about this problem a great deal, a fair amount, only a little, or not at all. First, how much do you personally worry about climate change or global warming?	Great deal	Fair amount	Only a little	Not at all	No response		
	Eurobarometer Climate change, 2017	And how serious a problem do you think climate change is at this moment?	Scale from 1 to 10, with '1' meaning it is "not at all a serious problem" and '10' meaning it is "an extremely serious problem						
	Leviston et al., 2014	How worried are you?	Scale from 1-4 1 with 1 of least concern to 4 of greatest concern						

AI.2: Source of opinion polls for adult ANTHROPOGENIC opinion on climate change

	Reference	Question	Answers						
ANTHROPOGENIC: Opinions on whether humans are causing climate change	Yale Climate Opinion Maps, 2016	Assuming global warming is happening, do you think it is…? Caused by human activities	Caused mostly by human activities	Caused mostly by natural changes in the environment	Other	None of the above because global warming isn't happening			
	Steentjes et al., 2017	Thinking about the causes of climate change, which, if any, of the following best describes your opinion?	There is no such thing as climate change	…entirely caused by natural processes	…mainly caused by natural processes	…partly caused by natural processes and partly caused by human activity	…mainly caused by human activity	…completely caused by human activity	Don't know
	Pew Research Center, 2016	Even if you are not sure, which of these three statements about the Earth's temperature comes closest to your view?	The Earth is getting warmer mostly because of human activity such as burning fossil fuels/lean	The Earth is getting warmer mostly because of natural patterns in the Earth's environment/lean	There is no solid evidence that the Earth is getting warmer/lean	No response			
	Gallup: Social Series, 2017	And from what you have heard or read, do you believe increases in the Earth's temperature over the last century are due to:	Human activities	Natural causes	No opinion				
	Climate Institute, 2016	Which one of the following statements is closest to your opinion?	I think that humans are the main cause of climate change	I think that natural cycles are the main cause of climate change	I think that climate change is due to a mixture of human causes and natural cycles	I'm unsure/don't know what the causes of climate change are			
	Leviston et al., 2014	Estimate the percentage that human activity contributes to climate change	Scale from 1 to 100 from '0 = not at all confident' to '100 = completely confident'						

AI.3: Source of opinion polls for adult IMMINENCE opinion on climate change

	Reference	**Question**	**Answers**						
NOW: Opinions on whether climate change is happening now	Leviston et al., 2014	Do you think that global warming is happening?	Yes	No	Don't know				
	Steentjes et al., 2017	As far as you know, do you think the world's climate is changing or not?	Yes, I think that the world's climate is changing	No, I do not think that the world's climate is changing	Don't know				
	Gallup: Social Series, 2017	Which of the following statements reflects your view of when the effects of global warming will begin to happen – they have…	Already begun	Within a few years	Within your lifetime	Not within lifetime, but affect the future	Never will happen	No opinion	
	Climate Institute, 2016	To what degree do you think we are experiencing the impacts of climate change in Australia?	A lot	A little	Not very much	Not at all			
	Yale Climate Opinion Maps, 2016	Global warming is already harming people in the US When do you think global warming will start to harm people in the United States?	They are being harmed right now	In 10 years	In 25 years	In 50 years	In 100 years	Never	

Appendix II – Opinion data on adults

Is climate change something to worry about?

AII.1: Overview of adult opinion in the developed world per country on whether climate change is something to worry about. * Derived from mean

Country	**% of respondents**	**n**	**Source**	**Error margin**	**Mean country data**
Austria	68%	1,001	(*European Commission: Eurobarometer Climate Change*, 2017)	+/- 2.8%	70%
Australia	54%	1,200	(Lowy Institute Poll, 2017)	+/- 2.8%	63.3%*
	60%	1,000	(Pew Research Center, 2017)	+/- 5.1%	
	66.5%**	5,030-5,219	(Leviston, Greenhill, et al., 2014)		
United States	36%	1,534	(Pew Research Center, 2016)	+/- 4%	48.3%*
	56%	18,000	(Yale Climate Opinion Maps, 2016)	+/- 7-9%	
	56%	1,505	(Pew Research Center, 2017)	+/- 5.1%	
	45%	1,018	("Gallup: Social Series," 2017)	+/- 4%	
France	79%	1,010	(Steentjes et al., 2017)		81.3%*
	79%	1,004	(*European Commission: Eurobarometer Climate Change*, 2017)	+/- 2.5%	
	83%	1,788	(*Pew Research Center - Climate Change Still Seen as the Top Global Threat, but Cyberattacks a Rising Concern*, 2019)	+/- 5.1%	
Germany	81%	1,001	(Steentjes et al., 2017)		72.7%*
	75%	1,537	(*European Commission: Eurobarometer Climate Change*, 2017)	+/- 2.8%	
	63%	1,002	(Pew Research Center, 2017)	+/- 5.1%	

Is climate changed human-caused?

AII.2: Overview of adult opinion in the developed world per country on whether climate change is caused by humans * Derived from mean

Country	**% of respondents**	**n**	**Source**	**Error margin**	**Mean country data**
Australia	61.7%	5,163	(Leviston, Greenhill, et al., 2014)		67.4%**
	69.30%	2,015	(Climate Institute, 2016)	+/- 2.9	
United States	48%	1,534	(Pew Research Center, 2016)	+/- 4%	56%**
	52%	18,000	(Yale Climate Opinion Maps, 2016)	+/- 7-9%	
	68%	1,018	("Gallup: Social Series," 2017)	+/- 4%	
France	91%	1010	(Steentjes et al., 2017)		91%
Germany	83%	1001	(Steentjes et al., 2017)		83%

Is climate change happening now?

AII.3: Overview of adult opinion in the developed world per country on whether climate change is happening now * Derived from mean

Country	% of respondents	n	Source	Error margin	Mean country data
Australia	78%	5,030-5,219	(Leviston, Greenhill, & Walker, 2014)	+/- 2.8%	77.5%
	77%	2,015	(Climate Institute, 2016)	+/- 2.9	
United States	62%	1,018	("Gallup: Social Series," 2017)	+/- 4%	65.5%**
	69%	18,000	(Yale Climate Opinion Maps, 2016)	+/- 7-9%	
France	92%	1010	(Steentjes et al., 2017)		92%
Germany	83%	1001	(Steentjes et al., 2017)		83%

Appendix III: Alignment of National Curricula with the physical basis of climate science

Table AIII. 1: Details of the learning objectives (LOs) in the Australian National Curriculum that align with concepts, understanding and basic knowledge that describe the physical science basis of the natural climate system in equilibrium

	Earth and water in the Solar System	**Greenhouse gases as molecules**	**Albedo**	**Earth's atmosphere**
Year 5 (10-11 years)	The Earth is part of a system of planets orbiting around a star (the sun) (ACSSU078)		Light from a source forms shadows and can be absorbed, reflected and refracted (ACSSU080)	Solids, liquids and gases have different observable properties and behave in different ways (ACSSU077)
Year 6 (11-12 years)				
Year 7 (12-13 years)	Predictable phenomena on Earth, including seasons and eclipses, are caused by the relative positions of the sun, Earth and the moon (ACSSU115) Change to an object's motion is caused by unbalanced forces, including Earth's gravitational attraction, acting on the object Classification of environmental resources and the forms that water takes as a resource (ACHASSK 182)			
Year 8 (13-14)		Differences between elements, compounds and mixtures can be described at a particle level (ACSSU152) Properties of the different states of matter can be explained in terms of the motion and arrangement of particles (ACSSU151 Energy appears in different forms, including movement (kinetic energy), heat and potential energy, and energy transformations and transfers cause change within systems (ACSSU155)		
Year 9 (14-15)			Energy transfer through different	

			mediums can be explained using wave and particle models (ACSSU182)	
Year 10* (15-16)	The motion of objects can be described and predicted using the laws of physics (ACSSU229)	The atomic structure and properties of elements are used to organise them in the Periodic Table (ACSSU186)	Energy conservation in a system can be explained by describing energy transfers and transformations (ACSSU190)	Global systems, including the carbon cycle, rely on interactions involving the biosphere, lithosphere, hydrosphere and atmosphere (ACSSU189) *

*Where the Greenhouse Effect is mentioned explicitly in the curriculum

Table AIII. 2: Details of the learning objectives in the Austrian national curriculum that align with concepts, understanding and basic knowledge that describe the physical science basis of the natural climate system in equilibrium

	Earth and water in the Solar System	**Greenhouse gases as molecules**	**Albedo**	**Earth's atmosphere**
1. Klasse (10-11 years)	Erfassen, dass es auf der Erde eine Regelhaftigkeit in der Anordnung klimatischer Erscheinungen gibt.			
2. Klasse (11-12 years)				
3. Klasse (12-13 years)	Einsichten in globale und lokale Wettervorgänge und Klimaerscheinungen gewinnen (Jahreszeit, Wasserkreislauf auf der Erde, Meeresströmungen, Windsysteme).		modellartig verschiedene Formen des Wärmetransportes und wichtige Folgerungen erklären können; Wärmeleitung, Wärmeströmung, Wärmestrahlung;	Einsichten in globale und lokale Wettervorgänge und Klimaerscheinungen gewinnen (Jahreszeit, Wasserkreislauf auf der Erde, Meeresströmungen, Windsysteme).
4. Klasse (13-14 years)		Einsicht in ein altersgemäßes Teilchen- bzw. Atommodell. Verstehen des Ordnungsprinzips der Elemente		
5. Klasse (14-15 years)		An Hand der Modelle vom Aufbau der Atome Einsicht in das Wesen und die Entwicklung chemiespezifischer Modellvorstellungen gewinnen und diese darstellen.		
6. Klasse** (15-16 years)			Schwingungen und mechanische Wellen: Erzeugung, Reflexion und Brechung, Beugung und Interferenz, Resonanz, stehende Wellen	

**Where climate change is mentioned explicitly in the curriculum

Table AIV: German to English translation of table AIII.2 above; 'Details of the learning objectives in the Austrian national curriculum that align with concepts, understanding and basic knowledge that describe the physical science basis of the natural climate system in equilibrium'

