**Pre-university students' causal reasoning about plant photosynthesis and reproduction: an exploratory study**


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Possible Journal for Publication:

Journal of Biological Education

August 2018

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## Abstract

In order to achieve a satisfactory level of biological literacy, it is fundamental that students develop the competence of providing complex causal explanations about biological phenomena, i.e., being able to explore multiple aspects of causes and effects and their interrelatedness. Previous research indicates that students from primary and lower secondary education causal reasoning is often based on simple linear levels of causation. These young students require special teaching and learning practices to aid them in developing the ability to reason causally about science subjects matter. In the present research, we investigated whether this is also the case considering pre-university biology students. Are upper-secondary students able to provide complex causal explanations about different biological phenomena? To answer this question, we chose a recently learned topic and a topic learned a few years ago, respectively: plants photosynthesis and flowering plants reproduction. Through the medium of individual semi-structured interviews with a series of prompting questions, we have explored the current pre-university students' causal reasoning status for these two biological processes. The nature of students' causal explanations for each topic was analyzed based on (1) whether they can reason about all the key mechanisms in the biological phenomena, (2) the type and number of steps that students utilize to explain the physiological processes, (3) which causal agents are employed/missing while students explain the mechanisms, (4) how students perceive and explain the possibility of influential factors causing a different outcome for the biological process. For all these dimensions investigated, our results suggest that pre-university students are not yet able to provide causal explanations about plants photosynthesis and flowering plants reproduction. These findings have implications that might require changes in the formal education.



## Keywords

*Biological literacy; causal reasoning; pre-university students; plant photosynthesis; plant reproduction.*

## Introduction

Scientific reasoning skills, the ability to explain scientific phenomena, is a well-known fundamental element for achieving a satisfactory level of scientific literacy (OECD, 2016). In explanations of natural phenomena, the reasoning process is usually resolved in the form of causal explanations, i.e., by explaining how and why something happens through the understanding of the causes underlying the natural phenomena (Salmon, 1978; Braaten & Windschitl, 2011). Moreover, effective reasoning about biological phenomena also demands the competence of providing complex causal explanations, i.e., being able to explore the multiple aspects of causes and effects and their interrelatedness (Perkins & Grotzer, 2000). Accordingly, worldwide educational systems share a common goal for biology education: that students become able to adequately apply causal reasoning to several different biological phenomena.

Nonetheless, various studies on students' causal reasoning in both primary and lower secondary biology education reveal that this educational objective is *not* readily accomplished with the current teaching-learning practice (Penner, 2000; Grotzer & Basca, 2003; Zuckerman, Grotzer, & Leahy, 2005; Grotzer *et al*., 2011; Grotzer *et al*., 2016). In fact, previous research indicates that reasoning skills of children and/or juvenile teenagers (8 to 14 years old) are mostly based on simple linear levels of causation as in, 'A causes B' (Grotzer, 2003) - even though young children are already able to grasp nonobvious causal mechanisms to explain biological processes (Grotzer & Tutwiler, 2014). When students rely on linear narratives of causation, they actually misconceive the real nature of causation and scientific reasoning. Accordingly, students also fail to achieve the much-strived biological literacy.

From a very young age (2 years old) human beings are already able to understand relatively simple relationships between causes and effects (Gopnik *et al*., 2001), mostly in the form of linear causations, and easy to observe. Researches claim that children might have an implicit notion of causality, which plays an important role in the development of different domains (Corrigan & Denton, 1996). Moreover, it has been argued that not only humans have the ability to apply causal reasoning, but rats may also understand cause and effect (Lovett, 2006) and crows have demonstrated being able to even reason about hidden causal agents (Taylor, Miller & Gray, 2012). Nevertheless, one cannot easily recognize the multiple causes and effects that completely explain how plants grow, for instance. This is because the nature of causation in biological phenomena is often complex: it is usually not directly visible, time and space between cause and effect can be distant, and the causation underlying biological phenomena can have multiple dimensions (Grotzer, 2003). Therefore, even though students are naturally capable of causal reasoning, they require appropriate teaching and learning practices to aid them in developing the ability to reason causally about biology subjects' matter.

