Wingert *et al.*
Evolution: Education and Outreach (2022) 15:4
https://doi.org/10.1186/s12052-022-00162-6

Evolution: Education and Outreach

RESEARCH

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The impact of direct challenges to student endorsement of teleological reasoning on understanding and acceptance of natural selection: an exploratory study

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Abstract

Background: Teleological reasoning is a cognitive bias purported to disrupt student ability to understand natural selection. Few studies have described pedagogical efforts to decrease student endorsement of teleological reasoning and measure the effects of this attenuation on the understanding and acceptance of evolution. This exploratory study examined the influence of explicit instructional activities directly challenging student endorsement of teleological explanations for evolutionary adaptations on their learning of natural selection over a semester-long undergraduate course in evolutionary medicine. In a convergent mixed methods design this study combined pre- and post-semester survey data (N = 83) on understanding natural selection, student endorsement of teleological reasoning, and acceptance of evolution, with thematic analysis of student reflective writing on their understanding and acceptance of natural selection and teleological reasoning.

Results: Student endorsement of teleological reasoning decreased and understanding and acceptance of natural selection increased during a course on human evolution with teleological intervention ($p \leq 0.0001$), compared to a control course. Endorsement of teleological reasoning was predictive of understanding of natural selection prior to the semester. Thematic analysis revealed that prior to the course students were largely unaware of the concept of teleological reasoning and their own tendency to think about evolution in a purpose-directed way, but perceived attenuation of their own teleological reasoning by the end of the semester.

Conclusions: This exploratory study provides initial evidence that class activities to directly challenge student endorsement of unwarranted design teleological reasoning reduces the level and effects of teleological reasoning in an evolution course. Students were unaware of their high levels of endorsement of teleological reasoning upon entrance into the undergraduate human evolution course, which is consequential because teleological reasoning is a predicter of natural selection understanding. As a result of developed anti-teleological pedagogy, students had decreased unwarranted teleological reasoning and increased acceptance and understanding of natural selection over the course of the semester. The data presented show that students are receptive to explicit instructional challenges to their teleological reasoning and that attenuation of this bias is associated with gains in natural selection understanding and acceptance.

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Keywords: Teleology, Evolution pedagogy, Natural selection

Background

Evolution by natural selection is the fundamental unifying and organizational theory of biology, but student understanding of this topic is tenuous and challenged by multiple factors, including religiosity, parental attitudes toward evolution, student acceptance of evolution, and cognitive obstacles, such as teleological reasoning (Gregory 2009; Smith 2010; Dunk et al. 2017; Barnes et al. 2017). Teleological reasoning is the cognitive tendency to explain natural phenomena by their putative function, purpose, or end goals, according to some prescribed direction or plan, rather than by the natural forces that bring them about (Kelemen 2012; Hammann and Nehm 2020). Design-based teleological reasoning is in opposition to the theory of evolution by natural selection because it suggests the common misunderstanding of natural selection as a forward-looking, rather than a blind, process (Kelemen et al. 2013; Kampourakis 2020). Design teleology purports that an adaptation occurred according to the intentions of an external agent (external design teleology) or to fulfil the needs of the organism (internal design teleology) (Kampourakis 2020). This can lead students to assume that all traits are adaptations that evolved toward a prescribed functional endpoint due to a sense of goal-directed agency or conscious intention (Moore et al. 2002; Trommler and Hammann 2020). Therefore, when students endorse design teleology they do not acknowledge the veridical evolutionary mechanisms of genetic variation from random genetic changes and sexual recombination or the importance of non-adaptive mechanisms such as genetic drift and gene flow. Several studies have shown that understanding evolution is disrupted by teleological reasoning (Barnes et al. 2017; Bishop and Anderson 1990; Demastes et al. 1996; Settlage 1994; Wingert and Hale 2021) and yet, science educators may underestimate the prevalence of the design teleological bias and its cognitive impacts (Moore et al. 2002). To suppress or regulate the design teleological bias with veridical views on the natural world is cognitively challenging, but necessary to accurately understand evolution (Gregory 2009; Kampourakis 2020; González Galli et al. 2020) and other biological sciences (Werth and Allchin 2020).

A growing literature shows that teleological reasoning is universal, especially in children, and therefore, part of typical cognitive development. As early as preschool, children develop an intuitive preference for teleological explanations over physical-causal explanations across multiple domains, including human-made artifacts and living and non-living things in nature (Kelemen 1999; Kelemen 1999; Kelemen and DiYanni 2005). Kelemen and colleagues have differentiated between the warranted use of teleological explanations to describe the origins of human-made artifacts and the unwarranted extension of teleology beyond human-made artifacts to also describe living and nonliving things in nature (Kelemen 1999; Kelemen 1999; Kelemen 2003). Teleological reasoning persists in high school (Settlage 1994; Jungwirth 1979; Richardson 1990; Southerland et al. 2001; Kampourakis and Zogza 2009; Pedersen and Halldén 1994), college (Kelemen and Rosset 2009; Stover and Mabry 2007; Jensen and Finley 1995), and graduate school (Brumby 1984). College-educated adults demonstrate a tendency toward teleological reasoning when they are uncertain or lack knowledge of an appropriate explanation and when they are under timed test conditions (Kelemen and Rosset 2009; Roberts et al. 2020). Even academically active physical scientists, who normally subscribe to physical-causal explanations consistent with their extensive scientific training, default to teleological explanations when their cognitive resources are challenged by a timed or dual task (Kelemen et al. 2013). Therefore, the picture emerging from this body of research indicates that teleological reasoning is universal (Schachner et al. 2017), but the strength of this bias can possibly be moderated after childhood by cultural factors, including education. Yet, extensive scientific education does not appear to completely revise and replace the bias (Kelemen et al. 2013; Wingert and Hale 2021; Järnefelt et al. 2015).

