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Evaluation of innovative digital microscopy and interactive team-based learning approaches in histology teaching

Histology teaching in veterinary science and other higher education clinical programmes has traditionally relied on light microscopy in a laboratory setting. However, increasing student numbers, limited flexibility of these tools for learning outside the lab, and, most recently, the COVID-19 pandemic, are driving the search for alternative approaches to delivery and sustaining of learning resources. Improved digital technologies, increasingly available through technology-enhanced learning facilities, can help address these issues. Thus, we created a digitized, interactive library of slide-mounted tissue specimens accessible through our institutional virtual learning environment, piloted its uptake by first-year BVSc students, tested it in combination with a team-based learning/flipped classroom strategy, and compared old and new approaches by evaluating student preferences and histology examination results. Students reported greater engagement with the new resource which appeared to influence exam results positively. We identify future areas of investigation and suggest developments to these approaches to encourage adoption across curricula.

Keywords: histology, digital microscopy, computer-assisted learning, team-based learning, instructional design, undergraduate education

Introduction

The understanding of functional anatomy both at microscopic and gross levels is an integral element of pre-clinical education in veterinary, medical, and dental curricula. Learning microscopy-based subjects such as histology and histopathology has traditionally relied upon didactic approaches combined with conventional tools, such as light microscopes and a bank of tissue slides in the laboratory. This method has provided learners with an opportunity to develop fundamental skills in light microscopy as well as an understanding of course content (Coleman, 2009; Merk, Knuechel, & Perez-Bouza, 2010). However, it has unfortunately suffered from persistent pedagogical disadvantages including great variability in the quality of educational tools (Dee, 2009; Foster, 2010; Pospíšilová, Černochová, Krajčí, & Lichnovská, 2012) thereby affecting the learning process. Consequently, it has been

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difficult for students to achieve the desired learning outcomes, which chiefly involve accurate identification of microscopic structures (Kumar et al., 2006; Krathwohl, 2002; Jefferson & Arnold, 2009).

Research has shown that misalignment between learning processes and teaching methods results in student disengagement with learning (Borg & Shapiro, 1996; McDermott, 1997). It is thus prudent for educators to incorporate a range of solutions in their teaching that can be tailored to the diverse needs of students in the classroom (Lage, Platt, & Treglia, 2000). This also requires institutions to identify who their current learners are, recognize their learning needs, and adapt suitable teaching environments to accommodate these. Today, higher education (HE) brings together, into the same classroom, diverse student groups possessing a wide variety of learning styles, i.e. the same student cohort will consist of learners who gather, organize and interpret information in individual, preferred ways to help them retrieve and work with it in future (Chick, 2018; Coffield, Moseley, Hall, & Ecclestone, 2004; Duffy & Jonassen, 2013). The mass marketing of HE means that lecturers are required to teach large groups of students in the same classroom, within short periods of time, while catering to their diverse needs, something that is not easily achieved. One of the first things that requires critical attention is the context which identifies today's learners. Branded as digital natives, most modern students represent a generation that has grown up with the presence of digital technology (Prensky, 2001), using information and communication technology widely in their everyday lives.

Fortunately, with the advancement of digital technologies in general, and the development of digital microscopy (DM) in particular, the use of whole-slide imaging technology has acquired considerable popularity in life sciences education. For studying histology, this has offered remedies for overcoming certain barriers related to conventional teaching tools (Blake, Lavoie, & Millette, 2003; Jefferson & Arnold, 2009; Macpherson & van der Ven, 2003). Similarly, the availability of fully equipped computer-assisted learning (CAL) spaces in any institution has the potential to supplement conventional histology teaching by eliminating inherent difficulties and presenting a valuable learning environment which can enhance students' experience and their learning process (Deniz & Cakir, 2006; Patel, Rosenbaum, Chark, & Lambert, 2006).

