Improving dichotomous keys for undergraduate teaching

Lisa Vollbrecht, marie Thérèse Rush, and Karl Cottenie

Department of Integrative Biology, College of Biological Sciences, University of Guelph, Guelph, ON Canada. Faculty supervisor: Dr. Karl Cottenie.
For correspondence, please email: lvollbre@uoguelph.ca.

Abstract

University of Guelph undergraduate students have been struggling to independently identify macroinvertebrates using dichotomous keys in the Biology of Polluted Waters course (BIOL*4350). The course currently uses dichotomous keys that lack definitions of complex anatomical terms and illustrations that place features in the context of the whole organism. This results in taxonomic bias, whereby some macroinvertebrate families are ignored in subsampling, especially for Ephemeroptera (mayflies). This is of particular concern to biotic assessment of stream quality that uses Ephemeroptera as biological indicators. An updated dichotomous key for Ephemeroptera with illustrations and definitions of anatomical terms integrated within the text of the key was developed at the University of Guelph in Winter 2012. The generation of the key utilized a local macroinvertebrate collection, published literature and existing keys. The effectiveness of the updated key was tested against the BIOL*4350 key by comparing the number of correct identifications produced by undergraduate student volunteers using both keys. Additionally, the number of correct identifications by student volunteers who had previously taken BIOL*4350 ($n=18$) and those who had not taken the course ($n=40$) were compared. It was predicted that students who had previously taken BIOL*4350 would produce more correct identifications than students who had not. The new key had a significantly higher proportion of correct identifications than the old key ($p<0.01$). No significant difference in identification ability existed between students who had or had not taken BIOL*4350 ($p=0.53$ and $p=0.38$). These results suggest the key developed through this investigation is a good starting point to develop similar keys and improve dichotomous identification in BIOL*4350 as well as other courses.

Keywords: dichotomous key; undergraduate teaching; macroinvertebrate, Ephemeroptera

Introduction

A dichotomous key is a series of statements about a certain group of organisms that is read in couplets and is used to identify an unknown specimen. Each couplet is a grouping of two statements describing two different phenotypes. By choosing the options that best describe a given organism, it can be properly identified (Timme 1991).

Macroinvertebrate identification labs are conducted as part of the Biology of Polluted Waters course (BIOL*4350) at the University of Guelph. During the last 12 years spent teaching the lab portion of BIOL*4350, the lab coordinator has subjectively noticed a steady decrease in the ability of students to independently use dichotomous keys without assistance from teaching staff to elaborate on terminology and diagrams (personal communication with mT Rush in 2012; unreferenced, see "Notes"). Illustrations in the keys are often shown without context of where to find the structure on the organism, which may be a part of the problem at hand (personal communication with mT Rush in 2012; unreferenced, see "Notes").

The difficulty of using dichotomous keys has important consequences resulting in misidentified organisms, thus

enabling taxonomic bias. Many Ephemeroptera families known to exist in the Speed and Eramosa Rivers were not identified in student subsampling counts (personal communication with mT Rush in 2012; unreferenced, see "Notes"). Unbiased enumeration of Ephemeroptera is especially important because the order is composed of biologically sensitive families used in the EPT (Ephemeroptera-Plecoptera-Trichoptera) Index for assessing stream quality (Mackie 2001). Taxonomic bias results in measuring a lower number of Ephemeroptera families than are actually present in the sample. When making qualitative assessments of stream quality based on this presence/absence data, as in the EPT index, results may be skewed and lead to an incorrect understanding of the aquatic system being studied (Stribling et al. 2003).

The use of illustrated teaching material is a helpful addition for many students while benefiting knowledge retention and reducing boredom (Randler 2008). Randler (2008) compared the use of illustrated identification (ID) books versus black and white dichotomous keys in elementary education. Both methods were noted for their

equal cognitive requirements during use, but the dichotomous key was praised for encouraging students to focus more on the individual anatomical features of the specimen, rather than on the holistic images presented in the ID book (Randler 2008). By enhancing the basic dichotomous key framework with diagrams to help orient the user in the context of the entire organism, it is expected that the ability of students to correctly identify specimens will greatly improve.