Given the universality and disruptiveness to biological learning of teleological reasoning, there is an emerging literature on how to address teleology in the classroom. González Galli et al. (2020) have proposed that a goal of biological education is to help students regulate their teleological reasoning when thinking about evolution. According to González Galli et al. (2020), in order to regulate teleological reasoning, the student must exhibit metacognitive vigilance that requires developing the following competencies: (i) knowledge of teleology, (ii) awareness of how teleology can be expressed both appropriately and inappropriately, and (ii) deliberate regulation of its use by the student (González Galli et al. 2020). Kampourakis (2020) suggests showing students that design teleology is problematic by explicitly addressing design teleology in the classroom and contrasting it with natural selection to evoke a conceptual tension between the two. However, while several authors have suggested that addressing teleological misconceptions

should be explicitly incorporated into evolution courses (Barnes et al. 2017; Richardson 1990; Bartov 1978, 1981; Gresch and Martens 2019; Jungwirth 1975; Tamir and Zohar 1991; Zohar and Ginossar 1998), we are aware of few empirical investigations on the effects of classroom efforts to systemically and explicitly address teleological reasoning in college students (Wingert and Hale 2021; Pedersen and Halldén 1994; Stover and Mabry 2007; Jensen and Finley 1995). Jensen and Finley (Jensen and Finley 1995) showed decreased student use of teleological explanations in an undergraduate introductory biology course that specifically included instruction on historical perspectives on teleology (i.e., Cuvier and Paley) and Lamarckian views on evolution. Similarly, Wingert and Hale 2021 provided evidence that instructional challenges to undergraduate student endorsement of teleological reasoning instruction significantly improves student understanding of fundamental concepts of evolution, decreases pervasive student misconceptions about evolution, and increases student acceptance of human evolution.

The purpose of this exploratory study was to determine if education intended to directly challenge design teleology in the context of a human evolution course (conceived according to the framework of González Galli et al. (2020)) reduces student endorsement of teleological reasoning and impacts understanding natural selection compared to a control course. We sought to build on the existing literature by assessing endorsement of teleological reasoning, acceptance of evolution, and understanding of natural selection with previously established measures in undergraduates before and after taking a course on evolution. The survey of student endorsement of unwarranted teleological reasoning used in the current study was a sample selected from Kelemen et al.'s (Kelemen et al. 2013) study of physical scientists' acceptance of teleological explanations in nature. We assessed student acceptance of evolution with the validated Inventory of Student Evolution Acceptance (Nadelson and Southerland 2012) and we measured understanding of natural selection with the Conceptual Inventory of Natural Selection (Anderson et al. 2002). Since natural selection understanding is a multifactorial issue (Gregory 2009; Smith 2010; Dunk et al. 2017; Barnes et al. 2017), we also measured student religiosity, parental attitudes, and prior evolution education. Additionally, we combined qualitative analysis of student responses to open-ended questions about their experiences exploring their tendencies to endorse teleological reasoning. The qualitative component allowed insights into the thought processes and difficulties students may have experienced when confronted with challenges to their teleological reasoning, but which may not have been observable on the surveys alone. Therefore, in a convergent mixed methods research design, we sought to address the following research questions: (RQ1) Does student teleological reasoning change over the course of a semester in response to explicit instruction on teleological reasoning? (RQ2) Do changes in teleological reasoning, or other factors, impact student understanding and acceptance of evolution? and (RQ3) What are students' metacognitive perceptions of their teleological reasoning in an evolution course?

Methods

Participants

Participants were undergraduate students (N = 83) at a public liberal arts college in the Southeastern United States. Fifty-one students (mean age (SD) = 23.4 (7.1) years, 64.7% female) were in a course on the evolutionary principles of human health and disease during three consecutive Fall semesters. The professor of the course had > 12 years of teaching experience. The control group was comprised of thirty-two students (mean age (SD) = 21.5 (6.3) years, 71.9% female) enrolled in a Human Physiology course taught by the same professor. This study was deemed exempt from further review by the Institutional Review Board at UNC Asheville and all participants provided signed informed consent before participating in the study. Prior to providing informed consent, students in the Human Physiology course were told that they would be part of the control group and would not experience intervention.

Course description

The evolutionary principles of health and disease course taught the fundamental principles of evolution in a mostly human context, with a specific focus on adaptation and maladaptation related to human health and disease. By considering human health from an evolutionary perspective, students gained insights into how the human body has adapted to its various environments, and why particular diseases occur in the modern world. This course explored the fundamentals of evolution, its relationship to the development of the human body over time, teleological thinking, pathophysiology attributable to evolution, and environmental and social evolutionary mismatches in the modern world which contribute to disease. This course consisted of lectures, group discussions on readings, weekly quizzes, and a final research project exploring the evolutionary principles of a chosen disease.

The activities to address teleological reasoning in the course included: (1) lectures related to core concepts in evolutionary biology. In lectures, students were given a definition and several examples of teleological reasoning compared with veridical evolutionary explanations.

Design-based teleological and veridical evolutionary mechanisms were contrasted for the following examples: formation of limbs in the first terrestrial animals, evolution of the giraffe neck, evolution of human bipedalism, and expansion of the hominin brain. The class discussed how teleological reasoning is often used in biological explanations and how design teleology can disrupt learning of evolution. (2) Students completed three consecutive weekly quizzes asking them to identify the design teleological statement(s) from a list of multiple statements on evolutionary mechanisms and to correct the teleological statements with veridical evolutionary mechanisms. The correct answers to these quiz questions were discussed with students after grading. (3) There were weekly class discussions on assigned readings, which included explicit discussions on the distinctions between design teleological reasoning and more veridical scientific explanations. Students were encouraged to identify teleological statements made by the author of the readings, professor, or other students during class discussions. Sometimes these statements were legitimate uses of teleology and sometimes they were illegitimate. For example, *The Story of Human Body* by Daniel Lieberman (Lieberman 2013) includes a sentence that some students initially thought was teleological: "Consequently, adaptations evolve to promote health, longevity, and happiness only insofar as these qualities benefit an individual's ability to have more surviving offspring." The semantic cue "evolve to" provided an opportunity to discuss that evolutionary biologists may appropriately use teleological statements as an organizing heuristic [i.e., selective teleology (Kampourakis 2020) or epistemological teleology (Trommler and Hammann 2020)], and here Lieberman, in the context of the full paragraph, is indeed describing natural selection through veridical mechanisms. On another occasion, a student stated that bipedalism evolved so that early hominins could ambulate with greater energy efficiency, which prompted a discussion leading to the conclusion that this was a goal-directed, design teleological statement. (4) Finally, a short writing assignment in the tenth week of the semester asked students to respond to four open-ended questions (see Study design and assessment section below) on their level of teleological reasoning, how learning about teleology affected their learning of evolutionary concepts, and how awareness of teleology fits in the context of their understanding of the broader world. The class then discussed these reflections.

The Human Physiology (control) course neither specifically taught evolutionary principles nor addressed student teleological reasoning at any point, but did include frequent evolutionary explanations in response to student questions when appropriate. Although it was not an evolution course, the inclusion of the Human Physiology course as a comparison group assesses the potential confounding effects of history, maturation, and testing.

