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Foundation biology students' critical thinking ability: Self-efficacy versus actuality

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Abstract

Critical thinking (CT) is a highly valued skill, based on feedback from a wide range of stakeholders, and thus academics have long sought to embed CT into undergraduate curricula. In this study, we investigated foundation biology students' self-efficacy of their CT skills (including three CT sub-elements), and whether such self-efficacies changed over a year of study. We also assessed students' actual CT ability, and whether there were differences in self-efficacy and actual ability between male and female students. While students' self-efficacy of their overall CT ability increased over the course of the year, this value was significantly lower than each of the CT sub-element efficacies, at both commencement and completion of the study. Conversely, students' actual CT skills did not change over the year, although females scored higher than males in the one of the two units of study. We conclude that (i) there is a disconnect between our students' self-efficacy of, and actual, CT ability; and (ii) there is a gender-based difference in their self-efficacy and actual CT ability. We recommend interventions to enhance foundation biology students' understanding of CT and through this, improve the concordance between their self-efficacy of their CT skills and their actual CT ability.

Keywords

Critical thinking; student self-efficacy; undergraduate science; metacognition; Dunning-Kruger effect; gender differences

Introduction

An ability to think critically is among the most highly valued of graduate skills and capabilities, based on feedback from industry and employers (Lowden et al. 2011; Rasul et al. 2013; Rayner & Papakonstantinou 2015), academics and other educators (National Council of Teachers 1989; Gordon et al. 2001; Stupple et al. 2017) and government (Quitadamo & Kurtz 2007). The ability to think critically underpins or is associated with many other valued student skills, including problem-solving (McCormick et al. 2015), creativity (Chan 2013; Siswono 2014), interpersonal skills (Rosenberg et al. 2012) and teamwork (Wiggs 2011; Davies 2013). As Bailey (2012) indicates, critical thinking (CT) is essential to all forms of intellectual endeavour, and it helps to make sense of everyday life (Hughes 2000). There are several core aspects or sub-elements of CT, including an ability to evaluate, infer, analyse, argue and rationalise (Facione 2007) across a number of domains; these include logical and deductive reasoning (Goyer 2013) and various forms of communication (Lidtke & Mulder 1998).

Due to the complexity involved in the process of thinking critically, a clear and concise definition of CT is yet to be universally accepted. However, that produced in a DELPHI study and reported by Facione (1990, p. 2) is one of the most commonly used:

> We understand critical thinking to be purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation and inference as well as explanation of the evidential conceptual, methodological, criteriological or contextual considerations upon which that judgment was based.

The multifaceted nature of CT unsurprisingly generates differences of opinion among educators, students and employers about the skills and dispositions that underpin it. To address this, Davies and Barnett (2015) proposed a model of CT comprising three aspects, one of which is defined as "critical rationality". Critical rationality is composed of an individual axis of criticality ("inner focus") along with a sociocultural axis ("outer focus"); in terms of pedagogy, this aspect is more appropriate for undergraduate assessment than the other two, "critical character" (personalities/dispositions) and "critical virtue" (morality/ethics). Critical rationality, which encompasses argumentation and reasoning, thus provides the theoretical framework for this study, which involves assessing students' CT abilities. In relation to this, a significant factor complicating the teaching of CT is that it is most commonly grounded within specific disciplines or domains, and that these are seldom integrated among discipline curricula, content and concepts (Jones 2015). Such disconnects may disproportionately enhance domain-specific facets of CT (e.g. application of discipline knowledge) at the expense of more general facets, although some researchers contend that CT cannot be developed in the absence of such knowledge (Bailin 2002; Willingham 2007).