	Earth and water in the Solar System	**Greenhouse gases as molecules**	**Albedo**	**Earth's atmosphere**
1. Klasse (10-11 years)	Recognize that there is a regularity in the arrangement of climatic phenomena on Earth			
2. Klasse (11-12 years)				
3. Klasse (12-13 years)	Obtain insights into global and local weather processes and climate phenomena (season, water cycle on earth, ocean currents, wind systems).		Be able to explain various forms of heat transport and important conclusions as a model; Heat conduction, heat flow, heat radiation;	Obtain insights into global and local weather processes and climate phenomena (season, water cycle on earth, ocean currents, wind systems).
4. Klasse (13-14 years)		Insight into an age-appropriate particle or atomic model. Understanding the principle of order of the elements		
5. Klasse (14-15 years)		Using the models of the structure of atoms, gain insight into the nature and development of chemistry-specific models and represent them.		
6. Klasse** (15-16 years)			Vibrations and mechanical waves: generation, reflection and refraction, diffraction and interference, resonance, standing waves	

**Where climate change is mentioned explicitly in the curriculum

Appendix IV – Frequency data for demographic factors

Table AIV. 1: Frequencies of responses for demographic factors: Country and Gender

			Response	Frequency (n)	Frequency (%)	Aggregated (%)
Country	Worry	Austria		78	17.2	
			No	0	0.0	1.3
			Probably not	1	1.3	
			Maybe	11	14.1	14.1
			Probably yes	20	25.6	84.6
			Yes	46	59.0	
		Australia		375	82.8	
			No	4	1.1	3.5
			Probably not	9	2.4	
			Maybe	27	7.2	7.2
			Probably yes	82	21.8	89.1
			Yes	253	67.3	
Country	Human	Austria		78	17.2	
			No	7	9.0	14.1
			Probably not	4	5.1	
			Maybe	8	10.3	10.3
			Probably yes	21	26.9	75.6
			Yes	38	48.7	
		Australia		375	82.8	
			No	10	2.7	5.3
			Probably not	10	2.7	
			Maybe	40	10.6	10.6
			Probably yes	101	26.9	83.6
			Yes	214	56.9	
Country	Now	Austria		78	17.2	
			No	3	3.8	5.1
			Probably not	1	1.3	
			Maybe	17	21.8	21.8
			Probably yes	21	26.9	73.1
			Yes	36	46.2	
		Australia		375	82.8	
			No	6	1.6	2.7
			Probably not	4	1.1	
			Maybe	36	9.6	9.6
			Probably yes	101	26.9	87.5
			Yes	228	60.6	
Gender	**Worry**	Female		208	45.9	
			No	1	0.5	1.9
			Probably not	3	1.4	
			Maybe	20	9.6	9.6
			Probably yes	53	25.5	88.5
			Yes	131	63.0	
		Male		245	54.1	
			No	3	1.2	4.1

			Probably not	7	2.9	
			Maybe	18	7.3	7.3
			Probably yes	49	20.0	88.6
			Yes	168	68.6	
Gender	**Human**	Female		208	45.9	
			No	8	3.8	6.7
			Probably not	6	2.9	
			Maybe	28	13.5	13.5
			Probably yes	62	29.8	79.8
			Yes	104	50.0	
		Male		245	54.1	
			No	9	3.7	6.9
			Probably not	8	3.3	
			Maybe	20	8.2	8.2
			Probably yes	60	24.5	84.9
			Yes	148	60.4	
Gender	**Now**	Female		208	45.9	
			No	4	1.9	3.4
			Probably not	3	1.4	
			Maybe	27	13.0	13.0
			Probably yes	59	28.4	83.7
			Yes	115	55.3	
		Male		245	54.1	
			No	5	2.0	2.9
			Probably not	2	0.8	
			Maybe	26	10.6	10.6
			Probably yes	63	25.7	86.5
			Yes	149	60.8	

Appendix V – Research Instrument

Questionnaire

Please write your code here:

____

Your gender:

Female

Male

Other

What subject do you enjoy most at school (choose only one)? (open question)

____

In your opinion, do you think Climate Change is something we all should worry about?

No Probably not Maybe Possibly Yes

In your opinion, do you think humans cause Climate Change?

No Probably not Maybe Possibly Yes

In your opinion, do you think the climate is changing now?

No Probably not Maybe Possibly Yes

Climate Science Questions

1. Could you arrange atmospheric layers[12] into the right order (the lowest layer of Earth's atmosphere being in the lowest position):

		Highest layer
Stratosphere		1
Exosphere		2

---

[12] As identified by Bodzin et al. (2014) understating the structure and composition of the atmosphere is important for CSL, particularly in relation to the different roles that ozone plays and to distinguish between weather and climate.

Thermosphere		3
Troposphere		4
Mesosphere		5
		Lowest Layer (Earth's surface)

2. Could you arrange the percentage of atmospheric gases into the right order (the lowest layer of Earth's atmosphere being in the lowest position):

A few gas particles per kilometer 75% of all atmospheric gases Less than 1 gas particle every few hundred kilometres 20-24% of all atmospheric gases Less than 1 gas particle every few kilometres	Highest layer 1 2 3 4 5 Lowest Layer (Earth's surface)

3. Many gases make up the Earth's atmosphere.(Please select the four answers that are the most correct)

☐ Oxygen – 78%, Carbon dioxide – 21%, Nitrogen – 0.9%, Other gases – less than 0.1%

☐ Water is only found in our atmosphere as rain – it is not found as a gas

☐ Carbon dioxide in our atmosphere is entirely man-made

☐ Nitrogen – 78%, Oxygen – 21%, Argon – 0.9%, Other gases – less than 0.1% (except when water is present as a gas)

☐ The carbon dioxide in our atmosphere is both natural and man-made

☐ Greenhouse gases take up over 25% of gases in our atmosphere

☐ Water can exist as a liquid (rain), a solid (ice and snow) and a gas in our atmosphere

☐ Water can exist as a gas in the atmosphere from four percent (4%) to zero percent (0%)

4. Where are these events found? Please put the event number with the right atmospheric layer (please note that the atmospheric layers are not sorted into their correct order):

1: The upper limit of Earth 2: Aurora Borealis and Aurora Australis (a.k.a Polar lights) 3: Ozone Layer 4: The coldest layer - and coldest temperature on Earth 5: Most of Earth's artificial satellites 6: The International Space Station (ISS) 7: Weather and most of Earth's water 8: Where meteors burn up 9: The Armstrong Limit 10: Also known as the 'ignorosphere' because it's too high for planes to fly through and too low for spacecraft to orbit	Stratosphere Exosphere Thermosphere Mesosphere Troposphere

5. Which is the most correct answer. 'Albedo' is: (Please select the most correct answer)

○ The white areas of Earth such as Polar Regions, ice caps, glaciers and snow – known as the cryosphere

○ The amount[13] of infrared radiation (or longwave radiation) that reflects back to space – on a scale of 0 to 10

○ The amount of greenhouse gases that we make by burning fossil fuels

○ The amount of solar radiation (sunlight or shortwave radiation) that reflects back to space – on a scale of 0 to 100

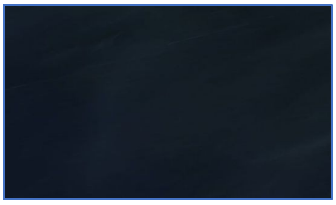
---

[13] Review has highlighted an error in this question insofar that albedo (as a non-dimensional, unitless quantity that indicates how well a surface reflects solar energy on a scale between 0-1) is not an amount. Corrections to future use of this research instrument should alter this question to better represent the definition and function of albedo. Please note that the result is unchanged as the scale (both in the correct answer and the scaled answers) correctly defines the meaning of the absorption or reflection of incident radiation as the 'most correct answer'.

- ○ The amount of solar radiation (sunlight or shortwave radiation) that is 'reflected' back to space – on a scale of 0 to 1

6. From the four images below, circle the image with the highest albedo: (Please choose only one)

Picture 1



Picture 2

Picture 3

Picture 4

7. What frequency do Greenhouse Gases respond to? They respond to: (Please select the most correct answer)

- ○ Long wave or infrared radiation that has bounced[14] off any part of Earth's surface
- ○ Long wave or infrared radiation that has bounced off a darker part of Earth's surface
- ○ Shortwave or solar radiation (sunlight) that has bounced off a darker part of Earth's surface
- ○ Shortwave or solar radiation that has bounced off a light part of Earth's surface
- ○ Electromagnetic or solar radiation that has bounced off any part of Earth's surface

8. When sunlight enters our atmosphere, what happens if it reaches light or white areas and surfaces? (Please select the most correct answer)

- ○ Lots of energy is lost as lighter areas have a high 'albedo' and they absorb the sunlight, turning it to infrared radiation and heat
- ○ Some energy is lost as light or white areas have a low 'albedo' and the sunlight will immediately reflect back to space with the same intensity

---

[14] While radiation does not bounce, it is frequently used when explaining climate change to younger audiences as they are unlikely to have knowledge about Earth's energy budgets, of concepts in physics such as emission, radiation and absorption, etc (Commoner, 1973)

- It loses a great deal of energy as lighter areas have a low ‘albedo’ and they absorb sunlight. Light areas alter the frequency of solar radiation – which then warms the surface and heats up the atmosphere
- Not much energy is lost as light or white areas have a high ‘albedo’ and the solar radiation can be reflected back to space with almost the same intensity
- Light areas alter the frequency of solar radiation: half the energy is lost as sunlight heats up the surface and the atmosphere, but the rest reflects back to space

9. What happens to solar radiation when it hits dark areas and surfaces (e.g. oceans and forests)? (Please select the most correct answer)

- Some energy is lost as dark areas have a low ‘albedo’ and the sunlight will immediately reflect back to space with the same intensity
- Dark areas alter the frequency of solar radiation: half the energy is lost as sunlight heats up the surface and the atmosphere, but the rest reflects back to space
- Lots of energy is lost as darker areas have a high ‘albedo’ and they absorb the sunlight, turning it to infrared radiation and heat
- Not much energy is lost as dark areas have a high ‘albedo’ and the solar radiation can be reflected back to space with almost the same intensity
- It loses a great deal of energy as darker areas have a low ‘albedo’ and they absorb sunlight. Dark areas alter the frequency of solar radiation - which then warms the surface and heats up the atmosphere

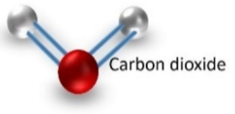
10. What proportion of our atmosphere is made up of Greenhouse Gases? (Please select the most correct answer)

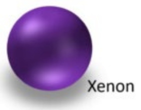
- We have about 1% carbon dioxide in our atmosphere – and this is the biggest greenhouse gas
- If we include water, we have about 0.5% - 1% of greenhouse gases in our atmosphere
- We have about 5% ozone in our atmosphere – and this is the biggest greenhouse gas
- If we include water, we have about 1% - 5% of greenhouse gases in our atmosphere
- We have about 5% carbon dioxide in our atmosphere – water is not a greenhouse gas