Study design and assessments

This study used a convergent mixed methods design (Creswell and Clark 2017), where all participants completed both the quantitative and the qualitative strands. In the quantitative strand, students were asked to complete three surveys in a single day during the first, and again during the last, week of the semester. The first survey measured students' understanding of natural selection with the Conceptual Inventory of Natural Selection (CINS), which consists of 20 multiple-choice questions each with one correct answer (Anderson et al. 2002). The validity and reliability of the CINS have been reported (Anderson et al. 2002; Nehm and Schonfeld 2008). The CINS includes six questions (items 4, 6, 8, 13, 19, 20) that either have teleological themes or teleological distractors as multiple-choice options, and therefore test teleological endorsements. These six questions were removed from all analyses of understanding of natural selection and analyzed separately as a secondary measure of teleological reasoning.

The second survey was a 36-item survey of teleological reasoning adapted from the larger measure created by Kelemen et al. (2013), which included 100 one-sentence explanations for "why things happen," presented as timed forced-choice statements to which participants responded as "true" or "false". Kelemen et al. (2013) used 30 test sentences describing scientifically unwarranted design teleological (i.e., inaccurate) explanations for various natural phenomena and 70 control sentences. The control sentences in the Kelemen et al. (2013) study included: 20 true causal explanations, 10 true teleological explanations, 30 false causal explanations, and 10 false teleological explanations. The Kelemen et al. (2013) measure was adapted in the current study to include 20 test sentences and 16 control sentences (4 true causal explanations, 5 true teleological explanations, 4 false causal explanations, and 3 false teleological explanations), chosen at random from each statement type (see Additional file 1). Only student responses to the twenty unwarranted teleological test statements were included in the analysis. An additional adaptation of the original measure is the use of a 5-point Likert scale in the current study to determine the student's level of agreement, rather than the previously used timed forced-choice test (Kelemen et al. 2013).

The third measure included the 24-item Inventory of Student Evolution Acceptance (I-SEA) which has been shown to be a reliable measure of evolution acceptance in college students (Nadelson and Southerland

2012; Nadelson and Hardy 2015). Students completed the full I-SEA and responses to both the full I-SEA and the human evolution subsection were included in this analysis. The third survey also included student demographic information, level of prior exposure to evolution, number of previous courses on evolution in high school and college, level of religiosity, specific religious affiliation, and parent attitude toward evolution. The following survey questions used a 5-point Likert scale ranging from *strongly disagree (1)* to *strongly agree (5)* for student responses. Student prior educational exposure was measured by asking students the extent to which they agreed with the statement, "In previous courses, I have learned a lot about evolution." Students' perceptions of their parents' attitudes about evolution were asked separately for each parent (or guardian), with the question, "What attitude do you think your mother/father (or guardian) has toward evolution?" Students were asked how important religion was in their life, using a 4-point Likert-type scale, ranging from *not important* to *very important*.

In the qualitative strand, students were asked to complete written responses to the following four open-ended questions during the tenth week of the semester: 1) Please describe your level of acceptance of evolution. 2) Have your views on evolution changed since an earlier point in your life? If so, what has caused this change? If not, please describe your reasons. 3) Have the readings and discussions in class been consistent with your views about life or has it been challenging? Please explain your answer. 4) Please describe your thinking about the causes of nature, evolution, and human life. Has your use of teleology changed over the semester?

Quantitative analysis

Spearman correlations examined the relationships between measures. Wilcoxon signed-rank tests examined paired within-group differences between pre-and post-semester. Mann–Whitney U tests examined between-group differences. Values are presented as mean (SD) and effect sizes are presented as Hedges' g. Internal consistency of the survey items was measured with Cronbach's alpha and criterion validity of the teleology measure was preliminarily assessed by Spearman correlation with the responses to the six teleology-themed questions on the CINS. Finally, we ran three independent multiple regressions using to determine the relative influence of each measured variable on students' acceptance of evolution and their understanding of natural selection at pre-and post-semester. GraphPad Prism Version 9.3.0 (San Diego, CA) was used for all statistical analyses, except for Cronbach's alpha (calculated with Microsoft Excel version 16.16.27) and the multiple regression analyses (calculated with R; R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was set at $p < 0.05$.

Qualitative analysis

Two reviewers independently scored the responses to the open-ended questions for their level of evolution acceptance using a 5-point Likert scale ranging from *strongly disagree* to *strongly agree.* Interrater reliability was calculated for these ratings. Next, a thematic analysis was conducted on the student responses to the open-ended questions. The first step of the thematic analysis was for both reviewers to independently read each student response and identify themes (see Additional file 2). Only the themes related to student teleological reasoning and learning/acceptance of evolution were included in this analysis. The reviewers then independently re-read the student responses and identified when the themes were mentioned. After interrater reliability was established, only counts from one rater (JW) were used in the analysis. If a student mentioned the theme at least once in their responses to any of the open-ended questions, a score of "1" was recorded for that theme in the student's response. The total number of mentions was summed across students for each theme.

Results

Forty-eight of the 51 students in the evolutionary principles of health course completed all surveys at both pre- and post-semester (94% response rate). Of the three students not completing the surveys, two students did not complete the surveys at pre-semester and the other left college before the end of the semester. In the control course, three students' responses were eliminated because these students reported that they were simultaneously enrolled in a course on evolution. Three additional students did not complete the pre- or post-surveys for unspecified reasons. Therefore, the control group was comprised of 26 students that completed all surveys at pre- and post-semester (90% response rate).

The following analyses included data from the evolutionary principles of health course only, henceforth referred to as teleology intervention (TI). Four percent (4%) of the students were sophomores, 36% juniors, 56% seniors, and 4% post-baccalaureate students. Prior to this course, students reported taking a mean (SD) = 0.43 (0.64) courses on evolution in high school and a mean (SD) = 1.25 (0.79) evolution courses in college. On 5-point Likert scales students self-scored their prior educational exposure on evolution as a mean (SD) = 3.27 (1.25) and scored their parents' attitudes toward evolution as a mean (SD) = 3.38 (1.23). Self-reported religious affiliation included: 10% Catholic, 0% Eastern Religion,

Table 1 Spearman correlations among pre-semester variables, assessed prior to presentation of course material

	Parental attitude	Student religiosity	Evolution acceptance (I-SEA)	Prior education	Teleological reasoning
Parental attitude	–				
Student Religiosity	−0.32	–			
Evolution acceptance (I-SEA)	0.58‡	−0.34*	–		
Prior education	0.28	−0.07	0.36*	–	–
Teleological reasoning	−0.19	0.35*	−0.44†	−0.25	–
Natural Selection Understanding (CINS)	0.15	−0.30*	0.30*	0.22	−0.65‡

* $p < 0.05$; † $p \leq 0.01$; ‡ $p \leq 0.001$

14% Fundamental Christian, 4% Jewish, 0% Muslim, 24% None, 16% Other Protestant, and 32% reported Other. On the importance of religion in the students' lives, 38% listed "not important," 20% "slightly important," 16% "moderately important," and 26% listed "very important."