In this investigation, a new dichotomous key was created to improve the key made by Mackie (2005), which was previously being used in BIOL*4350. Illustrations were drawn by hand after viewing the macroinvertebrate reference collection as well as previously published taxonomic keys. A beta-test was conducted using undergraduate student volunteers to assess the effectiveness of the new key compared with Mackie (2005). By enhancing the basic dichotomous key framework with diagrams to help orient the user in the context of the entire organism, focusing on only local taxa and removing species level characters from the key, it was expected that the ability of students to correctly identify specimens would greatly improve.

Illustrations in the new key depicted anatomical features difficult to describe in words and were integrated into the text instead of being grouped together on separate pages as in Mackie (2005). Definitions of less common anatomical terms were provided alongside the couplets. When possible, the life histories of the families were noted to educate students about mayfly lifestyles, such as an extended rostrum for burrowing or a flattened head for streamlining against rocks (Burks 1975). Additionally, the new key only described families found in the Speed and Eramosa Rivers, whereas the previously used key described species present in the rivers. Identifying to the family level is faster and is associated with less loss of accuracy in biotic indices compared with identification at the species level (Hilsenhoff 1988). Family level identification is all that is required in BIOL*4350, so having a family level key was expected to reduce confusion for students. It was expected that the couplets could address differences in more obviously discernible features than a species level key, which compares more minute anatomical differences and requires a much more sophisticated eye.

The newly created key for Ephemeroptera families in the Speed and Eramosa Rivers could potentially be a new educational tool applied in BIOL*4350 to reduce or eliminate taxonomic bias. Eliminating this bias would improve the accuracy of biotic indices that rely on unbiased subsampling counts to evaluate the health of aquatic systems. Ultimately, improving macroinvertebrate dichotomous keys will result in a better understanding of the issues in the Speed and Eramosa Rivers during the field study portion of BIOL*4350.

The following predictions were examined through beta-testing of the new Ephemeroptera key:

Hypothesis 1: A dichotomous key that features explanatory diagrams that place anatomical features in context of the whole organism, clear definitions of

terminology, and only identifies down to the necessary taxonomic level, will enhance the ability of undergraduate students to effectively and independently identify specimens.

Prediction 1: A dichotomous key that integrates the described illustrations and definitions into its couplets and only identifies to the family level will result in more correctly identified specimens than the dichotomous key currently used in BIOL*4350.

Hypothesis 2: Students who have previously taken BIOL*4350 will have an enhanced ability to correctly identify macroinvertebrates due to their previous exposure to Ephemeroptera identification.

Prediction 2: Students who have previously taken BIOL*4350 will identify a greater proportion of mayflies correctly, independent of which key they are using.

Materials and Methods

Dichotomous key design

Families of the order Ephemeroptera were examined under a dissecting microscope for preliminary observations and categorization based on initial appearances. Nine of the eleven Ephemeroptera families currently in the Speed and Eramosa Rivers are represented in the University of Guelph macroinvertebrate reference collection. The Polymitarcyidae and Baetiscidae were not available in the reference collection or from Trout Unlimited in the Alexander building on campus. Two of the families listed on the identification template used in BIOL*4350 were actually a family (Oligoneuridae) and a subfamily (Isonychiidae) that were combined. McCafferty (1998) was used to resolve this.

Background research from published taxonomic keys by Ward and Whipple (1959), Pennak (1978), McCafferty (1998) and Mackie (2005) were used as a supplement to observations of the reference collection to differentiate between Ephemeroptera families. The available families were photographed using a Leica EZ4D Camera Microscope, and the photos were loaded onto a laboratory laptop. From the digital pictures, hand-drawn illustrations were completed based on the distinguishing feature(s) of the family. The illustrations were then scanned and sized to be put directly into the key. The families absent from the reference collection were rendered from the published taxonomic keys and scanned into the key in the same way. Siphonuridae, Tricorythidae and Baetidae specimens were so degraded that it was very difficult to properly observe their characteristics. This resulted in more reliance on the published identification keys in order to complete the project.

Subjects

The completed key was beta-tested on a sample of 58 student volunteers. Volunteers were undergraduate science students in the second, third, or fourth year of their degree programs. There were 18 volunteers who had previously taken BIOL*4350 and 40 volunteers who had not. None of

the student volunteers involved in the study had previously failed BIOL*4350.

Beta-test procedure

Beta-testing followed the ethics protocol 12FE013 approved by the Research Ethics Board at the University of Guelph. During testing, each student was randomly presented with one key, either Mackie (2005) or the new key, and with one mayfly to identify. Working independently, they resolved the identity of their mayfly to the best of their ability and recorded on a data slip the number of the key they were using (Mackie = 1, new key = 2), the letter on the petri dish containing their mayfly (cryptically corresponding to the correct family name), the family they thought the specimen belonged to, and whether or not they had taken BIOL*4350.