Current thinking is that the cognition involved in CT is dynamic and context-specific, rather than stable over time and context (Abrahamse et al. 2016). This therefore suggests that students' CT abilities should improve and become more refined over time, although this depends on a number of factors, including the discipline (Quitadamo & Kurtz 2007; Lai 2011), the extent to which CT is specifically taught in or among disciplines (Lai 2011) and the CT test or tool used for benchmarking. Such tests include the California Critical Thinking Skills Test (Facione 1990), the Cornell Critical Thinking Tests (Ennis et al. 2005), the Ennis-Weir Critical Thinking Essay Test (Ennis & Weir 1985) and the Watson-Glaser Critical Thinking Appraisal (Watson & Glaser 1980). Unfortunately, few studies appear to have used any of these tests to assess foundation biology undergraduates' self-efficacy of their CT ability, and if these self-efficacies have changed over time. Consequently, very little is known of these students' self-efficacies concerning various CT sub-elements – analysis, evaluation, interpretation and synthesis of information – and whether these self-efficacies change over the course of their studies. Another vital question here is whether student self-efficacies concerning their CT skills match their actual CT abilities. This is because deficits in metacognitive skill, or an inability to distinguish accuracy from error, can cause misalignment between self-efficacy and actual ability (Kruger & Dunning 1999). Pedagogically, such disconnections result from what is now known as the Dunning-Kruger (D-K) effect (Dunning 2011), which essentially describes students' inability to accurately assess their actual competence.

There has long been a recognition of the importance of high-quality CT skills for science students and graduates (King et al. 1990; Hager et al. 2003; Rayner & Papakonstantinou 2015), and broad consensus about what CT entails among stakeholders. Further, a range of factors have been investigated as predictors of undergraduates' CT skills, including gender, age, grade-point average and involvement in on-campus activities (White et al. 2015). However, there appears to have been very little published on the links between students' self-efficacy and their actual CT ability upon their commencement, and over their first year, of study at university. This is despite the considerable body of scholarly literature published on innovations or interventions aimed at enhancing students' CT ability (Quitadamo & Kurtz 2007; Lin 2014), and/or their self-efficacy concerning their CT ability, over a unit, course or degree (e.g. Tsui 2002; Hager et al. 2003). One fundamental issue for university educators is that, as a consequence of their diverse learning backgrounds, commencing students are unlikely to have equivalent CT abilities. Given the importance employers place on graduates' CT skills (Rayner & Papakonstantinou 2015), and the greater diversity among students resulting from the massification (Altbach et al. 2009) and internationalisation (Sawir 2013) of higher education, it is vital that educators have a better understanding of commencing students' CT ability and whether such skills are enhanced over their the course of their studies.

In this paper, we set out to answer three questions. Upon commencement at university, what are the CT self-efficacy and actual CT ability of foundation biology students? Do these students' CT self-efficacies and their actual CT ability change over their first year of study? Is there a difference between males and females in their CT self-efficacy and actual CT ability, at both commencement and completion of their foundation year of study?

Methods

Undergraduate students at Monash University (Clayton campus) undertaking the two sequential foundation biology units (BIO1011 and BIO1022) completed identical surveys near commencement (March 2015) and completion (October 2015) of the academic year. The survey comprised four volunteer-response questions: Q1) Can you separate key points from other material in researching a topic related to your studies; Q2) Can you analyse the main theme in a research paper; Q3) Can you evaluate evidence to support a scientific argument; and (Q4) Do you have good critical thinking skills? These questions quantified student self-efficacies for each of the four CT skills categories reported by Davies & Barnett (2015): Lower-level (or Foundation), Higher-level, Complex and Thinking about thinking, respectively.

Students rated their self-efficacy for each survey question using a standard Likert-scale response from 1 (strongly disagree) to 5 (strongly agree). The study was administered under Monash Human Ethics permit CF13/2305 – 2013001213. Mean Likert scale (MLS) scores were subsequently calculated along with standard error using Microsoft Excel™. Survey responses were collated and standardised to exclude those of students not enrolled in the Faculty of Science, students without a tertiary entrance score (in this study, the Australian Tertiary Admission Rank; Messinis & Sheehan 2015), or students did not complete all aspects of BIO1011 and/or BIO1022 (n_{final} = 513, 48.2% of total enrolled students). The cohort consisted of 199 males and 314 females of roughly comparable age, with < 5% being mature-age students.