Pre-semester data

At pre-semester, students in the TI course with lower levels of teleological reasoning had higher understanding of natural selection (i.e., higher CINS scores) ($r = -0.65$; $p < 0.0001$) (Table 1). Students with lower levels of teleological reasoning had higher acceptance of evolution ($r = -0.44$; $p = 0.0017$) and lower religiosity ($r = 0.35$; $p = 0.014$). Students reporting that their parents had more positive attitudes toward evolution had higher acceptance of evolution ($r = 0.58$; $p < 0.0001$). There were no differences between the TI course and the control course on any measure at pre-semester (see Additional file 3).

To control for all other variables and illustrate the relative influence of each variable (parental attitude, religiosity, prior education, teleological reasoning, and natural selection understanding) on students' incoming acceptance of evolution (I-SEA), we conducted a multiple linear regression (Table 2): $R^2 = 0.45$; $F(5, 42) = 6.88$, $p < 0.0001$ (Adjusted $R^2 = 0.38$). Together, these variables accounted for 38% of the variance in student acceptance of evolution scores, with significant unique variance contributed only by parent attitude toward evolution (positively).

Multiple linear regression determined the relative influence of each variable on student understanding of natural selection (CINS without the six teleology questions) prior to instruction (Table 3): $R^2 = 0.42$; $F(5, 42) = 6.02$, $p < 0.00028$ (Adjusted $R^2 = 0.35$). Together, these variables accounted for 35% of the variance with significant unique variance contributed by incoming teleological reasoning (negatively). To summarize, parental attitudes toward evolution were the greatest predictor of students'

Table 2 Results from a multiple linear regression of pre-semester student evolution acceptance (I-SEA)

	B	SE B
Intercept	90.26	16.44
Parental attitude-evolution	5.62†	1.60
Student religiosity	−1.58	1.60
Prior educational exposure	2.03	1.53
Teleological reasoning	−4.24	2.96
$CINS_{pre}$	0.12	0.80
Adjusted R^2	0.38	

* $p < 0.05$; † $p \leq 0.01$; ‡ $p \leq 0.001$

Table 3 Results from a multiple linear regression of student pre-semester understanding of natural selection (CINS)

	B	SE B
Intercept	15.10	3.45
Parental attitude-evolution	−0.004	0.35
Student religiosity	−0.16	0.31
$ISEA\text{-}HE_{pre}$	0.004	0.031
Prior educational exposure	0.11	0.30
$Teleological\ reasoning_{pre}$	−2.18†	0.481
Adjusted R^2	0.35	

† $p \leq 0.001$

Table 4 Spearman correlations among post-semester variables, assessed after presentation of course material

	Parental attitude	Student Religiosity	Evolution acceptance (I-SEA)	Prior education	Teleological reasoning
Parental attitude	–				
Student religiosity	−0.35*	–			
Evolution acceptance (I-SEA)	0.49‡	−0.50‡	–		
Prior education	0.28	−0.03	0.41†		–
Teleological reasoning	−0.36*	0.20	−0.51‡	−0.37*	
Natural Selection Understanding (CINS)	0.28	−0.39†	0.39 †	0.18	−0.38†

* $p < 0.05$; † $p \leq 0.01$; ‡ $p \leq 0.001$

acceptance of evolution and teleological reasoning was the main predictor of natural selection understanding, prior to instruction.

Post-semester data

Natural selection understanding at post-semester (Table 4) was significantly correlated with post-semester measures of teleological reasoning ($r = -0.38$; $p = 0.0074$), student religiosity ($r = -0.39$; $p = 0.0064$), and acceptance of evolution ($r = 0.39$; $p = 0.0068$). Higher student religiosity was associated with lower levels of understanding of natural selection ($r = -0.38$; $p = 0.0064$) and lower levels of human evolution acceptance ($r = -0.53$; $p < 0.0001$). Students with lower levels of teleological reasoning had higher acceptance of evolution ($r = -0.44$; $p = 0.0017$).

We conducted a multiple linear regression to determine the relative influence of each variable, independently of the others, on the post-semester natural selection understanding (CINS) score. Overall, 45% of the variance was explained (Table 5): $R^2 = 0.52$; $F(6, 41) = 7.40$, $p < 0.0001$ (Adjusted $R^2 = 0.45$). Only pre-semester natural selection understanding ($p < 0.001$) contributed significant unique variance.

Pre-post comparisons

Wilcoxon signed rank tests examined whether variables changed in response to the course material (Fig. 1). Students improved their understanding of evolution (CINS without the six teleology questions) ($M_{Pre} = 9.00$ (2.92); $M_{Post} = 10.27$ (2.35); Hedges' $g = 0.48$; $P = 0.0001$). CINS score increased in 64.5%, stayed the same in 12.5%, and decreased in 23.0% of students at post-semester compared to pre-semester. Students' endorsement of teleological reasoning decreased over the course of the semester ($M_{Pre} = 3.00$ (0.80); $M_{Post} = 2.00$ (0.87); Hedges' $g = 1.20$; $P < 0.0001$). Student endorsement of teleological reasoning decreased in 96% of students and increased in two students. The decrease in endorsement of teleological reasoning is consistent with a significant improvement on the six CINS questions which had teleological themes or distractors ($M_{Pre} = 2.15$ (1.83); $M_{Post} = 3.54$ (1.81); Hedges' $g = 0.76$; $P < 0.0001$). Student acceptance of evolution (I-SEA) increased ($M_{Pre} = 100.50$ (15.55); $M_{Post} = 106.70$ (13.75); Hedges' $g = 0.42$; $P < 0.0001$) over the semester. Acceptance of evolution increased in 70.8%, stayed the same in 14.6%, and decreased in 14.6%, of our sample. More specifically, student acceptance of human evolution ($I\text{-}SEA_{HE}$) increased ($M_{Pre} = 32.65$ (6.63); $M_{Post} = 35.40$ (5.38); Hedges' $g = 0.46$; $P < 0.0001$). Student level of religiosity did not change during the semester. No significant changes were observed on any of these measures in the control group (Additional file 3).