Because of the way the test was conducted in the second year class, there ended up being more data collected overall for the Mackie (2005) key ($n=31$) than the new key ($n=25$). Although the keys were randomly laid out on the lab benches, participants did not evenly distribute themselves between the two keys as they sat down due to chance.

Statistical analysis

First, a test of proportions was conducted within each key group (Mackie or the new key) to determine if there was a significant difference in the proportion of correct identifications between students who had or had not previously taken BIOL*4350. Then, another test of proportions was conducted to evaluate the statistical difference in the proportion of correctly identified specimens between the two keys. Because the proportion of correct answers did not differ significantly between those who had and had not taken BIOL*4350, the data was compiled for both types of students within key groups. All tests were conducted using Microsoft Excel at a 95% level of significance.

Figure 1. The proportion of correctly identified Ephemeroptera specimens resulting from the use of two different dichotomous keys by 58 undergraduate science student volunteers. Mackie's key (2005) has complex terminology and diagrams, whereas the new key was designed to be easier for students to use. Significance at a 95% confidence level is denoted by (*).

Figure 2. The proportion of correctly identified Ephemeroptera specimens from use of two different dichotomous keys when considering whether or not students had previously taken BIOL*4350. Within key groups, there was no significant difference in the identification ability of students who took BIOL*4350 versus those who did not.

Results

The new key produced a higher proportion of correct identifications than Mackie's key ($z=-4.5289$, $p<0.0001$). Identifications were 80% correct when volunteers used the new key compared with 21% correct identification using the Mackie key (Figure 1).

Identification ability of the students who had taken BIOL*4350 and those who had not were compared in each of the two key groups (Figure 2). Of the volunteers who used either Mackie's key or the new key, there was no significant difference between the proportion of correct identifications given by the students who had previously taken BIOL*4350 and those who had not (Mackie: $z=0.0869$, $p=0.5346$; new: $z=0.2928$, $p=0.3848$).

The key was modified as a result of beta-testing and the revised key can be viewed in **Supplementary Information**.

Discussion

The study's first prediction was supported by the proportion of correct identifications using the new key. This suggests that the features of the new key enhanced the ability of students to correctly identify mayflies at the family level. Other studies investigating the effectiveness of dichotomous keys on woodlice and weed seedlings reported 75% and 70% correct identifications using similar key designs respectively (Morse *et al.* 1996; Stucky 1984). The proportion of correct identifications with the new key (80%) corresponds closely to these values, suggesting that the newly created key provides a level of effectiveness similar to other keys.

Although the new key was more effective overall, it is not possible to pinpoint which feature(s) enhanced correct identifications the most. The new key was different from the old in that it identified family versus species, and featured diagrams and definitions with simple terminology directly alongside the couplets being described. By only identifying

to the family level, the new key was also much shorter than Mackie's. A shorter key inherently reduces the likelihood of making an incorrect identification because there are fewer questions the student must answer (Choi 2002). For example, to identify an Ephemeridae specimen, a student would have to go through four couplets in Mackie's key compared with only two in the newly developed key.

Although the combination of features used in the new key improved the proportion of correct mayfly identifications compared with Mackie's key, student accuracy was not perfect. The most noticeable issue with the new key was the confusion of Caenidae with Heptageniidae. These two families both have members with anteriorly flattened heads, and by having a couplet addressing head shape come first in the key, a Caenidae specimen was easily mistaken for a Heptageniidae specimen. However, these two families differ greatly in their abdominal gill structures, so by moving this couplet to a position in the key before the one addressing head shape, misidentification of Caenidae specimens might be prevented. Further beta-testing will need to be conducted to establish if this is true.

The confusion of Caenidae and Heptageniidae does not account for all misidentifications using the new key. There were also two misidentifications of Oligoneuridae specimens, which may have been due to the orientation of the drawings in the key. Preserved Oligoneuridae naturally fall on their side when placed in a petri dish because their legs are pointed downward instead of out to the sides of the body like most other families. This means the legs lie in a cluster and the distinguishing feature of the family – long, bristled front leg hairs – are not clearly visible since they are collapsed against the leg. The illustration of Oligoneuridae in the key depicts a dorsal view of the head and right front leg with the bristled hairs drawn erect. If students do not move their mayfly to look at it dorsally, or manipulate the front legs of the specimen to affirm it has long bristled leg hairs, then they will misidentify the mayfly. In the revision of the new key, a text box will be added to the Oligoneuridae couplet indicating that the preserved specimen may be lying on its side with its legs less visible. Thus, students may be encouraged to look more carefully at the specimen. Additionally, students may have had a certain level of inaccuracy resulting from low motivation or a lack of effort invested, which are factors that cannot be controlled for.