The actual CT ability of study participants was determined by their grades for selected multiple-choice questions in each of the BIO1011 and BIO1022 examinations, conducted during June 2015 and November 2015 respectively. The methodology of analysing suitable multiple-choice exam questions to gauge students' CT ability is validated through its prior use by Masters et al. (2001) and Morrison and Free (2001). The selected questions (23 of 144 for BIO111 and 16 of 144 for BIO1022) were chosen for their alignment with each of the four CT skill categories stated below (Table 1). All selected exam questions contained various components of analysis, interpretation and synthesis, which are accepted sub-elements of CT (Facione 2007). Average CT scores were subsequently calculated along with standard error using Microsoft Excel™. The phrase "critical thinking" was never used during the surveys to prevent potential bias. To investigate the possible effect of gender on both students' self-efficacy of CT and their actual CT ability, results were analysed based on this variable. A possible confounding effect of secondary biology educational background was investigated and dismissed, given that mean CT scores for students with and without such prior learning, for both units, were not significantly different. Assessment of significant differences between means was carried out using unpaired Student's *t*-test and Microsoft Excel ™.

Table 1. CT skills taxonomies of foundation-year biology exam questions

CT skill taxonomy	**BIO1011 exam questions**
Foundation (Separate key points)	ATP rate; Cell division; Phylogeny; Allopatric speciation; Reproduction; Biogeography; Interspecific interactions
Higher-level (Analyse main themes)	Enzyme kinetics; Hypotonicity; Genetic inheritance I; Genetic inheritance II; Dominant and recessive phenotype; Co-dominance; Population genetics I; Phylogenetic clades
Complex (Evaluate evidence)	Enzyme reaction; Phospholipids; Family pedigree; Autosomal versus X-linked inheritance; Population genetics II; Evolution; Terrestrial animals
Thinking about thinking (Good CT skills)	Natural selection
CT skill taxonomy	**BIO1022 exam questions**
Foundation (Separate key points)	Nucleic acid complementation; Neuron action potentials; Human hormones I; Macrophage response to bacteria; Animal digestive systems
Higher-level (Analyse main themes)	Gene mutation; Body signals; Human hormones II; Embryogenesis; Marine animals; Osmoregulation
Complex (Evaluate evidence)	Reciprocal altruism; Evolution I; Evolution II; Ectothermic metabolism; T-cell receptors

Results

Overall cohort

Students' self-efficacy of CT sub-elements that increased over their foundation biology studies were their ability to (i) separate key points from other material in researching a topic (Q1) and (ii) analyse the main themes in a research paper (Q2) (Figure 1). Students' self-efficacy of their overall CT ability (Q4) likewise increased over time (Figure 1). However, students' self-efficacy to evaluate evidence to support a scientific argument (Q3) did not significantly increase over this period (Figure 1).