Table 5 Results from a multiple linear regression of student post-semester understanding of natural selection (CINS)

	B	SE B
Intercept	3.34	3.59
Parental attitude-evolution	0.23	0.24
Student religiosity	−0.36	0.25
$ISEA\text{-}HE_{post}$	0.013	0.026
Prior educational exposure	0.081	0.23
$Teleological\ reasoning_{post}$	0.35	0.41
$CINS\text{-}_{pre}$	0.51‡	0.11
Adjusted R^2	0.45	

‡ $p \leq 0.001$

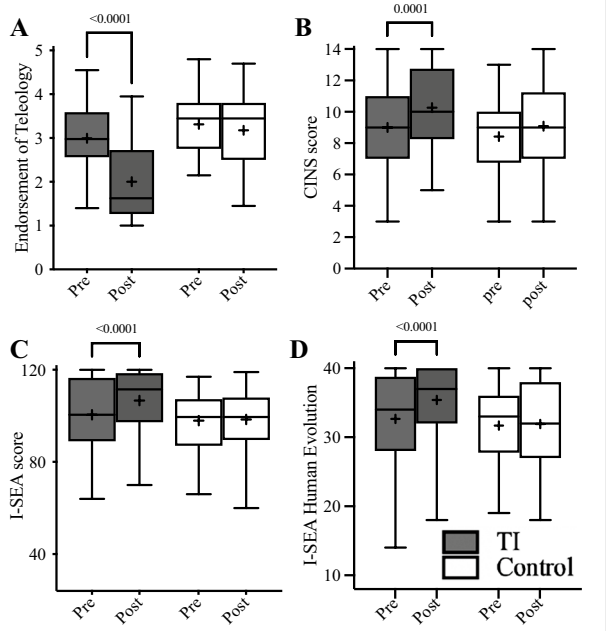

Fig. 1 Box and whisker plots of **A** student endorsement of teleological reasoning, **B** understanding of natural selection (CINS without six teleological questions), **C** acceptance of evolution (ISEA), and **D** acceptance of human evolution (ISEA-HE), at pre- and post-semester for the evolution course with teleological intervention (TI, gray) and control courses (white). P-values and means (+) are shown

Reliability and criterion validity of measures

As a measure of internal consistency for the CINS, Cronbach's alpha was 0.81 at pre- and 0.77 at post-semester. For the teleology survey used in this study, Cronbach's alpha was 0.91 at pre- and 0.89 at post-semester. For the I-SEA, Cronbach's alpha was 0.95 at pre- and 0.96 at post-semester. The scores from the 36-item teleology measure based on Kelemen et al. (2013) significantly correlated with incorrect responses from the six teleology-themed questions on the CINS at pre- ($r = 0.48$; $p = 0.0006$); and post- ($r = 0.53$; $p = 0.0001$) semester.

Qualitative analysis

Two raters independently scored each student response to the four open-ended questions during the tenth week of the semester to determine each student's level of acceptance of evolution, using a 5-point Likert scale. Kappa's interrater reliability was 0.95. The raters discussed the slight scoring differences and agreed on consensus ratings, where 69% of students completely accepted evolution, 16% mostly accepted evolution, 12% had neutral/unknown evolution acceptance, 4% mostly did not accept evolution, and 0% completely did not accept evolution.

The thematic analysis of the responses to the open-ended questions revealed that 69% of students mentioned that the concept of teleological reasoning as a way of thinking about the existence of an object or living thing was new to them during this course. The lack of awareness of teleological reasoning in students' own thinking prior to the course is shown in representative quotes below.

> *"I had never previously heard of teleological statements before this class. It's interesting to change my cognitive process of automatically attributing a purpose to the existence of things."*
> *"My use of the term teleology was non-existent before I took this class[…]teleology was nowhere to be found in my personal lexicon until I encountered the word in this class."*
> *"I have been seeing life in a less teleological way. I was new to the word teleology."*
> *"Before this class I didn't know what teleology was. I think it is a very interesting concept that I definitely accept, like most of the things in this class."*
> *"I am now able to look at evolution through a biological perspective which has helped me to really solidify my understanding. I have also begun to attempt to not think teleologically about evolution, which is something I had no concept [of] before this class."*

The vast majority of students (84%) mentioned that, as a result of the course, their use of teleological thinking/awareness has changed or decreased and that they are now more aware of veridical evolutionary mechanisms as causal factors, rather than an end goal, functionality or purpose-directed evolution, as causal factors in evolution. For example,

> *"My cognizant awareness of how teleology infiltrates thinking about how the world works has increased over the course of this class. It is so easy to fall into teleological reasoning, as if an intelligent designer crafted the material universe. However, I don't believe in such a creator, so it is important for my language to accurately reflect my perspective."*
> *"I find it fascinating how my way of thinking has changed. Instead of just thinking of the purpose of our lives I have become more aware of the causes as well."*

The majority of students viewed thinking non-teleologically about human evolution to be a persistent challenge during the semester. 71% of students mentioned that it is easier for them to think that evolution has a purpose and more difficult to think about evolution as a non-directed process.

"It is very easy to think of evolution as having a purpose and direction, so the idea that it is random was the hardest part for me to grasp."
"I still have a difficult time understanding the non-teleological way of thinking in evolution and the ideas of unguided, directionless occurrences."
"At first, thinking teleologically was very hard not to do and it was slightly confusing to refrain from this way of talking and thinking because it felt like the logical, natural way to explain things."
"There always seems to be a way to find exceptions to this non-teleological way of thinking and this was also evident in our class discussions. Natural selection being a completely random process does not make much sense to me since the goal is always to influence reproduction in a positive light. To me, evolution seems very purpose driven. If it was completely random and purposeless then isn't there a chance that the least fit individuals might be able to survive some of the time? There is a lot of research and information about teleology that I would love to read about and learn more from, but to be honest I struggle immensely to not see the purpose behind it. I believe that natural selection is a real process, but couldn't it also be a beautifully created process designed to help the fittest individuals adapt and survive? If it is really true that we are here completely by chance, and there was and is no real purpose for our own individual lives, then why does anything we ever do matter? Why would having a moral code matter? It is these questions I had to ask myself when we talked about this topic, and it is for these reasons I believe teleology to be impossible to reject."
"It is still so hard for me to not think teleologically when thinking about evolution. I feel like everything is supposed to have a purpose, but when really its just natural causes, and that we evolved this way by chance. I will say that my use of teleology has changed, but I still continue to use teleological statements because I was just raised to believe that everything happens for a reason."