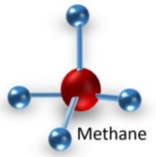
11. Which would best describe a Greenhouse Gas from the following options? (Please select the most correct answer)

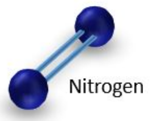
- A molecule that is always made up of more than two atoms (at least 3 atoms)
- A molecule that is mostly made up of carbon atoms
- A molecule that is usually made up of two or more different atoms
- A molecule that is made up of more than two carbon atoms
- A molecule that is made up of radioactive atoms

12. Which of these are Greenhouse Gases? (Please select the four answers that are the most correct)









13. How do greenhouse gases create heat? (Please select the most correct answer)

○ Greenhouse Gases are made up of between 1 and 4 atoms that can pick up infrared radiation – and this causes the atoms to spring apart from each other in different ways and release heat

○ Greenhouse Gases are made up of between 1 and 4 atoms that can pick up infrared radiation – this causes the atoms to explode, thereby releasing heat

○ Greenhouse Gases are made up of between 1 and 4 atoms that can pick up solar radiation – this causes the atoms to explode, thereby releasing heat

○ Greenhouse Gases, made up of at least two of the same kinds of atoms, react to infrared radiation which causes the atoms to spring apart from each other in different ways and release heat

○ Greenhouse Gases, usually made up of two or more different kinds of atoms, react to infrared radiation - causing the atoms to spring apart from each other in different ways and release heat

14. What makes some Greenhouse Gases more powerful at warming than others? (Please select the four answers that are the most correct)

☐ They spend more time in the atmosphere

☐ Greenhouse Gases with lots of atoms in their molecular structure are more powerful than those with less atoms in their molecular structure

☐ They are better at absorbing other molecules and this makes them more powerful

☐ They have atoms in them which are heavier than the atoms in other Greenhouse Gases and this means they can release more heat

☐ The closer the atoms in a Greenhouse Gases are bound to one another, the more heat they release

☐ They are much better at absorbing infrared radiation than other Greenhouse Gases and this makes them more powerful

☐ They have atoms in them that are lighter, and this means they can zip around faster and release heat

☐ The atoms in their molecular structure are loosely bound together and this allows them much more freedom of movement

15. What main jobs does an atmosphere do? (Please select the four answers that are the most correct)

☐ Protects us from solar storms and solar wind

☐ Keeps Earth warmer than it would be without Greenhouse Gases

☐ Creates ultraviolet radiation

☐ Protects lifeforms from ultraviolet radiation

☐ Provides the amino acids for life on Earth

☐ Allows water to be suspended as a gas and this leads to rain

☐ Protects us from Greenhouse Gases

☐ Provides oxygen for life on Earth

16. Atmospheric pressure is….? (Please select the four answers that are the most correct)

☐ 92 times weaker on Venus than on Earth – the same pressure you would find if you were 9100 metres above Earth's terrestrial surface

☐ kept on the surface of planets because of Greenhouse Gases

☐ low on Mars because Mars has a very thin atmosphere

☐ made up of all the gases in our atmosphere – the more atmosphere we have, the higher the atmospheric pressure

☐ high on Mars because Mars has a lot of atmosphere

☐ kept on the surface of planets by the force of gravity

☐ invisible on all planets

☐ 92 times stronger on Venus than on Earth – the same pressure that you would find if you were 910 metres below the surface of the ocean

17. Greenhouse Gases are…? (Please select the four answers that are the most correct)

☐ only caused by humans – we didn't have any before we started burning fossil fuels

☐ very rare on Earth – but they are so good at their job, they keep our planet 18 degrees warmer than would otherwise be there

☐ very abundant on Venus – in fact, so abundant that scientists believe that they have evaporated all the liquid water that was there. Venus is 462 degrees Celsius at the surface and it rains carbonic acid

☐ very rare on Venus – in fact, so rare that scientists believe that the only Greenhouse Gases found on Venus are in the water on the surface of Venus

☐ very abundant on Earth – which is why we are worrying about climate change

☐ very rare on Mars – but they are so good at their job, they keep the climate 18 degrees warmer than it should be

☐ very abundant on Mars – but because there is so little atmosphere, they can only warm up the planet when the sun shines…and then the heat dissipates to space

☐ both natural and caused by humans – the more we add, the bigger the effect we have on our climate

18. Which of these are the most correct? (Please select the four answers that are the most correct)

☐ Earth is found in the habitable zone of our solar system

☐ Climate is the average of all weather, taken over a period of more than 30 years

☐ Greenhouse gases are only found on Earth

☐ The kinds of plants and animals that are found in one area on Earth is largely determined by climate

☐ Climate is constant and never changes

☐ Knowing the atmospheric gases and atmospheric composition on other planets helps scientists calculate the climate and weather that is found there

☐ Venus is found in the habitable zone of our Solar system

☐ Atmospheric gases on other planets have no effect on the kind of climate or weather that is found there

19. The Goldilocks zone is …? (Please select the four answers that are the most correct)

☐ ... also known as the Circumstellar Habitable Zone. It is the area around a star that allows planets* orbiting in that area to have liquid water on their surface (*only if those planets have enough atmospheric pressure and enough gaseous water)

☐ ... not a real term used by scientists

☐ ... only big enough for one planet

☐ ... usually a good sign that, if a planet has enough gravity, that there might be liquid water on its surface

☐ ... a zone in a solar system that is ‘not too hot and not too cold’ – but is ‘just right’ to support life

☐ ... defined by the golden rays of the Sun as they radiate into the Solar System

☐ ... the area around a planet that supports life

☐ ... something scientists include when they are looking in space for other life-supporting planets that are similar to Earth

Participant Information Sheet - English

Researcher: My name is Inez Harker-Schuch and I am a PhD student at National Centre for the Public Awareness of Science at the Australian National University (ANU). I would like to conduct research in your child's school related to the implementation of digital educational games as a means of improving climate science understanding.

Project Title: Using digital tools to teach climate science to early adolescents

General Outline of the Project:

Purpose of research and Methodology: The purpose of this research is to investigate how digital educational games (scenarios, virtual reality, and 3D visualisations) could be used in the classroom for improving understanding in climate science and to investigate how these games can be used to help ensure young adults are fully conversant with climate science as a foundation for informed and cultivated decision-making. This research will attempt to extend the range of possibility for using digital tools in the classroom to teach climate science – and approach a methodology for doing this effectively. In addition, research indicates that the use of digital tools would be a very effective method for enhancing knowledge development and improving learning outcomes across a range of disciplines – and science communication researchers have suggested that such tools might be very effective in teaching wicked problems (climate science, GMOs, stem cell research etc.).

For those participating, we will be conducting an initial survey, followed by giving the students access to the climate science digital educational games – they will use them at school and can access them later as homework. After they have used the digital educational games, we will give them a follow-up survey to see how much they have retained from the material in the games. In addition, some students (12-14 students per school) will be asked to participate in small focus groups to discuss what they thought of the games and how they used them – and if there are ways we could improve them. We will return next year and conduct the same survey – to see how much knowledge they have retained from the year before.

Participants: The data will be collected from approximately 500 participants from year 7 and year 8 through survey/questionnaires and in focus groups. There will be approximately 500 students involved in the study and it will take place over 2 consecutive years.

Digital educational games: The experimental digital educational games we will be using to teach climate science are currently being programmed at the Australian National University and will be approved by a qualified pedagogue and psychologist before being used in this research. I have more than 8 years' experience teaching online (from primary to tertiary level) and have been involved in 2 different educational tool development projects.

The games will test the amount of knowledge that each student gains while using them. The games will be introduced in the classroom and the students will be given time to explore them then they will be asked to complete the games as homework. We anticipate that the games will increase the students understanding of planetary processes, and geo-physical characteristics that describe the scientific basis for climate science. These phenomena reinforce many of the early scientific constructs that this age group will be learning and constructing their formative scientific understanding.

Use of Data and Feedback: The purpose of this study is a doctoral thesis that will be examined by senior academic staff and then stored in an electronic and physical library. In addition, we would like to publish the findings in a peer-reviewed journal for dissemination in the scientific community. An executive summary will be compiled both for the department of education and for all participating schools and teachers. We will also provide 'Feedback to Participants' that will contain the coded data from our research and, eventually, our findings. This 'Feedback to Participants' can be obtained via the following link: https://onedrive.live.com/redir?resid=DBB0BB286D301145!10313&authkey=!AE1yqazf4SJyNJU&ithint=folder%2c

Data will be stored as per the requirements of the research code of conduct for a minimum of five (5) years. The data will be stored electronically both in an encrypted cloud maintained by the researcher and in the ANU data servers. Following the minimum period of data storage, the fully-encrypted data will be archived but it may be made available for later research of the type for which it was employed in this study.

We will ask participants to provide their final grades for the term and year we conduct our research in – this would allow us to see if their grades (and their subject preferences) have any effect on their understanding of climate science – and are requesting each parent/guardian and student for their permission to access this data.

Participant Involvement:

Voluntary Participation & Withdrawal: Participation is voluntary and each participant may, without negative consequences, decline to take part or withdraw from the research – or refuse to answer questions – without providing an explanation at any time until the work is prepared for publication. This right to withdraw from the research extends to the parents/legal guardians of participants, also. If a participant withdraws from the research, data from the questionnaire/survey will be destroyed and not used. For focus groups, isolating and destroying individual contributions may be impossible given the group nature of the discussion as removing individual comments is difficult – but if a participant requests part of their comment to be withdrawn, the researcher will endeavour to fulfil the request where possible. We will make these facts clear before the focus group begins and remind participants to be cautious of making statements they may wish to withdraw later. Focus groups will also be requested to inspect the Transcripts from focus groups that will be found in the 'Focus group transcripts' folder in the 'Feedback to Participants' folder: https://onedrive.live.com/redir?resid=DBB0BB286D301145!10313&authkey=!AE1yqazf4SJyNJU&ithint=folder%2c

Students who are not participating in the research will still have access to the digital climate science tools and be able to use them in the same way that other students use them and will, therefore, not be disadvantaged in any way.

What does participation in the research entail? For those participating, we will be conducting an initial questionnaire/survey, then participants will engage with the digital educational games (both in class and as homework). Approximately 10-14 days after the participants have had access to the tools, they will be asked to complete a follow up questionnaire/survey. A small, randomly-selected sample of 12-14 participants will be asked to join a focus group to discuss the games and how the participants fared using them. The focus group will be recorded on the proviso that all focus-group participants consent to it.