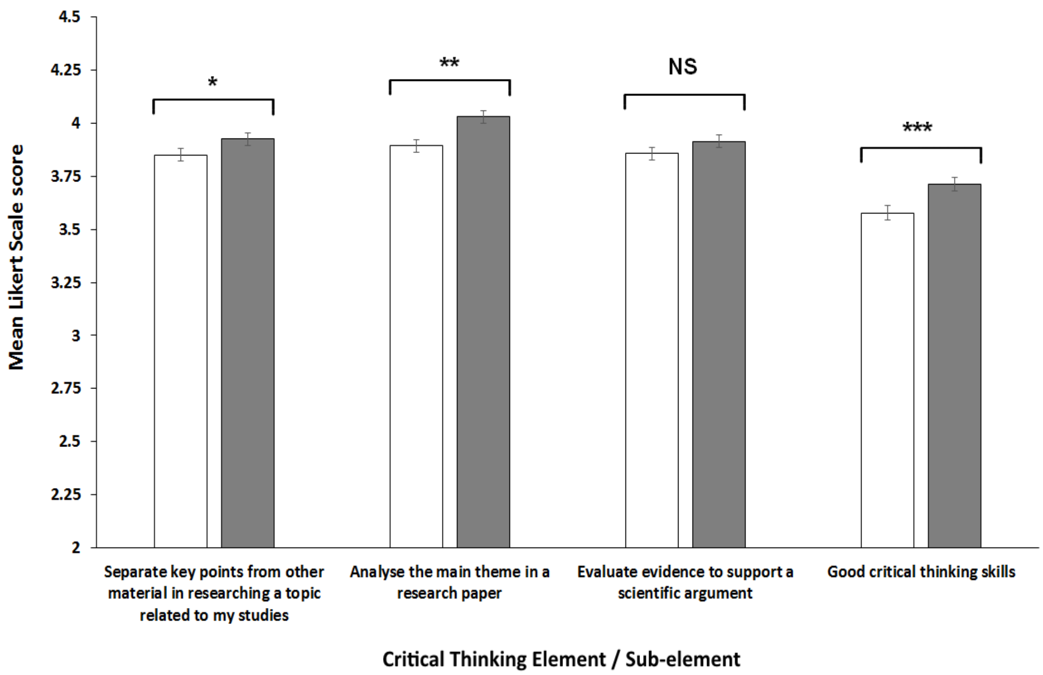

Figure 1. Students' self-efficacy of their critical-thinking skills (MLS score ± standard error) for two foundation biology units (n=513). Open columns represent BIO1011 (commencement survey), shaded columns BIO1022 (completion survey).
** p < 0.05, ** p < 0.01, *** p < 0.001, NS not significant.*

Students' self-efficacy regarding their overall CT ability (Q4) was significantly lower than each of the CT sub-elements (Qs 1-3) at both the commencement (all T values >3.1, all p values <0.0001) and completion (all T values >2.3, all p values <0.0001) of their studies (compare all four open columns and all four shaded columns of Figure 1). The cohort's actual CT ability did not significantly change over the course of their first-year studies, based on a comparison of the average CT score for BIO1011 (76.4 ± 0.4%) and BIO1022 (75.8 ± 0.5%).

Effects of gender

Male students' self-efficacy regarding CT sub-elements did not increase over the course of their foundation biology studies, except for Q2 (analysing the main theme of a research paper – Figure 2A). Likewise, their self-efficacy regarding their overall CT ability (Q4) did not change (Figure 2A). By contrast, the pattern for female students' self-efficacy regarding all the CT sub-elements and overall CT ability was the same as that of the unstratified cohort (see above): there were significant increases in self-efficacy for Q1, Q2 and Q4, but not Q3 (Figure 2B).

Similar to the overall cohort, male students' self-efficacy regarding their general CT ability (Q4) was significantly lower than each of the CT sub-elements (Qs 1-3) at both the commencement (all T values >1.3, all p values <0.005) and completion (all T values >1.6, all p values <0.0009) of their studies (compare all four open columns and all four shaded columns of Figure 2A). This pattern was likewise seen for female students, at both commencement (all T values >2.6, all p values <0.0001) and completion (all T values >1.7, all p values <0.0004) of foundation biology (again, compare all four open columns and all four shaded columns of Figure 2B). Comparing male and female self-efficacy for Qs 1-4 in both BIO1011 and BIO1022 revealed no significant differences except that females had a lower self-efficacy than males for Q1 and Q4 for BIO1011 (compare relevant open columns of Figures 2A and 2B; $T=1.2$, $p=0.01$ for Q1 and $T=1.6$, $p=0.001$ for Q4).

Actual CT ability for males decreased significantly ($T=2.0$, $p<0.0001$) over the course of the academic year, based on a comparison of the average CT score for BIO1011 (77.4 $\pm$ 0.7%) and BIO1022 (73.0 $\pm$ 0.8%). By contrast, there was no such decline for the female cohort, with no significant difference in the average CT score for BIO1011 (76.3 $\pm$ 0.6%) and BIO1022 (75.3 $\pm$ 0.6%). When comparing genders, females scored significantly higher than males for BIO1022 ($T=1.8$, $p=0.0002$) but not BIO1011.