According to Gordon Uno and Rodger Bybee (1994), an individual can be found occupying a position along a progression of biological literacy based on different understanding of biological concepts. These positions, from lower to higher levels, are distinguished in terms of (a) nominal – naïve explanations of biological concepts and misconceptions, (b) functional – correct use and definition of biological vocabulary but memorized responses, (c) structural – understand the scheme of biology and can explain biological concepts in one's own words, and (d) multidimensional – comprehend the place of biology among other disciplines and the interactions between biology and society. Therefore, we understand that an acceptable standard for causal reasoning skills can only start from the 'structural level' of biological literacy, because it depends on student's understanding of the conceptual schemes of biology and the ability of giving an explanation in their own words. Only then will students have a foundation to move further into a multidimensional competence in biology.

Although one might expect that pre-university students are able to provide adequate causal explanations, a study conducted by Abrams and Southerland (2001) indicates that twelfth grade students are not more likely than second, fifth and eighth grade students to offer causal explanations about the following four different biological phenomena: plant growing toward the sun, bird pelage change throughout the year, birds in a flying V formation, and cactus with very thick leaves. Specifically, the study revealed that regardless of school grade or age, most students were unable to offer any causal explanation of *how* a phenomena occurred and tended to rephrase the question with a *why* answer (Abrams & Southerland, 2001). Moreover, Abrams and Southerland's (2001) study was not intended to elaborate on assessing the quality of students' causal reasoning (i.e. analyzing the *how* answers). On these terms, there is a lack of information about what constitutes the pre-university students' (16 to 18 years old) causal reasoning.

In the present research, the biological phenomena of photosynthesis and flowering plants reproduction were selected as investigation context. Furthermore, we aimed to investigate whether there are significant differences in the students' causal reasoning structure in relation to a recently (photosynthesis) and previously (flowering plants reproduction) learned topics. We hypothesize that if a pre-university student has a good foundation in biology (i.e. he/she understands the scheme of biology), both a past and a recently learned topic could be satisfactorily explained (Uno and Bybee, 1994). Additionally, we prevented an investigation solely based on students' recently relearned topics, that could be subjected to a collection of newly memorized responses. Ultimately, the present exploratory study aims to answer the research question 'What are pre-university students' current spontaneous causal reasoning status?' regarding two of the most important biological phenomena on Earth: plants photosynthesis and flowering plants reproduction. Depending on the results of this research question, we might provide some insights about advisable procedures in order to support pre-university students in the development of causal reasoning.

## Methods

To address the character of our exploratory study, we determined that one-to-one semi-structured interviews is the preferred methodology approach for a qualitative data collection (Denscombe, 2014) and to further allow an in-depth analysis (Miles & Huberman, 1994; Chi, 1997). An interview guideline was developed to prompt students' spontaneous causal reasoning about each topic. Detailed information about the method settings and data analysis are presented below.

*Participants and Interviews Setting*

A total of 21 pre-university biology students were interviewed, 9 female and 12 male, aged 16-18. The students who volunteered and participated in this study were from four different schools located in the Netherlands: one international school (students pursuing biology Diploma Programme at higher level) and three Dutch bilingual schools (students pursuing biology Preparatory Scientific Education, VWO in Dutch). However, for the purpose of data analysis, we refer to a total of 18 students' interviews. The first three interviews were planned as pilot interviews to evaluate the functioning of the semi-structured interview protocol – and they revealed to provide the necessary information to develop the final interview protocol. In essence, the pilot interviews yielded insights about the efficiency of the prompting questions, and as a result: some questions were removed, new prompting questions were added, and language style was improved to match the target group. The final interview protocol version is available in the Appendix. In addition to the requirement that participants be pre-university students learning biology as one of their main subject matter for final exams, students had to match two additional preconditions: (1) having recently learned – i.e. in the last few weeks/months – the topic of plants photosynthesis, and (2) not having recently learned – i.e. neither in the current or previous school year – the topic of flowering plants reproduction.

In the beginning of the interview (for each topic separately), a short time-lapse video was presented to the student just before the researcher would start to make a series of prompting questions. These time-lapse videos (approximately 20 seconds each) had the objective to stimulate and to introduce students to the biological phenomena. The first part of the interviews was on the topic *plants photosynthesis*. This strategy was adopted to contribute to students' self-esteem and motivation to collaborate throughout the interview as they would answer questions related to a recently learned and more familiar topic first. The time-lapse video related to the phenomena plants photosynthesis consisted of various plants growing in a forest and struggling to reach the sunlight. The time-lapse video associated with the phenomena flowering plants reproduction consisted of a full-grown cherry tree with several flowers bud blooming.