Over a third of students (37%) mentioned that they viewed teleological thinking as a potential obstacle to learning/accepting evolution.

"It is very hard to not think of things as having a cause or reason behind them. I'm still slipping and it seems like everyone in this class does as well."
"We have a hard time thinking of things as natural and random, probably because you have to extend your thoughts past the human lifetime, to a more grand overarching idea about life. I definitely understand that nature does not have a purpose, but sometimes it's easy to explain things as if it does have a purpose for simplicity."
"I think it is difficult for humans to avoid attributing purpose to natural occurrences within nature because knowing the cause of everything helps us feel as though we have a better grasp on the way things are. […] Being in the course has transitioned my use of teleological thinking because I agree that it causes misunderstanding and misconceptions of the occurrence of natural events."

Discussion

This exploratory study provides initial evidence to support the inclusion of direct challenges to design-based teleological thinking in evolution courses. We combined quantitative and qualitative analyses to determine the effects of addressing students' endorsement of teleological reasoning in an undergraduate evolution course.

Change in student endorsement of teleology (RQ1)

Via in-class lectures, discussions, quizzes, and out-of-class reflective writing, students decreased their endorsement of design teleological reasoning. The findings of this study support those of others who have shown attenuation of student teleological reasoning in an evolutionary health course (Barnes et al. 2017; Wingert and Hale 2021) and an introductory biology course (Jensen and Finley 1995). However, the current study used a more comprehensive measure of teleological reasoning than the previous studies, which was a 36-item adaptation of the longer assessment by Kelemen et al. (2013). Cronbach alpha, as a measure of internal consistency of a survey, is notably higher in the current study than the three-question survey used previously by others (Barnes et al. 2017; Wingert and Hale 2021). While other studies have utilized a similar strategy of adapting the teleological survey of Kelemen et al. (Roberts et al. 2020; Banerjee and Bloom 2014), future research should seek to determine the validity of this survey strategy for assessing student endorsement of teleological reasoning. The significant correlation shown here between the 36-item teleology measure and the six teleology-themed CINS questions provides preliminary evidence of criterion validity for the teleology measure used in this study.

The data presented here support the pedagogical framework of González Galli et al. (2020) that introducing the concept of teleological thinking and providing repeated opportunities for students to practice challenging their tendency to endorse teleological reasoning attenuates this cognitive bias. However, teleological reasoning did not disappear, even with such rigorous

challenges. Although endorsement of teleological reasoning decreased by 33% (Hedges' g = 1.20), the fact that it persisted is evidence of the durability of this way of thinking. Others have similarly shown persistent teleological reasoning following anti-teleology instruction in an evolutionary course (Barnes et al. 2017; Wingert and Hale 2021; Pedersen and Halldén 1994; Stover and Mabry 2007; Jensen and Finley 1995). Kelemen et al. (2013) have shown that teleological reasoning persists even in professional physical scientists under speeded conditions. Therefore, our data support the pedagogical stance of González Galli et al. (2020) to not strictly aim instruction to eliminate teleological reasoning, but instead to shift the teaching focus onto preparing students to regulate their use of design teleological reasoning through metacognition. González Galli et al. (2020) argue that while teleological reasoning should be regulated, there may be some heuristic, explanatory, or predictive value in teleological statements, under appropriate scientific circumstances. See (González Galli et al. 2020; González Galli and Meinardi 2011; Kampourakis and Evolution 2020) for suggestions on teaching strategies to help students self-regulate their inappropriate use of teleology beyond those pedagogical strategies presented here.

Relationship between teleological reasoning and understanding and acceptance of natural selection (RQ2)

Our data show that student endorsement of teleological reasoning was a significant predictor of student understanding of natural selection prior to the semester. Furthermore, teleological reasoning was correlated with understanding of natural selection at both pre- and post-semester. However, in contrast to the findings of Barnes et al. (2017), teleological reasoning was not a predictor of post-semester CINS score. We were surprised by this finding given the large effect size in student endorsement of teleological reasoning and the strong correlation between teleological reasoning and CINS score at post-semester. These findings suggest that post-semester understanding of natural selection was likely influenced by several additional factors, including student acceptance and religiosity, and not teleological reasoning alone. Although not significant factors in the multiple regression, student endorsement of teleological reasoning, student religiosity, and acceptance of evolution, were all significantly correlated with CINS score at post-semester. Instead, the strongest predictor of post-semester CINS score was pre-semester CINS score. Therefore, our findings indicate that challenges to teleological reasoning remain pedagogically worthwhile since teleological reasoning was the strongest predictor of students' incoming understanding of natural selection. These findings support the suggestion of Evans and Rosengren (2018) that investigating one's intuitive teleological reasoning in biology may likely serve as a learning bridge for a deeper understanding of veridical evolutionary mechanisms, especially when metacognitive exercises allow for the identification and subsequent correction of teleological errors.

Student acceptance of evolution was also significantly correlated with understanding of natural selection at both pre- and post-semester. Multiple regression analysis showed that parent attitude towards evolution predicted student acceptance of evolution (and human evolution) more than religiosity or prior educational exposure, indicating that parent attitudes may be more important for student acceptance of evolution than strength of personal religious beliefs and prior education among this population.

Students' metacognitive perceptions of the use of teleological reasoning (RQ3)

Thematic analysis of student written responses revealed that the concept of thinking teleologically (i.e., viewing evolution as goal-directed rather than understanding veridical causal mechanisms) was new to most students prior to this course. Furthermore, students perceived an increased metacognitive awareness of their own teleological reasoning during the course. Therefore, not only does teleological reasoning have negative consequences on student understanding of natural selection, but students are mostly unaware they possess this cognitive bias prior to explicit teleological intervention, including anti-teleological instruction, weekly discussions, and reflection.

The thematic analysis revealed that the concept of teleology was entirely new to 69% of students, although the actual proportion is likely to be higher since students were not asked directly about their prior awareness of teleology. Importantly, 84% said they are now more aware of veridical mechanistic causes, rather than design teleology in biology, consistent with our quantitative measure that all, but two students, decreased endorsement of teleological reasoning. Yet, 71% described persistent difficulties thinking non-teleologically and nearly half mentioned that they view thinking teleologically as a cognitive obstacle to truly understanding evolution. Taken together, the qualitative data reveal that even as late as their Junior year, undergraduates are largely unaware of the concept of teleology and find thinking in non-teleological ways to be challenging, but worthwhile.