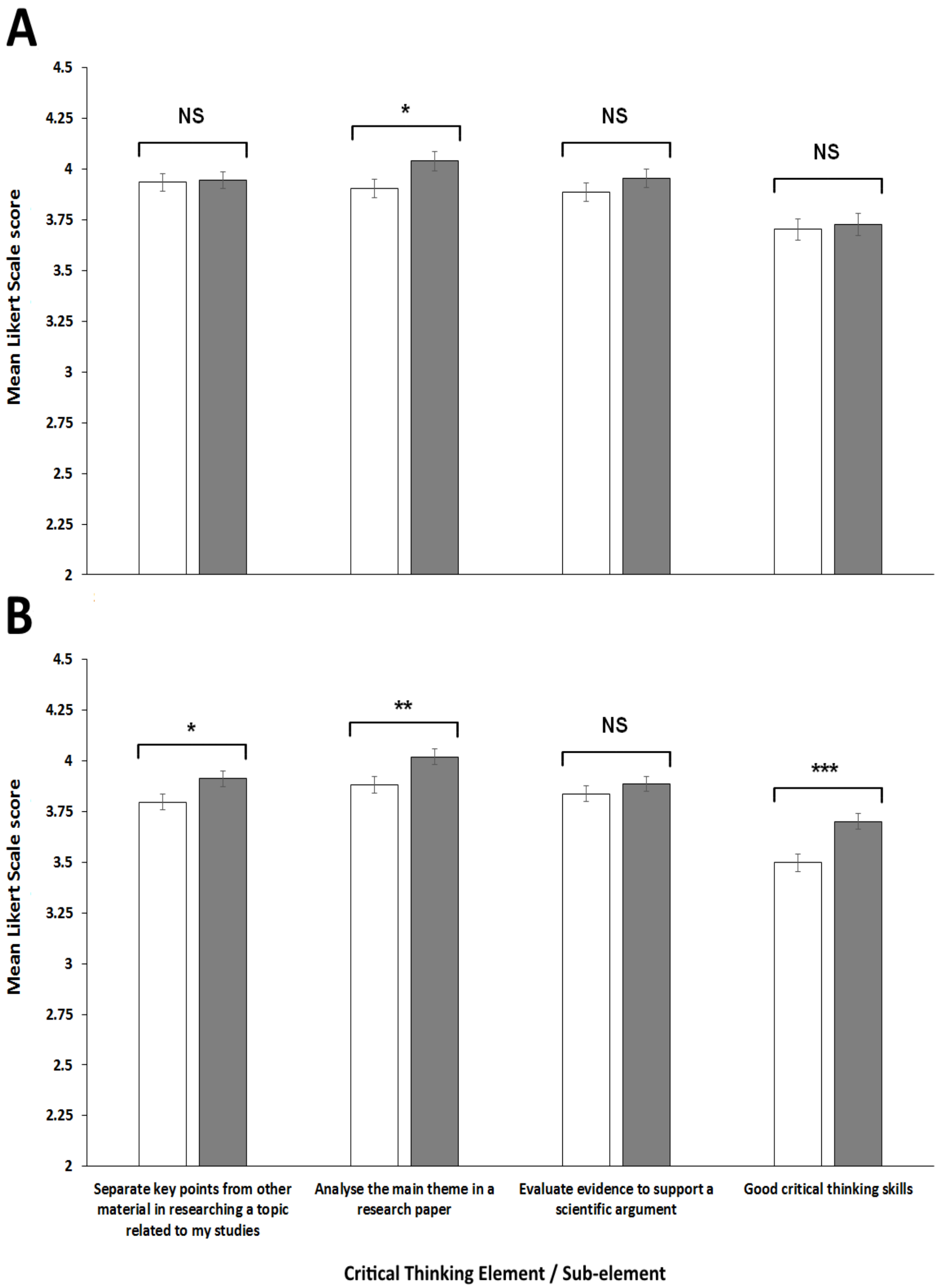

Figure 2. Students' self-efficacy of their critical-thinking skills (MLS score plus standard error) for the two foundation biology units, stratified by gender; (A) males (n=199) and (B) females (n=314). All other indications are as for Figure 1.

Discussion

The observed increases in students' self-efficacy regarding their overall CT ability (Thinking about thinking), self-efficacy regarding separate key points from other material in researching a topic (Lower-level or Foundation), and self-efficacy in analysing the main themes in a research paper (Higher-level) are consistent with predictions associated with the theoretical CT framework used for this study (Davies & Barnett 2015). These increases may have resulted from CT-related activities that the students undertook in their two biology units. However, it is equally possible that activities undertaken in other science units contributed to the observed increases, as disciplinary differences have been reported to have an effect on students' CT self-efficacy (Li et al. 1999).