The first question right after each time-lapse video was: 'Why do plants need light?' and 'Why do plants grow flowers?'. It is important to note that these questions had a functional character on purpose. Firstly, because students' answers (i.e. plants need light for photosynthesis and plants grow flowers for reproduction, respectively) would confirm that they are aware of these biological phenomena and would allow the interviewer to move further into mechanistic questions. Secondly, because previous research observed that students often focus on providing a 'why' (functional) response and they generally avoid searching for a 'how' (mechanistic) response about a biological phenomena (Abrams & Southerland, 2001). The rationale is that students would already have answered a functional question and would be more compelled to concentrate on the biological mechanism itself. After being able to answer the functional question, the interviewer would conduct a series of open and semi-open questions with a clear mechanistic character. This conduct was based on Abrams and Southerland's (2001) results that also indicate that students are generally unfamiliar with questions that require causal explanations. These questions were specially designed with the aim of prompting students' spontaneous causal reasoning:

- How does photosynthesis/flowering plants reproduction happen. What are the mechanisms?
- Could you explain a bit more about the steps in this process?
- Is there a situation in which photosynthesis/plants reproduction would happen faster or slower?
- Can you think about something that could limit the process of photosynthesis/plants reproduction?
- What else could affect the process of photosynthesis/flowering plants reproduction?

Each interview had the duration of about 20 minutes. The interviews were audio recorded and fully transcribed by one of the researchers. We used the free online web application oTranscribe (http://otranscribe.com) as an aid tool for the process of transcription. The transcripts were analyzed on students' answers and filling in a coding scheme that is based on the framework explained below.

*Data Analysis Framework and Coding Scheme*

Our data analysis framework was inspired by Perkins & Grotzer (2005) causal reasoning model which elaborates on the dimensions of mechanism, interaction pattern, agency and probability. The nature of students' causal explanations for each topic was analyzed based on (1) whether they can reason about all the key mechanisms in the biological phenomena, (2) the type and number of steps that students utilize to explain the physiological processes, (3) which causal agents are employed/missing while students explain the mechanisms, (4) how students perceive and explain the possibility of influential factors causing a different outcome for the biological process. The definition for each of these dimensions are being further elucidated:

- Key Mechanisms – the minimum elements/processes (see Table 1) that enable a satisfactory explanation regarding each biological phenomena, according to secondary education curriculum level. It is important to highlight that students were not required to use the exact biological terms to have an explanation considered satisfactory. Generic terms could also be used to explain the essence of the process. Moreover, when generic terms are used meaningfully it often reveals that the student is reaching the structural level of biological literacy (at least for the topic in question), because he/she can explain the biological process in his/her words.

Table 1. The Key Mechanism that enables a satisfactory explanation for each biological phenomena.

| **Photosynthesis** | **Flowering Plants Reproduction** |
|---|---|
| 1. absorption of light by chloroplast/chlorophyll | 1. flowers male and female reproductive organs |
| 2. water photolysis generates $O_2$, $H^+$ and electrons | 2. pollination via insects/wind/another agent |
| 3. generation of molecules NADPH/ATP | 3. fertilization of ovule generates zygote |
| 4. $CO_2$ fixation using NADPH/ATP creating glucose | 4. fruit/seed develops inside the flower/ovary |
| 5. cyclicity between NADP-NADPH and ADP-ATP | 5. mature seeds are dispersed via animals/wind |

- Type and Number of Steps – the type of explanations for each biological phenomena could be either exclusively made from a *linear* direction, i.e. processes always leading to an end; or they could also include a *cyclic* direction, i.e. feedback loops were also explained. The cyclic direction is especially relevant and expected within the mechanism of photosynthesis (the cyclicity between NADP-NADPH and ADP-ATP). The number of steps used to explain each phenomena was counted based on students' mentioning of agents (see definition below) causing an effect, leading to a chain of cause-effect.

- Causal Agents – defined as perceived entities (or factors) utilized to explain the biological process. Each causal agent was also categorized according to their location in the physiological phenomena and according to their visibility to the human naked eye or other senses. Examples of agents for both topics and their corresponding classification are presented in Table 2.