The purpose of this study was to evaluate existing methodologies used for teaching histology in the Department of Veterinary Education at the University of Liverpool, and to compare them to a new, efficient strategy allowing unrestricted access to the learning resource. It was expected that this would enhance students' learning experience by promoting more active engagement with course material and providing flexibility for self-directed learning (Costa & Kallick, 2014) independently as well as collaboratively (Le, Janssen & Wubbels, 2018; Smith & Macgregor, 1992). Technology-enhanced learning (TEL) facilities at the university were used to digitize glass slide-mounted veterinary tissue specimens and integrate them into our virtual learning environment (VLE). The aim of this step was two-fold: to preserve a valuable but dwindling resource, and to provide the option of using of CAL spaces for delivery of practical teaching sessions, as opposed to the traditional 'wet' laboratory. Moreover, it was intended to assist private study follow-up by enabling students to revisit content remotely; previously, students' only option had been to remain on campus outside of timetabled practical sessions in order to gain access to microscopy tools made available in self-directed 'consolidation' sessions.

Furthermore, previously, across our non-modular integrated curriculum, we had successfully introduced an innovative team-based learning (TBL) approach (Hazel, Heberle, McEwen, & Adams, 2013; Hrynchak & Batty, 2012) as part of an integrated learning strategy. In the current study, we tested this approach in one of our BVSc Year 1 histology teaching sessions and gauged students' attitudes towards it using an electronic survey.

A key measure of success of any given strategy lies in assessment results, so a preliminary investigation of any relationship between use of the digital resource and exam scores was carried out.

Materials and methods

Scanning of microscope slides and viewing of digital slides

Transformation of glass slide-mounted tissue sections into digital slide format was performed by capturing individual slide images through the ScanScope® CS system (Aperio Technologies®, Vista, CA). The scanner is equipped with two magnification changers to allow scanning at 20x and 40x (20x with 2x magnification changer) with a high-resolution objective lens (20x/0.75). It has the ability to load five glass slides at a time to facilitate automatic high-speed multiple slide-scanning in minutes, depending on tissue size. The scanner software (Aperio®, Digital Slide Information Management) instantly provides integrated digital slide processing, management, viewing and analysis tools for users (Staniszewski, 2009) and creates a single-file pyramidal tiled TIFF with non-standard metadata and compression (file extensions denoted as .svs).

The department's entire slide collection (*n*=100) – used to teach across the undergraduate curriculum – was scanned. All slides were carefully selected to ensure high-quality scans with minimal artefacts and were scanned at 40x magnification to replicate the functionality of the microscope in digital format and allow students to view structures at high power.

All files are now currently hosted on the University of Liverpool's server (https://aperio.liv.ac.uk/) with the Aperio-enabled software (Aperio® eSlide Manager, version 12.3, Leica Biosystems Imaging), an information management system for high-resolution digital slides. This intuitive web-based interface allows users to navigate and explore the .svs files either using a browser plugin (Webscope) or a desktop digital image viewing application Aperio®, Imagescope) which is freely downloadable from the Aperio website (ImageScope Download). With internet access, this online resource is currently accessible to all students, from anywhere, at any time, using specific login details. Both Webscope and Imagescope allow users to visualize the slides at a range of magnifications (4x–40x) and to capture high-quality 'snapshots' (https://www.leicabiosystems.com/digital-pathology/manage/aperio-eslide-manager/) suitable for manipulation in order to suit various learning and teaching purposes.

Integration of the digital slide resource into the VLE

The entire digital slide library was made available to students via the university's VLE, utilizing the Blackboard Learn 9.1 Q4 2016 platform. However, all weblinks to the digital slides provided via the Aperio server allow the flexibility to be integrated across multiple virtual learning platforms.

Utilization of CAL spaces and digital technologies

The university's CAL spaces are fully equipped with high-specification PCs (204 client PCs and one instructor PC) (Figure 1). All PCs are connected to the university's intranet system (MWS; Windows-based IT system), allowing staff and students to connect to the VLE, and are equipped with the classroom management software, NetSupport School (NetSupport® Ltd). This allows the instructor to remotely control transmission of his/her screen to all students, and, in turn, to view students' screens. This tool is particularly helpful for managing large cohorts, allowing efficient instruction, monitoring, and active interaction with students, either on an individual basis or with an entire class.