Our quantitative and qualitative data together support the importance of addressing design teleology in a human-focused evolution course. Our data confirm that students enter the classroom with high levels of

teleological reasoning, which disrupts their understanding of natural selection (Barnes et al. 2017; Hammann and Nehm 2020; Wingert and Hale 2021; González Galli et al. 2020). Nearly all students mentioned that their understanding of evolution deepened and many of these students associated their augmented knowledge and appreciation of evolution with their novel awareness of their own endorsement of teleological reasoning. Several students expressed satisfaction with the metacognitive process of evaluating their own bias about evolution. Therefore, guiding students in exploration of their use of teleological reasoning is a valuable function of the human evolution course. Additionally, the value of addressing teleological misconceptions and enhancing understanding of evolution extends beyond classroom goals, as application of evolution can help students make informed decision as educated members of society on topics such environmental and ecological issues as well as health-related choices (Barnes and Brownell 2016).

Limitations

A chief limitation of this study is related to the absence of a validated measure of teleological reasoning. However, this study used 36-items selected from Kelemen et al. (Kelemen et al. 2013), which had a very high Cronbach alpha and preliminary evidence for criterion validity in our sample. The demonstration of reliability and criterion validity of this measure in this sample is preliminary support for use of this measure and efforts to further validate this instrument.

Another potential limitation identified by Gouvea and Simon (2018) is that the wording of teleology questions in a survey may cause students to inappropriately agree with a teleological statement as veridical simply because they might identify a true relationship between the two variables in the question, not necessarily because they think the teleological statement is true. For instance, in a test statement used in this study like "Trees produce oxygen so that animals can breathe," Gouvea and Simon suggest that the student may not believe that oxygen production is caused by the role that trees play, but instead that the student may nonetheless agree with the statement to acknowledge the important role that trees play as oxygen producers (Gouvea and Simon 2018). However, the use of a Likert scale in our measure may correct for the possibility of inappropriately agreeing with a teleological statement because students would not have to fully accept the statement as they would if they were given only a two-alternative forced-choice option (Gouvea and Simon 2018). Furthermore, it is possible students may be confused by questions, especially ones that implicitly rather than explicitly present teleology (Gouvea and Simon 2018). However, insights from the qualitative data in this study allowed us to better understand the students' experiences of learning about design teleology in this course.

There are additional limitations to the data presented here. To protect privacy of students, all data were collected anonymously which prevented the direct linking of quantitative data with qualitative responses or final course grades. Therefore, we were unable to determine if certain themes in student writing were related to the quantitative measures of understanding natural selection, acceptance of evolution, or teleological reasoning. This study had a limited sample size and may lack generalizability to the wider population. Students who oppose human evolution are doubtful to elect a class on evolutionary medicine, which may cause selection bias and skew data toward acceptance and decreased teleological thinking compared with a representative sample. However, there were no differences prior to the semester between the teleology intervention and control groups on any measure.

In addition, Long (2012) suggested that students are aware of the expectations placed on them by the teacher to increase their understanding and acceptance of evolution in an evolution course which may influence their responses to both the surveys and open-ended questions. While the anonymity of the responses likely reduced this impact, there is a possibility that students were attempting to present what they think the professor wanted to see and not what the students actually think.

Finally, this study focused strictly on interventions to reduce illegitimate forms of design teleological reasoning, but there are scientifically legitimate uses of teleological statements. Several authors have described legitimate uses of teleology in biology, such as selective (in contrast to illegitimate design, see (Kampourakis 2020)) and epistemological (in contrast to illegitimate ontological, see (Trommler and Hammann 2020)) teleology. Future research should determine whether legitimate versus illegitimate uses of teleology are differentially affected by anti-teleological education.

Conclusion

Design teleological reasoning was a new concept for the vast majority of upper level undergraduates in an evolution course, but explicit and direct challenges to design

teleological thinking attenuated student teleological reasoning in a human evolution course. The concept of teleological reasoning should be defined for students and introduced with numerous examples of how it can be expressed and how it's inappropriate use can disrupt student understanding of veridical evolutionary mechanisms. Furthermore, students should be given repeated opportunities to practice regulation of their teleological reasoning through classroom discussion and reflective writing.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12052-022-00162-6.

Additional file 1. Teleology survey items slected from Kelemen et al. (2013).

Additional file 2. Themes from student responses decided upon by two reviewers for the thematic analysis.

Additional file 3. Between- and within-group differences.

Acknowledgements
Not applicable

Authors' contributions
JW: Conception and design of study, statistical analysis, data interpretation, prepared figures and tables, manuscript authorship. GB: Manuscript authorship. CT: Data analysis and interpretation, manuscript authorship. JL: Statistical analysis, data interpretation, manuscript authorship. All authors read and approved the final manuscript.

Funding
There was no funding for this project and the authors have no conflicts of interest.

Availability of data and materials
The datasets supporting the conclusions of this article are available in the Open Science Framework repository, https://osf.io/4cq3e/?view_only=252d3ee79e944ad48797f00a3a48131b.

Declarations

Competing interests
The authors declare no competing interests.

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Received: 3 January 2022 Accepted: 11 March 2022
Published online: 01 April 2022