Table 2. Examples of Causal Agents for each biological phenomena and their corresponding classification.

| **Entities (or factors) utilized to explain the biological process** | **Microscopic (special procedure is needed to make agent visible)** | **Macroscopic (visible with human eye or qualified by other senses)** |
|---|---|---|
| **Internal (part of the organism)** | Ovules, Zygote, Embryo, Chloroplast, Glucose, $O_2$, Electron, ATP, NADPH | Leaf, Flower, Stigma, Stamen, Pollen, Fruit, Seed |
| **External (outside the organism)** | $CO_2$, $H_2O$ (molecule/atoms), Light specific wavelength | Sunlight, Water (in general), Bees, Birds, Wind |

- Influential Factors – specific agents' properties that could cause a different outcome to the biological phenomena. As the category of causal agents, influential agents can also be classified according to its visibility and location in the physiological phenomena (i.e. macroscopic, microscopic, external, internal). Additionally, we analysed whether the student would explain the mechanism in which the influential agent causes an effect, or if the student would just mention (or guess) a possible influential factors.

*Inter-rater agreement*

Our data analysis framework was, in fact, the main product of the process of developing a reliable coding scheme and inter-rater agreement in order to code and analyse every interview transcript. This process was carried out through several cycles of analysis, discussions on the coding scheme (and improvements) and attaining final agreements about independent rating (Chi, 1997). Each stage of independent coding was thoroughly deliberated, and disagreements resolved. For an overview of the process, see Figure 1.