The second prediction was rejected, since there was no significant difference in the identification abilities of students who had versus had not taken BIOL*4350. This suggests that students who had taken the course previously did not have an advantage in identification ability compared to those who had not taken it. It is most likely the case that students do not master terminology as sophisticated as in Mackie (2005) in BIOL*4350 nor do they have any prior knowledge of it coming into the course; thus, they do not have any advantage in using the key even if they have already taken the course.

Thus, Mackie's key seems to require students to have a sophisticated working knowledge of entomological anatomy, which is not the case for many undergraduate biology

students. It is not necessary for students in BIOL*4350 to have a mastery of aquatic insect terminology since there is no entomology prerequisite for BIOL*4350 and identifying macroinvertebrates is only a small portion of the course. A key with such complex terminology as Mackie's is best suited to other courses at the university such as Biology of Aquatic Insects (ENVB*4220) where students have the necessary background on macroinvertebrate anatomy. Improving mayfly identification in BIOL*4350 will require a modified dichotomous key that is easier for students to understand with the background knowledge they already possess. Due to difficulties with copyrights, it has not been possible for such a key to be secured for use in the course. However, with continued testing, the new key created through this investigation could be a very useful addition to BIOL*4350.

Limitations and future directions

In the future, the newly developed key should be further tested to ensure that it is effective at identifying all families of mayflies in the Speed and Eramosa Rivers. Some families were not used during beta-testing (Baetidae, Baetiscidae, Polymitarcyidae and Tricorythidae) because no specimens were available or the specimens were heavily degraded. Perhaps in the next offering of BIOL*4350, the new key could be tested with families that could not be used during beta-testing since at that time, students would be catching fresh and fully-intact macroinvertebrates during the field portion of the course. Additionally, instead of laying out the materials prior to students coming into the lab, it would be best to have extra help so as to ensure an equal distribution of both keys to students.

Ongoing research into the effectiveness of macroinvertebrate dichotomous keys will greatly improve the experience of undergraduate students in BIOL*4350 at the University of Guelph. The information garnered from this study could easily be applied to create keys for the 18 other orders of macroinvertebrates that still require new dichotomous keys. The orders Plecoptera and Trichoptera should be addressed first because they are also included in the EPT index of stream quality, and this would help to further improve the accuracy of stream assessment biotic indices. Beyond the scope of BIOL*4350, the features of the key created in this study could be applied in other courses at the University of Guelph and at other institutions for the purpose of improving student identification skills.

Acknowledgements

I would like to thank: Gillian Martin for graciously donating some of her personal mayflies, Sheri Hincks for letting me approach her students during their lab period, and all of the volunteers who donated their time.

Notes

The personal communication with marie Thérèse Rush was conducted in the Science Complex at the University of Guelph in February 2012 as a preliminary deliberation for this research project.