The lack of an increase in students' self-efficacy in evaluating evidence to support an argument (Complex) is inconsistent with predicted outcomes associated with the CT framework (Davies & Barnett 2015). This outcome is intriguing, as many of the activities students undertook in these two units involved information and data collection, analysis and interpretation, all of which are strongly aligned with this skill (Jeong & Songer 2008). Iteration of the CT sub-elements, such as the evaluation of information, enhances students' overall CT ability (Finley & Waymire 2013), particularly where such skills are taught "directly and deliberately" (De Bono 1992, p. 7). It is possible that the lack of clear identification of CT sub-elements, such as the ability to evaluate evidence, in unit curricula may account for our students' static self-efficacy for this sub-element. If correct, it is beholden on educators to more clearly identify CT-aligned skills in practical activities, even to the level of articulating CT sub-elements where these occur in such activities, and where they are reiterated in subsequent ones. Further, this outcome demonstrates the need for specific activities or core units to enhance students' CT abilities, such as described by Rowe et al. (2015).

Students' significantly lower self-efficacy regarding their overall CT ability, compared to each of the CT sub-elements, may indicate that they properly identify "good CT skills" as the most complex level of CT – namely, "Thinking about thinking" (Davies & Barnett 2015). A second or interacting explanation is that students may have fundamental misconceptions about CT, which is supported by the fact that only 30% of BIO1011 students and 25% of BIO1022 students were able to correctly identify a set of survey keywords that most accurately define CT (data not shown). The CT sub-elements may be more identifiable to foundation-year undergraduates, as they are the more tangible, "doing" activities that are being reiterated from previous activities. By contrast, "good CT skills" may be a more nebulous concept for such students, given previous reports of undergraduates' inability to understand CT (Davies 2011; Mulnix 2012). Third, this finding regarding self-efficacy may reflect the absence of a clear articulation of CT in the practical (and other) activities that these students undertake. Together with previous literature on students' understanding of CT, our findings add further weight to our above recommendation about more clearly signposting CT skills in teaching and learning activities, so that students are able to reflect on these aspects of their learning and strengthen their metacognition about CT.

The lack of significant change in our students' actual CT ability over the course of this study is consistent with other research, which reported an apparent lack of improvement in students' CT ability over the short or longer term (Schendel 2015; Zimmerman et al. 2011). This adds weight to the contention of Green (2015) that academics, in general, do a poor job of teaching CT. Our results regarding students' actual CT ability, together with the broader literature on the inculcation of CT, suggest, first, that CT activities need to be more clearly identified in undergraduate science curricula. Second, our findings reinforce a need for greater investment in academics' professional development (Schendel 2016), and in particular that of sessional staff, who undertake the bulk of face-to-face teaching at Australian (Coates & Goedegebuure 2010) and international (Baldwin & Wawrzynski 2011) universities. These two recommendations regarding the enhancement of undergraduates' CT skills reinforce those of Abrami et al. (2008), who undertook a meta-analysis of empirical evidence on the impact of teaching on students' CT skills and dispositions.

That there is a disconnect between students' self-efficacy regarding their CT ability, which increased, and their *actual* CT ability, which did not change, is of considerable interest. It is also consistent with a range of studies reporting a possible D-K effect (Falchikov & Boud 1989; Dunning et al. 2003; Carter & Dunning 2008; Lindsey & Nagel 2015). The D-K effect has been previously described for a range of abilities, including generic skills such as adaptability and problem-solving (Hock-Eam & Yeok 2017), information literacy (Gross & Latham 2007) and numeracy (Nuhfer et al. 2016) and interpersonal skills such as teamwork (Hock-Eam & Yeok 2017). However, our study is one of the very few (e.g. Plencner 2014) to demonstrate a possible D-K effect for CT, which suggests the need for further research in this field.