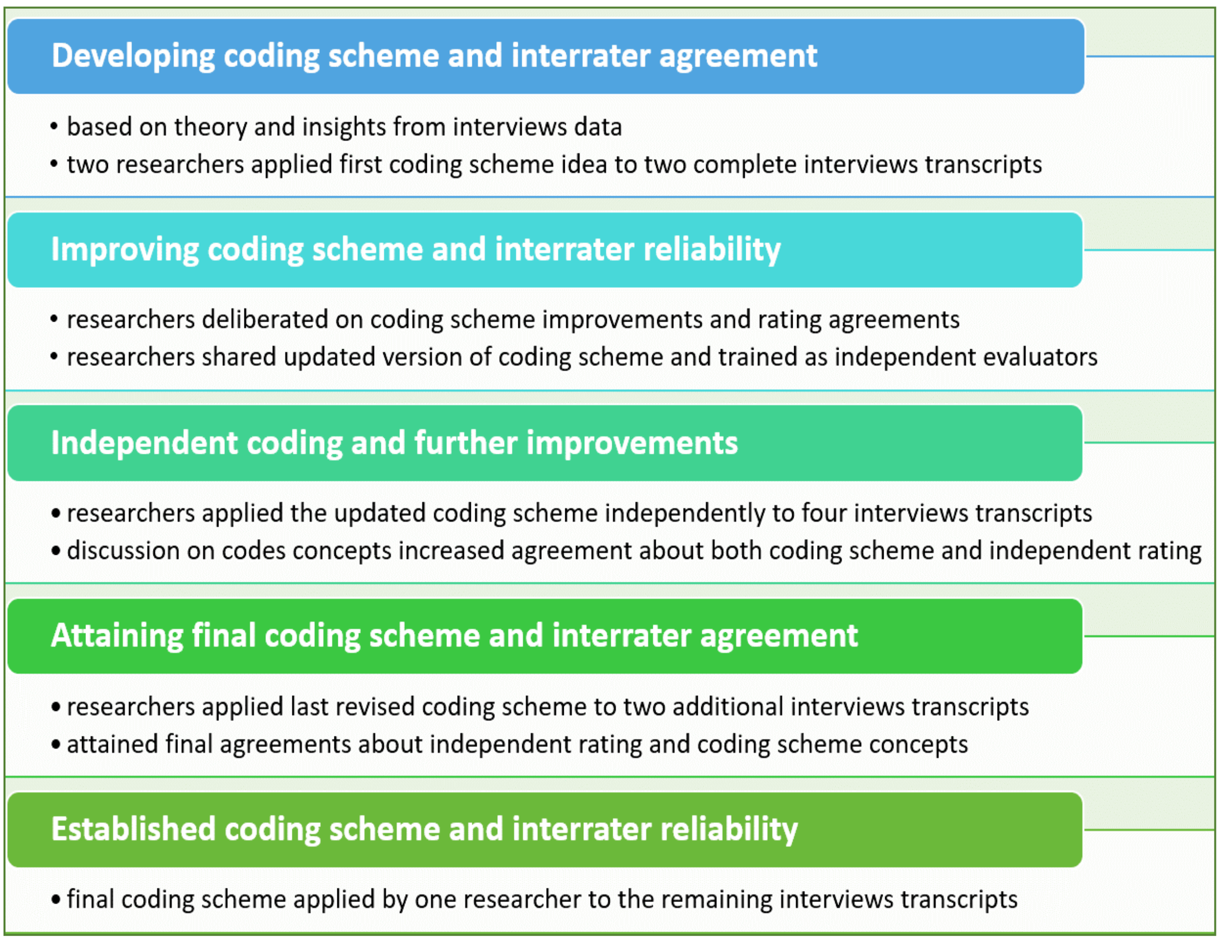


Figure 1. The process of developing a coding scheme framework and interrater reliability.

## Results and discussion

*Mechanisms in the biological phenomena*

This research investigated pre-university students' spontaneous causal reasoning ability on two biological phenomena: plants photosynthesis and flowering plants reproduction. The first results are on students' answers to the central <u>mechanisms</u>, which should provide the main causality relationships behind each phenomena. Conforming to the five core elements/processes that students were expected to be able to elaborate on, only one student was able to provide a satisfactory explanation (all the five processes) for the phenomena *photosynthesis*, and another single student was able to provide a satisfactory explanation for the phenomena *flowering plants reproduction*. Most students (i.e. 12 out 18 for photosynthesis, and 10 out of 18 for plants reproduction) could only elaborate on one or two of the key processes for each biological phenomena. Usually, students would explain the process of 'absorption of light by chloroplast/chlorophyll' and the process of 'pollination via insects/wind'. It is also interesting to note that both explanations refer to the beginning of the biological phenomena.

The interview excerpt below is an example of a typical student explanation of the phenomena photosynthesis and flowering plants reproduction, respectively. Notice that the student explanations seem to disregard most of the elements/processes that happen *in the middle* of the biological phenomena. Additionally, observe that the student often attempts to describe the beginning of the process (as in: absorption of light by chlorophyll; pollination by bees), skipping the subsequent causal explanations about the several mechanisms happening in the middle of the process, and jumping to the final outcome of the biological phenomena (as in: energy is produced; plants drop the seeds and new plants can grow). Here we emphasized student explanations, which are shown in **bold**.

Interviewer: How does photosynthesis happen? How does it happen, the mechanism?

Student 10: **Oh, it happens when the leaves of the plants catch the light, with, ah, I think it is called, ahm, there is this substance inside the leaves that is called chlorophyll, and they catch the light. When this happens, reaction follows and then energy is produced.**

Interviewer: Can you talk a little bit more about what is going on?

Student 10: **Ahm… I know, ahm, they are in leaves, and that they catch the light. But in order to do that they need to be in direct contact with light, so light has to shine on the leaf for the chlorophyll start the reaction with light.**

Interviewer: And what happens after that?

Student 10: **Well, after that, energy that is produced in the light reaction goes to a second reaction, that is called dark reaction, I think, and it doesn't need any light, that is not dependent on light. But it uses the substances that, ahm, come from the light reaction, which is dependent on light, so.**

-x-

Interviewer: How do plants reproduction happen? The mechanism…

Student 10: **Oh yeah, ok. So, the flowers, they, ahm, produce, ah, blossom, and in this blossom, there is, ah, ahm, things that can help other plants get fertilized, so bees land in the blossom and they, ah, take away the honey but they also take away something else, they bring to another pant.**

Interviewer: And what is this something else?

Student 10: **Ah, well, ah... it is called stuifmeel** [pollen in Dutch], **but I don't know how it is in English.**

Interviewer: What happens from that?

Student 10: **Then... it's ahm... within the plant it is ah…, then this little particle they go from the bee into the plant, so fertilization can happen**.

Interviewer: And what happens after the fertilization?

Student 10: **Ah... the plants like, ahm… drops the seeds and new plants can grow**.