Location and Duration: The research will take place in public schools during class time. The duration is a total of four class periods (three in one year and a fourth the following year) and, for those students participating in the focus groups, an additional half hour:

Year	**Task**	**Duration/min**
1st	Initial questionnaire/Survey	45
1st	Using digital educational games	45
1st	Focus group	30
1st	Follow-up questionnaire/survey	45
2nd	Follow-up questionnaire/survey	45
Total		210

Risks: As researchers in climate science, we also understand that learning about this complex issue can be somewhat threatening for a small minority of students (in the same way that AIDS or the threat of nuclear war was for some parents when they were at school) and, for this reason, we acknowledge that some distress may be experienced.

Please be assured that we are not teaching anything but the science. There is no need to formulate climate science as a threat – rather we will frame any aspects of climate science that need human intervention as opportunities and ventures; in the same way that we approach the disciplines of medicine and technology: with hope and human endeavour. Of course, young people are aware of the risk that climate change poses to humanity and research tells is that one of the most effective ways to safeguard against feelings of inadequacy or fear (that might be triggered by exposure to uncomfortable and threatening concepts) and build resilience in children/young people is to cultivate the individual's sense of control over a threatening problem and building their self-esteem – if they know they can do something about an issue, then they are less likely to be adversely affected psychologically. As a precautionary measure and because the comfort and security of each participant is important to us, we implement practices according to Seligman's 'The Optimistic Child' that cultivates skills of optimism and, in turn, builds resilience as a strategy to face uncomfortable and threatening concepts and ideas.

With regard to third-party identification – the cipher for the coded responses will be held on an encrypted cloud so that only the primary researcher will be able to identify respondents. Once the data has been prepared for publication, all identifying details of participants will be destroyed within the legal strictures of the law.

It is important for all participants to know that their responses to the questionnaire/survey are not assessed and none of their contributions are marked in such a way that will affect their academic grade. Each participant will be provided with a thorough answer at the end.

Benefits of this research: In the school community, in the student society and the broader public arena we hope to:

- Develop a methodology for teaching post-normal (wicked) science subjects in the classroom
- Develop a methodology for using digital tools for deep learning and knowledge development
- Give hope and encouragement to students to face issues related to climate science

positively and constructively
- Empower students to engage critically and intellectually on the climate science topic
- Inform and support teachers as they engage in teaching climate science to their students
- Align societal views of climate science more closely with scientific evidence and consensus
- Foster a scientific discourse within the larger community about climate science and how we can work as a community to manage and maintain climate equilibrium

With respect to teachers we offer:

- Free professional development in employing digital tools for teaching
- Free professional development in climate science studies
- Skill development for implementing digital tools in the classroom
- Skill development for approaching post-normal, socio-scientific problems (‘wicked’ issues)
- To empower teachers to engage with technology
- Exposure to state-of-the-art science communication strategies and methodologies

Confidentiality

Confidentiality: We will ensure that all records that relate to participants, their teachers and their school will not be described (within the strictures of the law) in such a way as to make identification possible. The data that is provided relating to their school performance will also be masked and coded to ensure no individual student can be identified, as far as the law allows. Audio recordings of the focus groups will be made and these will be transcribed with pseudonyms to further protect the identity of participants. Only the nominated researchers will have access to the raw data. Survey data will be coded for statistical analysis and all participants (in both the survey and the focus group) will be provided with a pseudonym to preserve confidentiality.

Data Storage

Where: The data will be stored electronically both in an encrypted cloud maintained by the researcher and in the ANU data servers.

How long: Data will be stored as per the requirements of the research code of conduct for a minimum of five (5) years.

Handling of Data following the required storage period: Following the minimum period of data storage, the fully- encrypted data will be archived but it may be made available for later research of the type for which it was employed in this study – either by the primary researcher or those engaged in this scientific field. Any data that is used beyond the scope of this study will maintain the confidentiality of participants.

Queries and concerns

Contact Details for More Information:

Any questions regarding the research or lodging of complaints can be directed to:

Inez Harker-Schuch (PhD candidate)
The National Centre for the Public Awareness of
Science (CPAS) Bldg 38A, The Australian National
University
Canberra ACT 2600,
Australia Tel: +61 2
6125 0498
Mobile: 0422999160
Email: inez.harker-schuch@anu.edu.au

Contact Details if in Distress: Should any aspect of this research cause you any form of distress, you are encouraged to contact Lifeline on 13 11 14.

Ethics committee clearance:

The ethical aspects of this research have been approved by the ANU Human Research Ethics

Committee. If you have any concerns or complaints about how this research has been conducted,

please contact:

Ethics Manager
The ANU Human Research Ethics
Committee The Australian National
University
Telephone: +61 2 6125 3427
Email: Human.Ethics.Officer@anu.edu.au

Thank you for your interest in this research project. Please feel free to contact the researcher if you would like to discuss further.

This information sheet is for you to keep. Yours sincerely,

Inez Harker-Schuch

Informationsblatt für Studienteilnehmer/innen

Über die Studienleiterin:

Mein Name ist Inez Harker-Schuch, ich absolviere derzeit mein Doktorat am „National Centre for the Public Awareness of Science“ an der Australian National University (ANU). Ich würde gerne an der Schule Ihres Kindes eine Untersuchung über die Integration von digitalen Lernwerkzeugen zum verbesserten Verständnis im Fachbereich Klimawissenschaften durchführen.

Projekttitel:

‘Verwendung digitaler Ressourcen im Bereich Klimawissenschaft für den Unterstufenunterricht’

Allgemeine Eckpunkte dieses Projektes:

Grund der Untersuchung und Methodologie:

Mit dieser Studie soll untersucht werden, wie digitale Lernwerkzeuge (Szenarien, Virtuelle Realität, 3D-Visualisierungen) zu einem verbesserten Lernverständnis im Bereich Klimawissenschaft beitragen können. Ferner soll festgestellt werden, inwieweit damit bei den herangehenden Erwachsenen ein grundlegendes Basiswissen über Klimawissenschaften gefestigt werden kann, welches ihnen später ermöglicht, fundierte Entscheidungen in diesem Bereich zu treffen.

Diese Untersuchung soll auch ein Wegbereiter sein, damit vermehrt Möglichkeiten für die Anwendung digitaler Ressourcen im Klimaunterricht ausgeschöpft werden können – ein Ansatz zu einer effektiven Methodologie.

Die Forschung weist bereits darauf hin, dass der Einsatz von Lerntools sinnvoll für den Unterricht der sogenannten „wicked problems“ sein könnten, also von Lehrstoffen, die mit pädagogischen Hürden behaftet sind wie zum Beispiel Klimawissenschaft, GMO oder Stammzellenforschung. Die Studie beginnt mit einer Erhebung des Vorwissens der teilnehmenden Schüler/innen mittels Fragebogen. Dann erhalten die Schüler/innen Zugang zu den digitalen Lernmaterialien. Ihre Arbeit an diesen Lernwerkzeugen können sie anschließend zu Hause noch einmal in Form einer Hausaufgabe überprüfen. Im Anschluss daran erheben wir das über die digitalen Lernwerkzeuge erlangte Wissen mittels Fragebogen. Zusätzlich werden einige Schüler/innen (6 bis 8 pro Schule) gebeten, ihre Meinung zu diesen Lernwerkzeugen in Kleingruppen zu diskutieren. In diesen Kleingruppen soll auch besprochen werden, wie diese Schüler die Materialien verwendeten und ob es ihrer Meinung nach Verbesserungsmöglichkeiten gibt. Im darauffolgenden Jahr wollen wir die Studie erneut durchführen, um festzustellen, wie viel Wissen den teilnehmenden Schüler/innen aus dem Vorjahr verblieben ist.

Studienteilnehmer/innen:

Die Daten werden von circa 250 teilnehmenden Schüler/innen der 7. Und 8. Schulstufe mittels Fragebogen und in Kleingruppen erhoben. Insgesamt nehmen an der Studie rund 500 Schüler/innen teil, der Zeitraum der Durchführung erstreckt sich über 2 aufeinanderfolgende Jahre.

Digitale Lernwerkzeugen:

Die in Zukunft im Unterricht von Klimawissenschaft vorgesehenen digitalen Lernwerkzeuge aus dieser Untersuchung werden derzeit an der Australian National University programmiert. Vor deren Einsatz im Unterricht werden diese Unterrichtsmaterialien noch von qualifizierten Pädagogen und

Psychologen geprüft. Ich persönlich kann auf achtjährige Erfahrung im Online Unterricht zurückblicken (in allen Bildungsebenen von Grundschule bis Universität) und ich bin in zwei unterschiedlichen Entwicklungsprojekten für digitale Lernwerkzeuge involviert. Evaluiert wird auch, wieviel Wissen sich die Studienteilnehmer/innen im Verlauf der Verwendung der konkreten Lernwerkzeuge aneignen konnten. Die Spiele werden in der Klasse vorgestellt und die Schüler/innen erhalten Zeit, diese kennenzulernen. Im Anschluss sind die Teilnehmer/innen aufgefordert, die begonnenen Aufgaben zu Hause fertigzustellen. Es ist zu erwarten, dass die Schüler/innen durch diesen spielerischen Zugang planetare Prozesse und geophysikalische Charakteristiken, die die wissenschaftliche Basis für die Klimawissenschaft bilden, besser verstehen lernen. Es sind genau diese Phänomene der wissenschaftlichen Konstrukte, die dieser Altersgruppe nähergebracht werden sollen. Damit wird das formative wissenschaftliche Verständnis der Teilnehmer/innen aufgebaut.

Datennutzung und Feedback:

Diese Studie ist Grundlage einer Doktorarbeit, die nach Prüfung durch die akademischen Fachkräfte in einer elektronischen und physischen Bibliothek aufbewahrt wird. Zusätzlich möchten wir die Studienergebnisse in einschlägigen Wissenschaftsjournalen veröffentlichen, um der wissenschaftlichen Gemeinschaft dazu Zugang zu verschaffen. Eine Kurzfassung ergeht an das Bildungsministerium sowie an die teilnehmenden Schulen und Lehrer. Die Studienteilnehmer/innen erhalten auch ein „Feedback“, in dem die Forschungsdaten und Ergebnisse in kodierter Form enthalten sind. Der Link zu diesem Feedback ist unter der folgenden Internetadresse abrufbar:

https://onedrive.live.com/redir?resid=DBB0BB286D301145!10313&authkey=!AE1yqazf4SJyNJU&ithint=folder%2c

Die Daten werden den Anforderungen des wissenschaftlichen Verhaltenskodex zufolge mindestens fünf (5) Jahre gespeichert. Ferner werden diese Daten elektronisch abgelegt, sowohl in einer von den Forschern administrierten und verschlüsselten Cloud als auch in den Datenservern der ANU. Im Anschluss an die Mindestdauer der Datenspeicherung werden die vollkommen verschlüsselten Daten archiviert, jedoch für nachfolgende Forschungsvorhaben, die dem Typus der vorliegenden Studie entsprechen, zugänglich gemacht.