References

- Burks BD. 1975. The mayflies or Ephemeroptera of Illinois. Los Angeles (CA): Entomological Reprint Specialists. 216 p.
- Choi SH, Neiminen TA, Bahr M, Bahr N. 2002. In: Jeffery PL, editor. Problematic futures: Educational research in an era of uncertainty. Australian Association for Research in Education Annual Conference. p. 1-9.
- Hilsenhoff WL. 1988. Rapid field assessment of organic pollution with a family-level biotic index. *Journal of the North American Benthological Society*. 7(1): 65-68.
- Mackie GL. 2001. Applied aquatic ecosystem concepts. Dubuque (IA): Kendall/Hunt Publishing Company. 784 p.
- Mackie GL. 2005. Aquatic flora and invertebrate fauna of the Speed River watershed: including exotic and endangered species. No publisher. ISBN 0-9010-44571.
- McCafferty WP. 1998. Aquatic entomology: the fishermens' and ecologists' illustrated guide to insects and their relatives. Toronto (ON): Jones and Bartlett Publishers. 448 p.
- Morse D, Tardival GM, Spicer J. 1996. A comparison of the effectiveness of a dichotomous key and a multi-access key to woodlice. Available from: <http://kar.kent.ac.uk/21343/>
- Pennak RW. 1978. Freshwater invertebrates of the United States. 2nd ed. New York (NY): Wiley. 664 p.
- Randler C. 2008. Teaching species identification – a prerequisite for learning biodiversity and understanding ecology. *Eurasia Journal of Mathematics Science and Technology*. 4(3): 223-231.
- Stribling JB, Moulton SR, Lester GT. 2003. Determining the quality of taxonomic data. *Journal of the North American Benthological Society*. 22(4): 621-631.
- Stucky JM. 1984. Comparison of two methods of identifying weed seedlings. *Weed Science*. 32: 598-602.
- Timme SL. 1991. In: Goldman CA, editor. Tested studies for laboratory teaching. Proceedings of the 12th conference of the Association for Biology Laboratory Education. p. 101-110.
- Ward HB, Whipple GC. 1959. Freshwater biology. New York (NY): Wiley. 1276 p.

Supplementary Information

Ephemeroptera Families in the Speed and Eramosa Rivers of Guelph, Ontario

1a. Possesses a large thoracic shield
(McCafferty 1981; Pennak 1978; Ward and Whipple 1959)
⇒ **Baetiscidae**

1b. Does not possess a large thoracic shield
⇒ **Continue to 2**

2a. Possesses a frontal process for burrowing
⇒ **Continue to 3**

Frontal process refers to elaborate, rigid mouthparts. May look like either of these illustrations.

2b. Does not possess a frontal process for burrowing
⇒ **Continue to 4**

No mouthparts visibly extend beyond the head when viewed dorsally.

3a. Frontal process tusks curve **inwards** at the tips
(McCafferty 1981)

⇒ **Polymitarcyidae**

3b. Frontal process tusks curve **outwards** at the tips
(McCafferty 1981)

⇒ **Ephemeridae**

4a. No gills on abdominal segment 2

⇒ **Ephemerellidae**

4b. Has gills on abdominal segment 2

⇒ **Continue to 5**

5a. Gills on segment 2 are operculate
⇒ **Continue to 6**

Operculate gills are rigid, opaque flaps which have the same attachment point as the regular abdominal gills.

5b. Gills on segment 2 are not operculate
⇒ **Continue to 7**

6a. Operculate gills are square and overlapping
⇒ **Caenidae**

6b. Operculate gills are triangular and do not overlap
⇒ **Tricorythidae**

<p>7a. Head is flattened anteriorly ⇒ Heptageniidae</p>	<p>7b. Head is not flattened anteriorly ⇒ Continue to 8</p>
<p>8a. Abdominal gills are forked, pointed or clustered (McCafferty 1981) ⇒ Leptophlebiidae</p> <p>Located here, they may be shaped like any of the gills depicted below.</p>	<p>8b. Abdominal gills are rounded ⇒ Continue to 9</p>

<p>9a. Hairs on front legs are long and brush-like ⇒ Oligoneuridae</p> <p>Look carefully – hairs may be collapsed against the leg in preserved specimens.</p>	<p>9b. Hairs on front legs are not long and brush-like ⇒ Continue to 10</p>
<p>10a. Antennae are 2-3 times the width of the head (McCafferty 1981; Pennak 1978; Ward and Whipple 1959) ⇒ Baetidae</p>	<p>10b. Antennae are less than or equal to 2 times the width of the head (McCafferty 1981; Pennak 1978; Ward and Whipple 1959) ⇒ Siphonuridae</p>

Image Acknowledgements (listed by couplet)

1a/2a/4a/6a/7a/7b/8a/8b/9a Rendered from a combination of personal photos and McCafferty (1981)
 1b/5a/5b Rendered from a combination of personal photos and Ward and Whipple (1959)
 2b/3a/3b/4b/9b/10a/10b Drawn only from personal photos

References

- McCafferty WP. 1998. Aquatic entomology: the fishermen's and ecologists' illustrated guide to insects and their relatives. Toronto (ON): Jones and Bartlett Publishers. 448 p.
- Pennak RW. 1978. Freshwater invertebrates of the United States. 2nd edition. New York (NY): Wiley. 664 p.
- Ward HB, Whipple GC. 1959. Freshwater biology. New York (NY): Wiley. 1248 p.