There were a few students who did not elaborate on any of the five main processes. For instance, considering the topic photosynthesis, three students just named some of the agents necessary for the biological phenomena. These were presented through an answer composed by a single and shallow linear stage of causation A -> B ($CO_2$ + $H_2O$ + light -> glucose + $O_2$), without the student showing any attempt to elaborate on intermediating mechanisms. These results are congruent with Tina Grotzer (2003) research on children and juvenile teenagers (8 to 14 years old), where students reasoning skills were mostly based on simple linear levels of causation as in ‘A causes B’.

Regarding the topic flowering plants reproduction, three students held major misconceptions (in addition to single linear level of causation) which made infeasible to include their answers as acceptable explanations of the biological phenomena – yet, the development and perpetuation of misconceptions can also have roots in poor causal reasoning. We understand that when students provide incorrect mechanistic explanations – while still seeking for sensemaking – those are certainly interesting and relevant information for investigating of students' spontaneous causal reasoning (Russ *et al*., 2009). However, the current study specific case (where a few students bared major misconception) was settled outside the context of an attempt to provide mechanistic explanations. Furthermore, it is reasonable to consider that there were no significant differences in students' causal reasoning ability depending on whether a topic was recently learned (plants photosynthesis) or not (flowering plants reproduction).

*Type and number of steps to explain each phenomena*

Next, the results about students' type of explanations revealed that these are often exclusively composed of multiple *linear* steps. These results are equivalent for both recently and past learned topics: plants photosynthesis and flowering plants reproduction. Nevertheless, there were two students who elaborated on the *cyclicity* between NADP-NADPH and ADP-ATP within the process of photosynthesis. Besides, even though students provided several *steps* to answer the 'how questions' for each biological phenomena, only about half of these steps were indeed meaningful to explain the key mechanisms. The interview excerpt below illustrates this situation.

Notice that within the steps number **5** and **6** the student only mentions the final products (i.e. glucose and oxygen), without an attempt to explain the basic biological mechanisms that actually generate these vital final products. In addition, steps number **7** and **8**, although revealing that the student holds desirable additional knowledge, it is not an augment of information to explain the key fundamental mechanisms in the process of photosynthesis. Here we emphasized the number of steps, which are shown in **bold.**

Interviewer: How does photosynthesis happen?

Student 15: **1.** Photosynthesis happen when light and water and carbon dioxide is taken in by the plant. **2.** This light is used in the light reaction, I don't know exactly how the light is a sort of transformer, **3.** I think it's the chloroplasts, I think, they use it to, well, to perform reactions, to keep the reactions going. **4.** Then, ahm… in the plant there is this process, and a lot different reactions going on, the light and the dark reaction again. **5.** It will produce glucose, which the plant will take for himself, or itself, and **6.** the oxygen which is produced as well will be released into the air.

Interviewer: And how $CO_2$ affects photosynthesis? How does it work *in* the process of photosynthesis?

Student 15: Ahm well, only $CO_2$?

Interviewer: $CO_2$ or water...

Student 15: **7.** Well, water is taken in by roots, of course… it is transported up into the plant, or into the tree... ahm, **8.** and carbon dioxide is cached by the down side, so under the leaf where there are little huidmondjes [stomata in Dutch].

*Causal agents employed and causal agents missing*

Students rarely utilized internal microscopic causal agents to explain the biological phenomena. As to the topic of flowering plants reproduction, the agents *ovule, ovary, pollen tube, zygote* and *embryo* were generally missing. Also, regarding the of topic plants photosynthesis, there were important internal microscopic causal agents which were rarely used as *$H^+$, electrons, ATP, ADP, NADPH, NADP*. Moreover, very few students made use of effective generic terms (students' own words) to represent an agency that they would not know or would not recall its the exact name.

This lack of internal microscopic causal agents might explain (at least in part) the common situation in which students seem to disregard what happens in the middle of the biological phenomena – the steps between cause and effect on the underlying levels of biological organization. This outcome may relate to students' lack of recognition of the importance of these agents for providing a satisfactory explanation, or even to the possibility that students do not understand how these agents operate in the biological phenomena. We believe that might be a combination of both cases. Additionally, previous studies state that students usually face difficulties to (re)connect molecular knowledge to the phenomena at the levels of cells, organs and organisms (Van Mil *et al*., 2016).