Die Teilnehmer/innen werden ersucht, ihre Semester- und Jahresnoten des Schuljahres, in dem diese Studie durchgeführt wird, zur Verfügung zu stellen. Damit können Rückschlüsse auf eine Interrelation der Abschlussnoten (der bevorzugten Lerngegenstände) und das Verstehen der Klimawissenschaft gezogen werden. Wir ersuchen die Eltern aus diesem Grund um die Erlaubnis, auf diese Daten zugreifen zu dürfen.

Teilnahme an der Studie:

Teilnahme & Ruckzug:

Die Teilnahme an dieser Studie ist freiwillig und die Teilnehmer/innen können sich ohne negative Auswirkungen irgendeiner Art zu jedem beliebigen Zeitpunkt von der Studie zurückziehen oder die Teilnahme verweigern – auch die Beantwortung von Fragen verweigern – ohne dafür einen Grund anzugeben, bis die Studie zur Publikation vorbereitet wird. Das Recht, sich von der Studie zurückzuziehen, erstreckt sich auch auf die Eltern/gesetzlichen Vertreter der Teilnehmer/innen. Ziehen sich Teilnehmer/innen zurück, so werden deren Daten in der Untersuchung gelöscht und nicht verwendet. In den Kleingruppen kann es auf Grund der natürlichen Gegebenheiten der Diskussionsform unter Umständen unmöglich sein, individuelle Beiträge zu isolieren und zu vernichten. Sollte ein Teilnehmer, eine Teilnehmerin fordern, seinen oder ihren Kommentar zurückzuziehen, wird sich der Forschungsbeauftragte bemühen, diesem Verlangen wo immer möglich nachzukommen. Wir werden auf diese Tatsache vor Beginn jeder Kleingruppendiskussion hinweisen und die Teilnehmer/innen zur Vorsicht bezüglich Aussagen auffordern, die sie eventuell später zurückziehen möchten. Diese Kleingruppen werden auch aufgefordert, die sogenannten „Transcripts“ der Arbeit dieser Kleingruppen durchzusehen. Diese „Transcripts“ befinden sich im „Focus group transcripts“ Folder innerhalb des „Feedback to Participants“ Folder unter dem Link:

https://onedrive.live.com/redir?resid=DBB0BB286D301145!10313&authkey=!AE1yqazf4SJyNJU&ithint=folder%2c

Auch Schüler/innen, die nicht an der Studie teilnehmen möchten, erhalten Zugang zu den digitalen Klimawerkzeugen und können diese genauso verwenden und erlernen wie die Studienteilnehmer/innen, sie werden demnach in keiner Form benachteiligt.

In welcher Weise erfolgt die Teilnahme an dieser Studie?

Die Teilnehmer/innen füllen einen ersten Fragebogen aus und erhalten dann Zugang zu den digitalen Lernmaterialien. Ungefähr 7-14 Tage nach dem Zugang zu diesen Lernwerkzeugen werden die Teilnehmer/innen aufgefordert, einen Folgefragebogen auszufüllen. Eine zufällig ausgewählte Kleingruppe von 6 bis 8 Teilnehmer/innen nimmt sodann an der sogenannten “Fokusgruppe” teil, in der die Lernspiele diskutiert und das Erlebnis der Verwendung dieser Lernwerkzeuge erörtert werden soll. Die Diskussionen der Fokusgruppen werden aufgenommen, jedoch nur unter der Bedingung, dass alle Teilnehmer/innen dieser Gruppen zustimmen.

Ort und Dauer:

Die Studie wird während der Unterrichtszeiten an den öffentlichen Schule durchgeführt. Die Dauer erstreckt sich insgesamt auf vier Unterrichtseinheiten (drei im ersten Jahr der Studie, eine Unterrichtseinheit im Folgejahr). Für die Teilnehmer/innen der Fokusgruppen sind zusätzlich weitere 30 Minuten vorgesehen:

Jahr	Inhalt	Dauer/min
1.	Fragebogen Teil 1	45
1.	Einsatz digitaler Lernwerkzeuge	45
1.	Kleingruppen	30
1.	Fragebogen Teil 2	45
2.	Fragebogen Teil 2	45
Gesamt		210

Risiken:

Als Forscher im Bereich der Klimawissenschaften sind wir uns der Tatsache bewusst, dass das Erfahren dieser komplexen Zusammenhänge auf eine Minderheit der Schüler/innen als bedrohlich erachtet werden könnte (in einer Weise wie das Thema AIDS oder die Drohung eines atomaren Krieges auf die Eltern der Teilnehmer/innen während ihrer eigenen Schulzeit wirkte). Wir anerkennen, dass die Schüler/innen das Thema unter Stress wahrnehmen könnten. Wir versichern jedoch, das Thema Klimawissenschaft nach unserem besten Wissen nicht als Bedrohung darzustellen, sondern es sollen im Gegenteil jene Aspekte unterstrichen werden, die in Zukunft die Intervention der Menschheit als Gelegenheit und Unternehmung formuliert, in derselben Weise wie das Thema Medizin oder Technik angesprochen wird: als Hoffnung und menschliches Unternehmen. Eine der effektivsten Arten, gegen eine Depression einzuschreiten, die entsteht, wenn Menschen unbequemen und bedrohlichen Konzepten ausgesetzt werden, und Kinder/Jugendliche demgegenüber widerstandsfähiger zu machen, liegt darin, das Bewusstsein zu steigern, dass das Individuum Kontrolle über solche bedrohlichen Phänomene haben kann. Damit wird letztlich das Selbstwertgefühl gesteigert. Denn mit dem Bewusstsein, dass wir etwas dagegen tun können, sind wir auch weniger den negativen psychologischen Auswirkungen ausgesetzt. Als Vorsichtsmaßnahme für die Sicherheit und zum Wohl jedes einzelnen der Teilnehmer/innen gehen wir nach den Vorgaben von Seligmans "The Optimistic Child" vor. Seligman baut auf die Kultivierung von Fähigkeiten und Optimismus, wodurch wiederum Widerstandsfähigkeit und eine Strategie im Umgang mit bedrohlichen Konzepten und Ideen entwickelt werden.

Was die Identifizierung der Chiffrierung durch Dritte betrifft geben wir verbindlich an, dass die kodifizierten Antworten innerhalb der verschlüsselten Cloud verbleiben, innerhalb der einzig der oberste zuständige Studienbeauftragte die Antwortgeber identifizieren kann. Nachdem die Daten für die Publikation bereitstehen, werden sämtliche Details der Teilnehmer/innen nach strikten Anforderungen des Gesetzes gelöscht. Wichtig für die Teilnehmer/innen ist ferner die Tatsache, dass keine der Antworten aus den Fragebögen bewertet werden und keine der Beiträge in einer Weise geprüft werden, die irgendeinen Einfluss auf eine Zeugnisnote haben könnte. Alle Teilnehmer/innen werden nach Abschluss ausführlich über die Ergebnisse aufgeklärt.

Zu den Vorteilen dieser Studie:

In der Schulgemeinschaft, unter den Schülern und auf der breiten öffentlichen Ebene hoffen wir folgende Effekte zu erzielen:

- Entwicklung einer Methodik für den Unterricht post-normaler (wicked) Wissenschaftsgegenstände im Klassenzimmer
- Entwicklung einer Methodik zur Verwendung digitaler Werkzeuge für vertiefendes Lernen und Wissenserweiterung.
- Vermittlung von Mut und Hoffnung für den positiven und konstruktiven Umgang mit der Thematik Klimawissenschaft bei Schülern.
- Vermittlung des Rüstzeuges für Schüler, zur kritischen und intellektuellen Auseinandersetzung mit klimawissenschaftsbezogener Thematik.
- Information und Support für Lehrer beim Umgang mit Unterrichtsmaterialien aus dem Gebiet der Klimawissenschaften.
- Weitere Annäherung des gesellschaftlichen Blickwinkels auf die Klimatologie an wissenschaftlich fundierte Tatsachen und den wissenschaftlichen Konsens.

- Förderung der wissenschaftlichen Debatte über Klimatologie auf breiterer gesellschaftlicher Ebene und Anregungen, wie wir als Gemeinschaft selbst auf die Steuerung und die Aufrechterhaltung des klimatischen Gleichgewichtes einwirken können.

Unser Angebot für Lehrer/innen:

- Unentgeltliche Einschulung in die Nutzung der digitalen Lernwerkzeuge im Unterricht
- Unentgeltliche Einschulung in den Unterricht von Klimawissenschaften
- Begleitung bei der Entwicklung von Fähigkeiten zum Einsatz von digitalen Medien im Unterricht
- Begleitung bei der Handhabung von post-normalen soziowissenschaftlichen Unterrichtsgegenständen (wicked issues)
- Begleitung des Lehrkörpers beim Umgang mit technischen Gegebenheiten
- Zugang zu fortschrittlichen Strategien der Wissenschaftskommunikation und deren Methoden

Vertraulichkeitsklausel

Vertraulichkeit:

Wir stellen sicher, dass sämtliche Aufzeichnungen in Verbindung mit Teilnehmer/innen, deren Lehrkräften und Schulen (im Rahmen der strikten Auslegung des Gesetzes) nicht so beschrieben werden, dass diese identifiziert werden könnte. Die im Zusammenhang mit den Schulleistungen bereitgestellten Daten werden maskiert und kodifiziert, damit jede individuelle Identifizierung von Schüler/innen unmöglich gemacht wird, wobei auf die gesetzlichen Rahmenbedingungen strikte geachtet wird. Die Diskussionen in den Fokusgruppen werden als Ton aufgezeichnet, diese werden in der Folge transkribiert und mit Pseudonymen versehen, sodass die Identität der Teilnehmer/innen in jedem Fall gewährleistet wird. Nur die dazu ernannten Studienmitglieder erhalten Zugang zu den Rohdaten. Daten aus den Untersuchungen werden zum Zwecke der statistischen Analyse kodifiziert, und alle Teilnehmer/innen (in Studie und Fokusgruppen) erhalten ein Pseudonym, um die Vertraulichkeit zu sichern.