References

Anderson DL, Fisher KM, Norman GJ. Development and evaluation of the conceptual inventory of natural selection. J Res Sci Teach. 2002;39(10):952–78.
Banerjee K, Bloom P. Why did this happen to me? Religious believers' and non-believers' teleological reasoning about life events. Cognition. 2014;133(1):277–303.
Barnes ME, Brownell SE. Practices and perspectives of college instructors on addressing religious beliefs when teaching evolution. LSE. 2016;15(2):ar18.
Barnes ME, Evans EM, Hazel A, Brownell SE, Nesse RM. Teleological reasoning, not acceptance of evolution, impacts students' ability to learn natural selection. Evolution. 2017;10(1):7.
Bartov H. Can students be taught to distinguish between teleological and causal explanations? J Res Sci Teach. 1978;15(6):567–72.
Bartov H. Teaching students to understand the advantages and disadvantages of teleological and anthropomorphic statements in biology. J Res Sci Teach. 1981;18(1):79–86.
Bishop B, Anderson C. Student conceptions of natural selection and its role in evolution. J Res Sci Teach. 1990;27(5):415–27.
Brumby MN. Misconceptions about the concept of natural selection by medical biology students. Sci Educ. 1984;68(4):493–503.
Creswell JW, Clark VLP. Designing and Conducting Mixed Methods Research. SAGE Publications; 2017. 521 p.
Demastes SS, Good RG, Peebles P. Patterns of conceptual change in evolution. J Res Sci Teach. 1996;33(4):407–31.
Dunk RDP, Petto AJ, Wiles JR, Campbell BC. A multifactorial analysis of acceptance of evolution. Evolution. 2017;10(1):4.
Evans EM, Rosengren KS. Cognitive Biases or Cognitive Bridges?: Intuitive Reasoning in Biology. In: Teaching Biology in Schools. Routledge; 2018.
González Galli LM, Meinardi EN. The role of teleological thinking in learning the darwinian model of evolution. Evo Edu Outreach. 2011;4(1):145–52.
González Galli L, Peréz G, Gómez Galindo AA. The self-regulation of teleological thinking in natural selection learning. Evolution. 2020;13(1):6.
Gouvea JS, Simon MR. Challenging cognitive construals: a dynamic alternative to stable misconceptions. LSE. 2018;17(2):34.
Gregory TR. Understanding natural selection: essential concepts and common misconceptions. Evolution. 2009;2(2):156.
Gresch H, Martens M. Teleology as a tacit dimension of teaching and learning evolution: a sociological approach to classroom interaction in science education. J Res Sci Teach. 2019;56(3):243–69.
Hammann M, Nehm RH. Teleology and evolution education: introduction to the special issue. Evolution. 2020;13(1):16.
Järnefelt E, Canfield CF, Kelemen D. The divided mind of a disbeliever: Intuitive beliefs about nature as purposefully created among different groups of non-religious adults. Cognition. 2015;140:72–88.
Jensen MS, Finley FN. Teaching evolution using historical arguments in a conceptual change strategy. Sci Educ. 1995;79(2):147–66.
Jungwirth E. The problem of teleology in biology as a problem of biology-teacher education. J Biol Educ. 1975;9(6):243–6.
Jungwirth E. Do students accept anthropomorphic and teleological formulations as scientific explanations? J Coll Sci Teach. 1979;8(3):152–5.
Kampourakis K. Conceptual obstacles to accepting evolution. In: Evolution U, editor. Cambridge. UK: Cambridge University Press; 2020. p. 42–62.
Kampourakis K. Students' "teleological misconceptions" in evolution education: why the underlying design stance, not teleology per se, is the problem. Evolution. 2020;13(1):1.
Kampourakis K, Zogza V. Preliminary evolutionary explanations: a basic framework for conceptual change and explanatory coherence in evolution. Sci & Educ. 2009;18(10):1313–40.
Kelemen D. The scope of teleological thinking in preschool children. Cognition. 1999;70(3):241–72.
Kelemen D. Function, goals and intention: children's teleological reasoning about objects. Trends Cogn Sci. 1999;3(12):461–8.
Kelemen D. British and American children's preferences for teleo-functional explanations of the natural world. Cognition. 2003;88(2):201–21.
Kelemen D. Teleological minds: How natural intuitions about agency and purpose influence learning about evolution. In: Rosengren K, Brem S, Evans EM, Sinatra G, editors. Evolution challenges: Integrating research and practice in teaching and learning about evolution. Oxford: Oxford University Press; 2012.
Kelemen D, DiYanni C. Intuitions about origins: purpose and intelligent design in children's reasoning about nature. J Cogn Dev. 2005;6(1):3–31.
Kelemen D, Rosset E. The Human Function Compunction: teleological explanation in adults. Cognition. 2009;111(1):138–43.

Kelemen D, Rottman J, Seston R. Professional physical scientists display tenacious teleological tendencies: purpose-based reasoning as a cognitive default. J Exp Psychol Gen. 2013;142(4):1074–83.
Daniel E. Lieberman. The Story of the Human Body: Evolution, Health, and Disease. In New York, NY: Pantheon; 2013. p. 13.
Long DE. The politics of teaching evolution, science education standards, and being a creationist. J Res Sci Teach. 2012;49(1):122–39.
Moore R, Mitchell G, Bally R, Inglis M, Day J, Jacobs D. Undergraduates' understanding of evolution: ascriptions of agency as a problem for student learning. J Biol Educ. 2002;36(2):65–71.
Nadelson LS, Hardy KK. Trust in science and scientists and the acceptance of evolution. Evolution. 2015;8(1):9.
Nadelson LS, Southerland S. A more fine-grained measure of students' acceptance of evolution: development of the inventory of student evolution acceptance—I-SEA. Int J Sci Educ. 2012;34(11):1637–66.
Nehm RH, Schonfeld IS. Measuring knowledge of natural selection: a comparison of the cins, an open-response instrument, and an oral interview. J Res Sci Teach. 2008;45(10):1131–60.
Pedersen S, Halldén O. Intuitive ideas and scientific explanations as parts of students' developing understanding of biology: the case of evolution. Eur J Psychol Educ. 1994;9(2):127.
Richardson DR. A survey of students' notions of body function as teleologic or mechanistic. Adv Physiol Educ. 1990;3:1.
Roberts AJ, Wastell CA, Polito V. Teleology and the intentions of supernatural agents. Consciousn Cogn. 2020;80:102905.
Schachner A, Zhu L, Jing L, Kelemen D. Is the bias for function-based explanations culturally univeral? Children from CHina endorse teleological explanations of natural phenomena. J Exp Child Psychol. 2017;157:29–48.
Settlage J. Conceptions of natural selection: a snapshot of the sense-making process. J Res Sci Teach. 1994;31(5):449–57.
Smith MU. Current Status of Research in Teaching and Learning Evolution: II Pedagogical Issues. Sci Educ. 2010;19(6):539–71.
Southerland SA, Abrams E, Cummins CL, Anzelmo J. Understanding students' explanations of biological phenomena: conceptual frameworks or p-prims? Sci Educ. 2001;85(4):328–48.
Stover SK, Mabry ML. Influences of teleological and lamarckian thinking on student understanding of natural selection. Bioscene. 2007;33(1):11–8.
Tamir P, Zohar A. Anthropomorphism and teleology in reasoning about biological phenomena. Sci Educ. 1991;75(1):57–67.
Trommler F, Hammann M. The relationship between biological function and teleology: implications for biology education. Evolution. 2020;13(1):11.
Werth A, Allchin D. Teleology's long shadow. Evolution. 2020;13(1):4.
Wingert JR, Hale RE. Teaching evolutionary principles in health promotion: a pilot study. Pedag Health Prom. 2021;7(1):60–70.
Zohar A, Ginossar S. Lifting the taboo regarding teleology and anthropomorphism in biology education—Heretical suggestions. Sci Educ. 1998;82(6):679–97.

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