*Influential factors cause a different outcome*

Lastly, we present the results on students' ability to perceive and explain causally the effects of (potential) influential factors that could produce a different outcome to the biological phenomena. Most students were able to mention some of the *macroscopic external* and *macroscopic internal* influential agents, for instance: no light, no water, no leaves, no bees, no wind, no flowers. Fewer students also mentioned *microscopic* influential agents: not enough nutrients, not enough $CO_2$, to cite a few. However, many of the influential agents mentioned by students were not supported by any causal explanation (see Table 3), revealing that students were also simply guessing some of these potential influential factors.

The only main difference between the results for each biological phenomena is that for the recently learned topic (photosynthesis) students could easily name/guess a larger number of potential influential agents – yet without providing a corresponding larger number of causal explanations. This result also indicates that students are not being prepared to reason causally, and their educational focus might be based on memorizing biological vocabulary and simple ready-made responses. Finally, as one could also expect (i.e. based on the results already presented above), the few influential agents explained were usually macroscopic and related to the beginning of the biological phenomena.

Table 3. Number of influential agents mentioned versus explained for each biological phenomena.

| Student number | Photosynthesis Total mentioned | Photosynthesis Explained | Plants Reproduction Total mentioned | Plants Reproduction Explained |
|---|---|---|---|---|
| 1 | 8 | 1 | 2 | 0 |
| 2 | 4 | 0 | 1 | 0 |
| 3 | 4 | 0 | 3 | 1 |
| 4 | 2 | 2 | 3 | 1 |
| 5 | 8 | 1 | 3 | 2 |
| 6 | 4 | 2 | 2 | 1 |
| 7 | 3 | 2 | 2 | 1 |
| 8 | 4 | 1 | 2 | 1 |
| 9 | 4 | 2 | 6 | 3 |

| | | | | |
|---|---|---|---|---|
| **10** | **4** | **1** | **2** | **2** |
| **11** | **6** | **2** | **2** | **1** |
| **12** | **5** | **3** | **4** | **2** |
| **13** | **3** | **0** | **3** | **0** |
| **14** | **4** | **0** | **3** | **0** |
| **15** | **8** | **1** | **0** | **0** |
| **16** | **6** | **2** | **5** | **0** |
| **17** | **6** | **2** | **2** | **0** |
| **18** | **4** | **3** | **1** | **1** |

## Educational Implications

The present preliminary study on pre-university students' current spontaneous causal reasoning status about the biological phenomena 'plants photosynthesis' and 'flowering plants reproduction' indicates that students are not prepared to provide elaborated causal explanations for neither the past, nor the recently learned topic. In fact, students appear to lack the skills of critical thinking (and analysis) while explaining biological phenomena, and they end up limited to the nominal and functional levels of biological literacy, as defined by Gordon Uno and Rodger Bybee (1994). Here we speculate on the possibility that the same scenario repeats for the various biological phenomena that students are expected to master in secondary education – nonetheless an extended research is highly recommended in order to confirm or refute this prospect.

This initial exploratory study reveals some critical issues that require more focus on future educational practices. Examining pre-university students' spontaneous causal reasoning ability provided us with valuable information about some of the directions in which education might take in order to support students in the development of a satisfactory level of causal reasoning. First and foremost, previous research has already indicated that teachers often either overview the various dimensions of causation or assume it is difficult to teach the complex explanatory nature of biological phenomena (Perkins & Grotzer, 2000; Perkins & Grotzer, 2005). Here we confirmed that pre-university students are still affected by formal education (ultimately teachers) deficiency in providing their students with the correct tools to causal reason. Our results reemphasize that biology teachers might need an improved educational support in order to correctly guide their students through the process of causal reasoning. Therefore, we suggest that teachers take a careful look at the MACH (Methods, Analogy, Context, How) model of mechanistic explanations recently developed by Caleb Trujillo and colleagues (2015), as a potential starting guideline to improve their practice – but also as a potential metacognitive tool to be offered to pre-university students to help monitor their own causal explanations (Trujillo *et al.*, 2016).