Datenspeicherung

Ort:

Die Daten werden elektronisch in einer verschlüsselten Cloud in den ANU Datenservern gespeichert

Dauer der Speicherung: Die Daten werden den Anforderungen des wissenschaftlichen Verhaltenskodex zufolge mindestens fünf (5) Jahre gespeichert.

Handhabung der Daten nach Ablauf der erforderlichen Speicherdauer: Im Anschluss an die notwendige Mindestdauer der Speicherung werden die vollkommen verschlüsselten

Daten archiviert, können jedoch für fortfolgende Studien desselben Typs wie die vorliegende Studie verfügbar gemacht werden, entweder durch den Studienleiter oder von Personen, die in dieses wissenschaftliche Feld involviert sind. Für sämtliche Daten, die über dies gegenwärtige Untersuchung hinaus genutzt werden, wird die Vertraulichkeit gegenüber sämtlichen Teilnehmer/innen gewährleistet

Anfragen und Beschwerden

Kontaktdetails für weiterführende Information:

Jegliche Fragen bezüglich dieser Forschungsstudie oder Beschwerden richten Sie direkt an:

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Canberra ACT 2600, Australia Tel: +61 2 6125 0498

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Freigabe durch die Ethikkommission:

Die ethischen Aspekte dieser Studie wurden durch den Ethikausschuss der ANU Human Research Ethics Committee genehmigt. Jegliche Rückfragen oder Beschwerden bezüglich der Ausführung dieser Studie richten Sie bitte an:

Ethics Manager

The ANU Human Research Ethics Committee

The Australian National University

Telephone: +61 2 6125 3427

Email: Human.Ethics.Officer@anu.edu.au

Danke für Ihr Interesse an diesem Forschungsprojekt. Weitere Anfragen dazu richten Sie bitte an die Studienleiterin. Dieses Informationsblatt verbleibt zu Ihren Händen.

Hochachtungsvoll,

Inez Harker-Schuch

Consent Form - English

Research title: Using digital tools to teach climate science to early adolescents

As parent/legal guardian of ………………………………………………………., I have read and
(name of child)
understood the Information Sheet you have given me about the research project, and I have had any questions and concerns about the project (listed below) addressed to my satisfaction:

……………………………………………………………………………………………………

…………………………………………………………………………………………………

I agree to permit my son/daughter to participate in the project. YES ☐ NO ☐

I agree to the focus group interview being audio-recorded. YES ☐ NO ☐

I agree to the grades of the participants being supplied: YES ☐ NO ☐

I agree to be identified in the following way within research outputs:

Pseudonym (questionnaire/survey): YES ☐ NO ☐

Pseudonym (focus group): YES ☐ NO ☐

Signature of parent/legal guardian:…………………………………………….

Signature of child:………………………………………………………………..

Consent Form - German

Forschungstitel: Die Verwendung digitaler Instrumente, um Jugendlichen Klimawissenschaft zu lehren

Als Erziehungsberechtigte/r von……..…………………………………………...….bestätige ich,
(Name des Kindes)
dass ich das mir übergebene Informationsblatt über das Forschungsprojekt gelesen und verstanden habe, und dass meine Fragen und Anliegen bezüglich des Projektes (siehe unten aufgelistet) zufriedenstellend beantwortet wurden:

……………………………………………………………………………………………………
…………………………………………………………………………………………………

Ich stimme zu, dass ich meinem Sohn/meiner Tochter die Teilnahme am Projekt erlaube

YES ☐ NO ☐

Ich bin mit einer Tonaufzeichnung der Fokusgruppen-Interviews einverstanden..

YES ☐ NO ☐

Ich stimme zu, dass der/die TeilnehmerIn auf folgende Weise in den Forschungsergebnissen bezeichnet wird: YES ☐ NO ☐

Ich stimme zu, dass der/die TeilnehmerIn auf folgende Weise in den Forschungsergebnissen bezeichnet wird:

Pseudonym/Code (Fragebogen/Umfrage) YES ☐ NO ☐

Pseudonym (Fokusgruppe) YES ☐ NO ☐

Unterschrift des Erziehungsberechtigten:…………………………………………….

Unterschrift des Kindes:………………………………………………………………..

Comparison of CSL research instruments

Please note, only questions relating to the physical/chemical mechanisms that describe Earth's climate in equilibrium were included for comparison.

Consumers' knowledge about climate change, Tobler et al. (2012) Climate Change 114:189-209

Overcoming skepticism with education: interacting influences of worldview and climate change knowledge on perceived climate change risk among adolescents, Stevenson et al. (2014) Climatic Change 126(3):293-304

Of the 41 response items used in the Tobler et al. (2012) questionnaire there were 19 correct and 22 incorrect statements; respondents marked each statement as true, wrong or they did not know; n = 916; mean age = 55 years (also used by Stevenson et al. (2014) in middle school students aged between 11 to 14 to measure climate knowledge in interactions with worldview). 8 of the 41 response items cover aspects of the physical/chemical mechanisms that describe Earth's climate in equilibrium (showing alignment with the KDs 1-4) and were included for the comparison (incorrect statements are also included if they fall within the criteria). The other response items covered impacts/consequences, historical emissions, variability to the climate system and human causes. The Tobler et al. (2012) analysis used the nonparametric Mokken scale (van Schuur, 2003) which analyses each respondents pattern and explicitly assesses how items differ with regard to distribution. The Stevenson et al. (2014) analysis used path analysis (an extension of multiple linear regressions that allow for the analysis of several regression simultaneously) and created two interaction terms for each knowledge and worldview to test the likelihood that observations fit the proposed causal model:

- Burning oil produces CO_2 *(alignment with the CSL research instrument – KD2: Greenhouse gases as molecules).*
- The warming of the Earth's atmosphere caused by greenhouse gases is called the greenhouse effect *(alignment with the CSL research instrument – KD2: Greenhouse gases as molecules; KD3: Albedo).*
- Carbon dioxide (CO_2) is a greenhouse gas (*alignment with the CSL research instrument – KD2: Greenhouse gases as molecules).*
- Greenhouse gases partly retain the Earth's heat radiation (*alignment with the CSL research instrument – KD2: Greenhouse gases as molecules; KD3: Albedo).*
- Without humans, there would be no greenhouse effect *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD3: Albedo).*
- The ozone hole is the main cause of the greenhouse effect *(alignment with the CSL research instrument– KD4: Earth's atmosphere).*

- At the same quantity, CO_2 is more harmful to the climate than methane *(alignment with the CSL research instrument – KD2: Greenhouse gases as molecules).*
- Water vapor is a greenhouse gas *(alignment with the CSL research instrument – KD2: Greenhouse gases as molecules).*

Investigating climate change understandings of urban middle-level students, Bodzin et al. (2014) Journal of Geoscience Education, 62: 417-430

Of the 28 multiple choice questions used in the Bodzin et al. (2014) questionnaire, 11 of those cover aspects of the physical/chemical mechanisms that describe Earth's climate in equilibrium and were included for the comparison; n=868; age: 13-14 years. Respondents had a multiple-choice question with three incorrect answers and one correct answer (correct answer only shown). and the anchoring heuristic may contribute to further confusion if these two topics are brought up in the same lesson/context/time-period. Correct responses were given one point and incorrect responses were given zero points (question order follow Table I order in Bodzin et al. (2014) article for readability):

- Q4: The trapping of heat within Earth's atmosphere is called the …. Greenhouse effect *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD3: Albedo).*
- Q18: A surface that reflects more sunlight has a…higher albedo *(alignment with the CSL research instrument– KD3: Albedo).*
- Q3: Which does not act as a significant greenhouse gas? … Nitrogen *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*
- Q9: Ozone existing in the lower troposphere is … a harmful pollutant created by the burning of fossil fuels *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*
- Q14: Argon, carbon dioxide, and other trace gases make up approximately … one … percent of Earth's atmosphere *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*
- Q16: The three gases that contribute the most to the total greenhouse effect are … carbon dioxide, water vapour, and methane *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*
- Q20: Materials that absorb lots of energy without a large temperature increase have a … high heat capacity *(alignment with the CSL research instrument– KD3: Albedo)*
- Q19: What two gases make up most of Earth's atmosphere … nitrogen and oxygen *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*

- Q8: Atmospheric gases that contribute to increasing Earth's surface temperature are called… greenhouse gases *(alignment with the CSL research instrument– KD2: Greenhouse gases as molecules; KD4: Earth's atmosphere).*
- Q1: Climate is defined as weather patterns that change on a scale of at least a few … decades *(alignment with the CSL research instrument–KD4: Earth's atmosphere).*
- Q7: What three factors have the most influence on seasonal weather patterns[15] … *(alignment with the CSL research instrument–KD1: Earth in the Solar System).*
- Q15: The layer of the atmosphere that is closest to Earth's surface and where most weather is generated is called the … troposphere *(alignment with the CSL research instrument– KD4: Earth's atmosphere).*

Comparison to the CSL Framework:

In comparison to the CSL Framework, the KD that both research instruments prioritise is KD2: Greenhouse gases as molecules. After knowledge related to KD2, Tobler et al. (2012) then prioritise knowledge related to the greenhouse effect that incorporates both KD3: Albedo and KD4: Earth's atmosphere. After knowledge related to KD2, Bodzin et al. (2014) then prioritise knowledge related to KD4: Earth's atmosphere. Bodzin et al. (2014) refer, indirectly, to Earth in the Solar System (Q7). However, as insolation, the Circumstellar Habitable Zone and the comparison of Earth to other terrestrial planets has been identified by other researchers as important knowledge to understand the physical/chemical mechanisms that describe Earth's climate in equilibrium (Christ, 2020; Nielbock & Türk, 2017), it is important to include this KD, as well. It is also worth noting that I do not refer to the greenhouse effect in the CSL research instrument. The greenhouse effect, in many ways, encompasses several aspects of the KDs, but not all of them i.e. Earth in the Solar System. Furthermore, since different KDs explain essential concepts of the greenhouse effect, an overall understanding of the greenhouse effect can be viewed as an implied, rather than explicit, aim of the CSL framework and research instrument.

In order for the CSL research instrument to be useful to the development of a CSL framework that can be used in the classroom, pedagogical considerations necessitated structuring the questions, where possible, on to levels of complexity or learning progressions. This allows for a baseline of knowledge of CSL to be established and, in addition, forms a proto-framework. Therefore, structuring the CSL research instrument on the SOLO taxonomy at the KD level meant that there were several questions for each KD. Rather than use a multiple-choice question approach (one correct answer) as taken by Bodzin et al. (2014), we elected to scale the answers in order to obtain very specific, nuanced answers which allows us to obtain an additional measure of knowledge depth for each question.