That males' self-efficacy regarding both their overall CT ability and two of the three CT sub-elements did *not* increase over time indicates that for this discipline and under these conditions, gains in CT self-efficacy are greater for females compared to males, which is consistent with other research (Vogt et al. 2007). This may mean that female students have a greater ability than males to identify some facets of CT during their learning activities, as was reported by Steward and Al-Abdulla (1989). That female students had significantly lower overall CT self-efficacy and lower self-efficacy for Foundation CT (Davies & Barnett 2015) than males at thecommencement of their university studies, and that these differences did not persist over the study period, is consistent with Srinivasan (2017), who reported the same pattern for female college students' self-efficacy regarding their chemistry laboratory skills. This most interesting finding may indicate underlying gender differences in science undergraduates' CT self-efficacy, albeit without knowing how such differences may arise.

Investigation of gender differences in actual CT ability has been carried out across a range of disciplines, age groups and contexts (Terenzini et al. 1996; Walsh & Hardy 1999). Our finding that females had a higher actual CT ability than male peers by the end of the study period is consistent with previous research (Rudd et al. 2000; Walsh & Hardy 1999). However, this research is not unequivocal, with other studies finding no difference in CT ability between males and females (e.g. Myers & Dyer 2006), or reporting higher CT ability in males (King et al. 1990; Li et al. 1999). Given the range of conflicting research findings in both intra- and inter-discipline contexts, a meta-analysis of the literature on gender differences in *both* actual and self-perceived CT ability is perhaps long overdue.

One potential limitation regarding the assessment of our students' actual CT ability may have been the instrument used in this study. Although the analysis of suitable exam questions may not be an ideal measure of CT ability, the method is validated in the sciences by other researchers, including Morrison and Free (2001). Furthermore, only one exam question was used to analyse students' actual ability regarding the "Thinking about thinking" CT sub-element, and while this is unlikely to have affected our overall conclusions, we acknowledge it as a limitation of the study. This illustrates the difficulty of developing multiple-choice exam questions that authentically test students' higher order CT skills; nevertheless, it is a challenge that should be addressed. In terms of a discipline-specific tool, Gunersel et al. (2008) reported on the positive effect of a web-based instrument to promote CT skills in biology undergraduates; with some modification, this might be useful for future assessment of our students' actual CT ability. Carmichael and Farrell (2012) have similarly reported on the effectiveness of an online tool designed for developing students' CT skills. It is also acknowledged that the timing of our CT tests – 11 weeks after the self-efficacy survey during BIO1011, and three weeks after the corresponding survey during BIO1022 – may have had a confounding effect on our results. Future research in this area should thus seek to better align surveys with measures of students' CT ability, notwithstanding the logistics involved in coordinating undergraduate curricula.

Summary and conclusions

This study offers the following answers to the research questions: First, at the commencement of their university studies, foundation biology students ranked their overall CT ability lower than they ranked their ability in each the three CT sub-elements in this study. Second, students' CT self-efficacy changed significantly over their first year of study. There was an increase in the overall cohort's self-efficacy in separating key points from other material in researching a topic, and in analysing the main theme in a research paper, as well as in having enhanced CT skills. However, *actual* CT ability did not significantly change over time. Third, upon commencement of their studies, females had a lower CT self-efficacy than males for both separating key points from other material in researching a topic and overall CT skills, even though these differences disappeared over time. Conversely, while there was no difference in actual CT ability between males and females midway through the year, females had a significantly higher actual CT ability than males at completion of their foundation biology studies, indicating a cumulative gender-based difference within this cohort.

Good CT ability has long been correlated with academic success across a range of disciplines, including medicine (Scott & Markert 1994), business (Jenkins 1998), pharmacy (Allen & Bond 2001) and psychology (Williams et al. 2003). Both the centrality of CT as a highly regarded graduate attribute and its important predictive value for student academic success suggests that teachers and curricula, across the entire educational spectrum (primary, secondary and tertiary), should build students' CT ability through authentic, iterated and scaffolded interventions. Through this, undergraduates will have a more accurate understanding of both what CT means and their actual CT ability, which together have considerable potential for improved academic success and their development of valuable employability skills.

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