Another fundamental element to be acknowledged is that causal reasoning about biological phenomena, as in photosynthesis and flowering plants reproduction, requires that students – and first, teachers – enjoy a clear understanding of the microscopic scenarios present in the biological processes. This is because the core (or the middle) of physiological phenomena usually occurs in the microscopic level. Therefore, all of the fundamental microscopic agents and processes – which are neither obvious or simple – require much more emphasis and attention in biology classes. Previous research has also pointed out that learning and teaching microscopic mechanisms is an ongoing weak point in biology education, although these studies are often focused on genetics biological phenomena (Knippels *et al*., 2005; Haskel-Ittah & Yarden, 2018). Although the emphasis has been place on the topics of genetics, their suggestions for educational practice to overcome the difficulties in teaching/learning these microscopic biological phenomena might also be extended to a diversity of biological phenomena that likewise require a better perception of the microscopic world. Furthermore, we recommend an extended research to confirm that the same benefits are attained when applied to a variety non-genetics subject matter – yet regarding microscopic biological mechanisms.

Finally, during one of the interviews a student realized that he/she could not explain the core of the process of flowering plants reproduction, although the student also affirmed that this is an essential biological phenomena that everyone should know. In the student own words:

Student 17: **Okay, and uh... okay, and how does apple, the fruit, grows? I wouldn't know. It sounds like something everyone should know!**

Again, how does an apple fruit grow? This sounds like a simple question with an equally simple answer. But biology has a beautiful touch of mystery to be discovered and good causal reasoning can take all of us there! This is our last reflection and recommendation for biology education: teachers and students, do not forget to explore the causal reasoning that explains a biological phenomena, otherwise you might also be missing to experience one of the greatest beauties in the study of life.

**Acknowledgements**

We would like to thank Cynthia Azevedo Lanzetti for her kind help in reviewing the English language in the earlier version of the manuscript. We are thankful to all schools, coordinators and teachers who accepted our invitation to collaborate for data collection. We are especially grateful for every student who participated in the interviews and made this research possible.

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**Appendix** **Final Semi-Structured Interview Protocol**

Pre-University Students Causal Reasoning About Plants Physiological Phenomena

**Plants Photosynthesis & Flowering Plants Reproduction**

Total time for each interview: Approx. 20 minutes

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➔ **Plants Photosynthesis**

1) Introduce the short video

   https://www.youtube.com/watch?v=VgXCsZu_xyw&feature=youtu.be

**General open question(s)**

2) Why do plants need light?
3) What happens in plants photosynthesis?
4) What do you think about plants photosynthesis?

➔ **Plants Reproduction**

1) Introduce the short video

   https://www.youtube.com/watch?v=iV5N3HUusZI&feature=youtu.be

**General open question(s)**

2) Why do plants grow flowers?
3) What happens in plants reproduction?
4) What do you think about plants reproduction?

Note that the question "What happens in plants photosynthesis/reproduction?" is a general starting question. It does not necessarily lead to a causal reasoning dimension (i.e. how does **x** happen…, what causes **x**…, what if **y**…).

**Prompting questions referring to causal reasoning**

➔ **Plants Photosynthesis**

→ Mechanism:
- How does photosynthesis happen?
  - What are the mechanisms involved in the process of photosynthesis?
- What happens after… (according to student previous answer)?

→ Additional prompting questions:
- Via what steps does photosynthesis happen?
  - Could you explain a bit more about the steps in this process?
- What are the effects of… (according to student answers) during plants photosynthesis?

→ Influential factors:
- Is there a situation in which photosynthesis would happen faster or slower?
  - Can you think about something that could limit the process of photosynthesis?
- What else could affect the process of photosynthesis?
  - Does photosynthesis always happen?

→ Additional questions:
- How do plants know to do photosynthesis?
- Can you think about other factors that cause the process of photosynthesis?
  - Maybe some internal (and/or external) agents?

**Prompting questions referring to causal reasoning**

➔ **Plants Reproduction**

→ Mechanism:

- How does flowering plants reproduction happen?
    - What are the mechanisms involved in the process of flowering plants reproduction?

- What happens after… (according to student previous answer)?

→ Additional prompting questions:

- Via what steps does plants reproduction happen?
    - Could you explain a bit more about the steps in this process?

- What are the effects of… (according to student answers) during plants reproduction?

→ Influential factors:

- Is there a situation in which flowering plants reproduction would happen faster or slower?
    - Can you think about something that could limit the process of plants reproduction?

- What else could affect the process of flowering plants reproduction?
    - Does flowering plants reproduction always happen?

→ Additional questions:

- How do plants know to reproduce?

- Can you think about other factors that cause the process of plants reproduction?
    - Maybe some internal (and/or external) agents?

**Is there anything else that you would like to add (or say) in this interview?**

End of the interview