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[15] No answer was provided in the Bodzin et al. (2014) article and despite a search for supplementary materials in three university library databases, I was unsuccessful in finding it

Since the Tobler et al. (2012) instrument tested true/false/don't know, we are unable to determine where strengths and weaknesses lie in relation to respondent knowledge and, as described, this was not deemed a suitable approach for the purpose of this research due to cultural cognition and the differences between asking personal belief versus scientific understanding (see also 'post-truth', page 9).

The work from Tobler et al. (2012) (and that which follows on from Tobler et al. (2012), specifically and importantly Shi et al. (2015, 2016)) and Bodzin et al. (2014) has heavily informed the development of my thesis and has provided an important foundation on which to construct the CSL framework. The research instruments from Tobler et al. (2012), Stevenson et al. (2014) and Bodzin et al. (2014) significantly contribute to understanding the importance of knowledge deficit interventions in relation to climate friendly attitudes, and offer valuable insights and recommendations into developing instructional learning activities. However, a comprehensive, structured, age-appropriate curriculum that incorporates climate communication theory and practice that can be deployed in the secondary school classroom is still needed. It is clear from the inclusion of questions that are related to the physical/chemical mechanisms that describe Earth's climate system in equilibrium in both the Tobler et al. (2012) and Bodzin et al. (2014) research instrument that knowledge related to these processes is also considered important by others investigating the role of knowledge deficit interventions.

Rationale for selection of questions for the research instrument

The research instrument follows an Earth System Science (ESS) approach that attempts to consider the system as a whole and linked to other systems. Essentially, KD1-4 form the essential knowledge foundation needed for developing a conceptual model of Earth's climate system as a basis for understanding variability and anthropogenic climate change in later KDs (KD5-9). The questions in each KD (please see Appendix V for all questions), as described in Section 4.1.4, were organised by the SOLO taxonomy with the first ST level being an easy task (ST1 unistructural: identify/name/find/label/recognise), the second level building on the first ST (ST2 multistructural: describe/list/outline/continue/order), the third connecting and relating the knowledge from the second ST level into a coherent whole (ST3 relational: compare/distinguish/contrast/explain cause/deconstruct/apply), and the fourth extending the acquired knowledge form the first three ST levels into other knowledge domains (ST4 extended abstract: create/formulate/design/predict/invent/argue/reflect/hypothesise).

Note 1: The key concepts provide context for each KD and specific content described may not be included in the questions but serve as a foundation or anchor for further knowledge development i.e. the role that gravity plays in structuring Earth's atmosphere can be considered an advanced knowledge. An answer on gravity, therefore, is included as planetary mass partly explains climate formation.

Note 2: The learning progressions were not always arranged in order as they frequently primed upcoming questions i.e. giving respondents the answer or concept in a previous answer

Note 3: The performance of each KD at the SOLO taxonomy (ST) level does not necessarily increase as the KD becomes more complex. To begin with, incidental knowledge will be different between respondents. However, this may also be due to a lack of difficulty in the research instrument i.e. ST4 in KD1 might not be as difficult as ST4 in KD2 and also in the KD itself. CSL content was prioritised over matching the question to levels of complexity.

Note 4: Ideally, all questions at ST level 1 would be images. However, visually representing some phenomena is difficult without advanced graphics in the survey instrument e.g. the CHZ could not be visually represented in the survey. This may have affected performance in ST1 for those questions without images.

KD1: Earth and water in the Solar System

Overview of KD:

This KD focuses on climate at a macro scale and explores the importance of climate in the Solar System as a factor for habitability. Understanding the Circumstellar Habitable zone (CHZ) allows students to recognise how Earth's proximity to the Sun affects its potential for liquid water at the terrestrial surface and how this, in turn, supports life. The comparison of terrestrial planets is important as Venus (~460°C) and Mercury (~425°C) provide context for students to understand the powerful effect of greenhouse gases on Venus' temperature in spite of Mercury's closer proximity to the Sun. The formation of a climate is partly limited by planetary mass which, in turn, affects atmospheric pressure. When exploring KD4 (Earth's atmosphere), the importance of atmospheric pressure becomes relevant for the hydrological cycle (the suspension of rain in the atmosphere) the Armstrong limit and the importance of the Troposphere for life.

Key concepts:

- Improving students confidence to discuss how Earth's climate is affected by its position in the Solar System.
- The unique position of Earth in the Circumstellar Habitable Zone (CHZ) as an essential factor for liquid water at Earth's surface.
- Understanding why atmospheres are important for life and surface liquid water.
- Understanding that gravity (and planetary mass) is an essential factor in climate formation.
- The importance of greenhouse gases in atmospheric warming and how they compare on different planets.
- The role of gravity in maintaining an atmosphere and the potential effect of gravity on atmosphere structure and how atmospheric pressure compares on each planet.
- How the search for 'pale blue dots' are linked to the search for extra-terrestrial life as they imply habitable climates.
- The interaction between Earth and water in the Solar System (KD1) and Earth's atmosphere (KD4).

Question 15 (ST4)

Reflecting on the tasks of an atmosphere as a condition for the hydrological cycle and sustaining life at a planetary scale, this question provides context for or elaborates on knowledge related to Earth's atmosphere. It is associated to KD1 as it relates to life, water, and habitable conditions. This question would be associated to ST4 due to the extended abstract nature of this question (extrapolation to other KDs and the need to understand the role of gravity on atmospheric pressure as an important part of the hydrological cycle).

Question 16 (ST2)

Identifying and comparing the physical properties of the terrestrial planets helps students conceptualise the formation of climates at astrophysical scales and provides a 'natural laboratory' setting to better understand Earth's climate. For example, knowledge of atmospheric pressure (planetary mass and the force of gravity) is important for understanding the formation of climate and the effect it has on the atmosphere of a terrestrial planet.

Question 17 (ST2)

Similar for question 16, identifying and comparing the abundance of GHGs and planetary temperatures helps students conceptualise the formation of climates at astrophysical scales and provides a 'natural laboratory' setting to better understand Earth's climate. Understanding how GHG abundance affects temperature provides a rationale for students to recognise that only trace amounts of GHGs are necessary for a habitable climate and that climate can be varied by human behaviour.

Question 18 (ST3)

Defining climate and distinguishing important climate facts related to KD1 and climate, such as 1) the role of climate on species diversity (Köppen-Geiger climate classification) since climate and weather define which species is found where; and 2) how atmospheric gases affect climate on other planets, this question helps students develop a conceptual model of the Earth in the Solar System.

Question 19 (ST1)

Naming and identifying the Circumstellar Habitable Zone (CHZ) establishes climate habitability at the core of the Earth in the Solar System knowledge domain. Since liquid water is an ideal solvent and is a requirement for life as we know it, this question provides context for Earth's unique habitable conditions and how the search for 'pale blue dots' is also linked to the search for extra-terrestrial life. This question highlights that the CHZ has an established definition and improving students' awareness of this definition and description improves the share of CSL in the broader public arena.

Learning progression: If we apply these questions in KD1 to learning progression that can be used in the classroom, students first identify the CHZ as an area around a star that can support life. By having a planet with sufficient atmospheric pressure within the CHZ, they are then able to see the effect of greenhouse gases on the global surface temperature as a condition of its habitability. The comparison of conditions then provides context for Earth's unique habitable conditions and connects weather and climate to species diversity.

KD2: Greenhouse gases as molecules

Overview of KD:

This KD explores the properties of GHGs (structure and function) in Earth's atmosphere in order to overcome misconceptions related to GHGs, including 1) identifying which gases are GHGs; 2) GHG abundance/significance; 3) their relative warming potential; and 4) the influence of infrared radiation .

Key concepts:

- Improving student confidence to discuss GHGs as molecules
- Overcoming misconceptions related to trace GHGs
- Improving understanding about water vapour as a GHG
- Identifying greenhouse gases as molecules
- Describing and defining greenhouse gases
- Categorising GHGs according to their global warming potential (GWP)
- Reflecting on the effect of greenhouse gases as a percentage of Earth's atmosphere

Question 10 (ST3)

Since climate denialists use the trace amounts of GHGs in Earth’s atmosphere as reasons to deny climate change or argue global warming is implausible (Contoski, 2017), providing context for the effect of greenhouse gases on Earth’s climate helps students establish an understanding of their global warming potential and effect. Furthermore, misconceptions about water vapour as a significant GHG prevail (Bodzin et al., 2014). This question explores student understanding about GHG abundance and the role of water vapour.

Question 11 (ST1)

Aside from being able to distinguish other atmospheric gases from GHGs, being able to define and schematically recognise a GHG is an essential construct for understanding GWP (Q14). Coupled with GWP knowledge (Q14), this question also highlights the danger of manmade GHGs e.g. SF_6, which are significantly more dangerous than natural GHGs due to the large number of atoms in their molecular structure and the exceptionally long residence times. This question highlights that GHGs can be identified and improving student’s awareness of their structure improves the share of CSL in the broader public arena.

Question 12 (ST1)

Although somewhat similar to Q11, this question asks students to visually identify a GHG from non-GHGs. This question, as visual, is a simpler question to answer than Q11, but cannot go before as it may prime the respondent. Since this question was designed to be at SOLO Taxonomy (ST) level 1, it is an image.

Question 13 (ST2)

This questions re-tests respondent’s definition of GHGs and explores their understanding of the role of infrared. Understanding the physical mechanism at the molecular level of warming – bending and stretching – helps students conceptualise GWP at later stages of CSL.

Question 14 (ST4)

This question covers knowledge related to GWP. Understanding GWP allows students to compare GWP of different gases and recognise that, at the molecular level, emissions of GHGs are not equal – some are significantly more powerful than others and their effect is only mitigated by their abundance.

Learning progression: If we apply these questions in KD2, students should first visually and simply identify a greenhouse gas in order to understand that their structure is an essential reason for why they are able to react to infrared. With knowledge of that structure, they are than able to define and describe a greenhouse gas and state which form of radiation causes them to react and how this reaction causes them to release heat. Understanding how they warm provides context for why only trace amounts are found in Earth's atmosphere and provides an opportunity to discuss abundance. The structure of GHGs then provides context for GWP which, due to several additional concepts such as residence time, becomes the last knowledge domain.

KD3: Albedo

Overview of KD:

This KD explores significant features of the greenhouse effect including how incoming solar radiation is either absorbed or reflected by Earth's surface and, that which is absorbed, is then partly reemitted as infrared radiation. Aside from explaining major components of the greenhouse effect, albedo is important in understanding knowledge related to natural and human-driven feedbacks and how this alters Earth's climate at later stages of CSL (KDs 5-9).

Key concepts:

- Identify the warming effect of solar radiation on a dark surface
- Describe regions with high albedo
- Describe albedo and how it is expressed as a scale
- Compare and contrast the interaction between greenhouse gases and shortwave and longwave radiation
- Improving student confidence to discuss the greenhouse effect
- Express albedo as a scale on Earth's energy system as an influence on warming

Question 5 (ST2)[16]

The first question asks students to define and describe albedo. By describing albedo and recognising albedo as a scale, students may be better able to cognitively process concepts of reflectivity and its

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[16] Review has highlighted an error in this question insofar that albedo (as a non-dimensional, unitless quantity that indicates how well a surface reflects solar engery on a scale between 0-1) is not an amount. Corrections to future use of this research instrument should alter this question to better represent the defintion and function of albedo. Please note that the result is unchanged as the scale (both in the correct answer and the scaled answers) correctly defines the meaning of the absorption or reflection of incident radiation as the 'most correct answer'.

influence on radiative forcing. This question highlights that albedo has an established definition and improving students' awareness of this definition and description improves the share of CSL in the broader public arena.

Question 6 (ST1)

Although somewhat similar to Q5 (and following the same structure as KD2, Q12), this question asks students to visually identify an image with the highest albedo. This question, as visual, is a simpler question to answer than Q5, but cannot go before as it may prime the respondent. Since this question was designed to be at SOLO Taxonomy (ST) level 1, it is an image.

Question 7 (ST3)[17]

This question tests the student's understanding of how infrared radiation is emitted from Earth's surface in relation to dark or light surfaces (albedo). This questions tests student understanding in the conceptual model of the greenhouse effect.

Question 8 and 9 (ST3; ST4, respectively)

These two questions are linked insofar that they are a reverse of one another. For example, although albedo is explicitly embedded in the model of the greenhouse effect the first question tests respondents on their understanding of reflective surfaces and infrared and Q9 tests respondents on their understanding of dark surfaces and infrared. These questions explicitly test respondents conceptual understanding of albedo.

Learning progression: If we apply these questions in KD1 to learning progressions that can be used in the classroom, students first visually identify an image of an area with a high albedo in order to recognise that albedo relates to reflectivity. This then provides a rationale for understanding that albedo is a scale that measures how much light is reflected back to space. Understanding reflectivity provides a foundation for understanding how dark and light surfaces affect the types of radiation that are reflected or emitted from Earth's surface. Understanding how albedo affects the types of radiation establishes a foundation on which to conceptually model solar radiation dynamics at the Earth's surface

KD4: Earth's atmosphere[18]

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[17] In question 7, respondetns were asked which surface aöbedo 'bounces' off. While radiation does not bounce, it is frequently used when explaining climate change to younger audiences as they are unlikely to have knowledge about Earth's energy budgets, of concepts in physics such as emission, radiation and absorption, etc (Commoner, 1973)

[18] As identified by Bodzin et al. (2014) understating the structure and composition of the atmosphere is important for CSL, particularly in relation to the different roles that ozone plays and to distinguish between weather and climate.

Overview of KD:

Since misconceptions between ozone depletion and climate change are common, providing explanations of Earth's atmosphere allow students an opportunity to understand where the ozone layer is, become familiar with the trace amounts of greenhouse gases and their effect on warming and the effect/limits of Earth's gravitational pull. Where possible, the questions lead to increasing levels of complexity. Due to poor CSL in this KD, Bodzin et al. (2014) recommend that middle school curriculum explicitly focuses on the atmosphere

Key concepts:

- Providing a rationale to differentiate between weather and climate
- Resolving misconceptions regarding associations between climate change and ozone depletion
- Improving understanding about the structure of Earth's atmosphere
- Improving understanding about the composition of Earth's atmosphere
- Fostering understanding of Earth's atmosphere as a limited resource

Question 1 (ST2)

Arranging the atmospheric layers into the right order helps students recognise that Earth's atmosphere is layered – setting up the foundation for understanding how liquid water is kept at the Earth's surface and where it is found in Earth's atmosphere, particularly in relation to weather. Since weather only takes place in the troposphere, this further assists students in differentiating between climate and weather.

Question 2 (ST1)

Arranging the percentage of atmospheric gases found in Earth's atmosphere tests students understanding of gravity, which is essential in understanding Earth's atmosphere. This question also allows students to recognise our habitable atmosphere has planetary boundaries both physically and as a resource. This question, though simpler to answer than Q1, could not be put first in the research instrument as the concept of 'atmospheric layers' is an important first concept in order to conceptually consider how gravity affects the ordering of those layers. With 75% of atmospheric gases in the Troposphere, this question provides context for Q3 and the presence of liquid water at Earth's terrestrial surface which impacts both climate and weather.

Question 3 (ST3)

Having knowledge about the composition of Earth's atmosphere is important as it shows the effect of trace amounts of greenhouse gases on atmospheric warming and provides further context for the hydrological cycle, once again in relation to weather and climate. While we might assume that everyone will know what they are breathing, identifying nitrogen as the most abundant gas in Earth's atmosphere, according to Kahan (2015), is relatively difficult.

Question 4 (ST4)

Identifying the different characteristics of Earth's atmosphere allows students to distinguish between ozone depletion and climate change, the protective barrier of Earth's atmosphere, where weather is found, and the physical limits of life i.e. Armstrong Limit/breathable atmosphere.

Learning progression: Recognising that Earth's atmosphere is layered provides a foundation for understanding that each layer has different properties and characteristics. Recognising that the atmosphere is not uniform allows students to name the layers (this is higher level of difficulty as there are five labels – the first task depends on recognising that gravity sorts the layers from the highest percentage at the surface to lowest at the border to space). Following on from this, students can explore what Earth's atmosphere is composed of, which is known to be a relatively difficult science knowledge. With an understanding of how Earth's atmosphere is composed, students are then able to assign particular events and characteristics to specific layers in the atmosphere. These events further help students in cementing knowledge and providing context for atmospheric structure and composition.

Appendix VI – Climate Science Literacy (CSL) Framework

Table AVI.1: Climate Science Literacy (CSL) Framework - Order of KDs as a result of tested outcomes – based on Biggs and Collis (1982) and the SOLO Taxonomy for the Knowledge Domains related to Natural climate system in equilibrium

KD order	Name of KD	Question score	ST level	SOLO Taxonomy - Learning Objectives
KD1 KD CSL level: 61.01	Earth and water in the Solar System	66.40	1	Identify the range of the circumstellar habitable zone a.k.a Goldilocks Zone
		65.70	1	Name the zone around our Sun that can support liquid water at its surface
		63.01	2	Describe the role gravity plays in maintaining Earth's atmosphere and how this impacts the presence of liquid water
		57.31	3	Explain the role of atmospheric pressure on the climates of the rocky planets in our solar system
		52.63	4	Reflect on the atmospheric composition and abundance of greenhouse gases on the rocky planets in our solar system
KD2 KD CSL level: 50.47	GHGs' as molecules	66.77	1	Identify an image of a Greenhouse gas
		51.29	2	Describe the factors that increase the global warming potential of a greenhouse gas
		48.76	2	Describe how greenhouse gases react to infrared radiation and contribute to atmospheric warming
		46.24	3	Distinguish a greenhouse gas from a non-greenhouse gas in the atmosphere
		39.30	4	Reflect on the effect of greenhouse gases as a percentage of Earth's atmosphere
KD3 KD CSL level: 47.37	Albedo	58.28	1	Identify the warming effect of solar radiation on a dark surface
		49.68	1	Describe regions with high albedo
		48.49	2	Describe albedo and how it is expressed as a scale
		47.42	3	Compare and contrast the interaction between greenhouse gases and shortwave and longwave radiation
		32.99	4	Express albedo as a scale on Earth's energy system as an influence on warming
4 KD CSL level: 30.41	Earth's Atmosphere	43.78	1	Identify the effect that causes layering of Earth's atmosphere and sort the layers into the percentage of gases found in each layer
		28.87	2	Describe the gaseous composition of Earth's atmosphere as a sum of percentages
		26.28	3	Classify the atmospheric layers in the order they present in our atmosphere
		22.92	4	Reflect on what properties in the atmosphere define the events/phenomena/technology that occur in the different layers

Appendix VII – Thesis question analysis

Table AVII: Overview of random guessing analysis of responses

Question (App V)	KD (Chap 4)	KD (App VI)	Type of question/answer	Pre-test % correct	Post-test % correct	Assessment	Random Guess Score/%
1	2	4	arrange 5 items in order	25.99	35.21	20% for each correct	20
2			arrange 5 items in order	44.54	52.67	20% for each correct	20
3			select 4 of 8	29.07	31.61	25% for each correct	50
4			arrange 10 items in order	23.32	26.58	10% for each correct	- *
5	3	3	5 increasingly correct	33.32	38.10	Scaled: 100%; 75%; 50%; 25%; 0%	50
6			one correct of four	48.13	73.57	Only one correct	25
7			5 increasingly correct	48.13	51.81	Scaled: 100%; 75%; 50%; 25%; 0%	50
8			5 increasingly correct	47.88	56.42	Scaled: 100%; 75%; 50%; 25%; 0%	50
9			5 increasingly correct	58.85	60.72	Scaled: 100%; 75%; 50%; 25%; 0%	50
10	4	2	5 increasingly correct	40.02	50.31	Scaled: 100%; 75%; 50%; 25%; 0%	50
11			5 increasingly correct	46.45	56.92	Scaled: 100%; 75%; 50%; 25%; 0%	50
12			select 4 of 8	66.77	67.21	25% for each correct	50
13			5 increasingly correct	50.06	51.31	Scaled: 100%; 75%; 50%; 25%; 0%	50
14			select 4 of 8	51.31	50.56	25% for each correct	50
15	1	1	select 4 of 8	63.40	63.22	25% for each correct	50
16			select 4 of 8	58.17	56.98	25% for each correct	50
17			select 4 of 8	53.05	58.92	25% for each correct	50
18			select 4 of 8	66.46	65.65	25% for each correct	50
19			select 4 of 8	65.77	71.01	25% for each correct	50

*Random-guessing probability analysis was conducted and showed that 1 random correct guess (for a score of 10%) had a 36.79% probability of being accurate, a 2 correct guess (for a score of 20%), the probability was 18.39%, and for a 3 random correct guess (score of 30%) the probability was 6.13%.