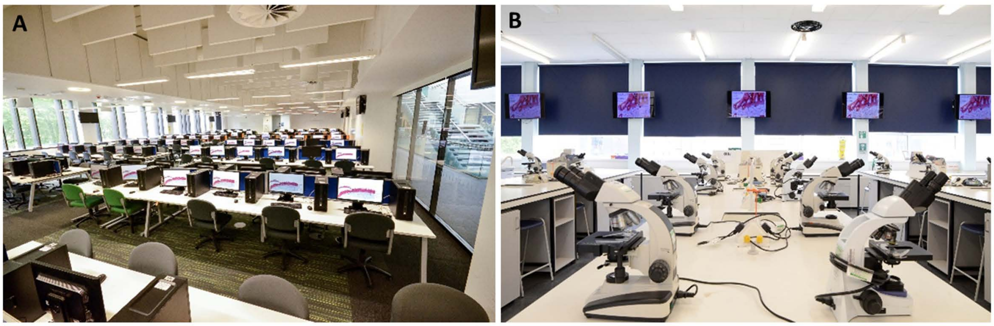

Figure 1 (A) View of computer-assisted learning (CAL) spaces (capacity, *n*=170) using digital slides in a histology practical session. Students are able to directly observe and instructors are able to demonstrate and project slides on all PC monitors simultaneously.
(B) View of a typical conventional laboratory setting where students can use microscopes and glass slides and observe the instructor's demonstration on wall-mounted monitors.

Participants, questionnaire evaluation, and statistical analysis

Histology is primarily taught in the first year of the BVSc programme which holds 162 students (82% female, 18% male; mean age of twenty years, range of eighteen to forty years). Data were collected during the academic year 2016–2017. At the end of the second semester, we conducted a voluntary and anonymized online survey through the online EvaSys™ system using a combination of Likert-type four-point scale 'agree/disagree' statements, dichotomous questions, multiple-choice questions, and a text box for free comments. The survey was distributed to all students in one of the histology sessions and included questions related to the use of DM with conventional light microscopy (see questions in Figure 3), teaching methods (see questions in Figures 4 and 5), and the types of resources provided for the course. The raw data obtained from the survey were exported to Microsoft Excel for application of descriptive statistical analysis and graphical representation.

Data related to digital slide resource users were obtained from the University's VLE through its statistical tracking tool. Statistical analysis software, STATA (Release 14, College Station, TX: StataCorp LP), was used to measure the correlation between practical ('spot') exam results and the use of digital slides according to Spearman's rank correlation coefficient.

Results

Student survey and statistical tracking record of the digital slide resource

Table 1 shows the number of histology sessions delivered in the first year of the veterinary curriculum, where approximately eighty-eight slides are used to demonstrate the microscopic structures of various organs. Summing across all sessions delivered during the academic year studied, a total of 14, 777 views ('hits') occurred, with the highest number (3,588) identified for the gastrointestinal (GI) system session. This was (albeit anecdotally) attributed to an element of coursework that students are required to submit early in their histology training (first semester) which involves demonstrating knowledge by drawing histological features of GI organs, viewable within the digital images.

Table 1 Overall statistical tracking data of the digital slides resource used for all practical sessions

Session No.	Session name	No. of slides	Total no. of hits
1	Epithelial tissue	6	781
2	Muscular tissue	7	752
3	Glandular tissue	6	905
4	Connective tissue	10	1,106
5	Urinary system	4	839
6	Cardiovascular system	7	933
7	Respiratory system	4	669
8	Lymphoid system	5	729
9	Gastrointestinal system	11	3,588
10	Nervous system	7	2,055
11	Integument	4	551
12	Reproductive systems	10	934
13	Endocrine system	7	935
	Total	88	14,777

A total of 139 students (86%) responded to the online survey and provided their views on the implementation and use of the DM resource. Overall the resource was found to be very useful and was extensively used, not only in practical sessions but also outside of teaching hours. These findings were consistent with data obtained from the statistical tracking record used for all teaching sessions (Figure 2).

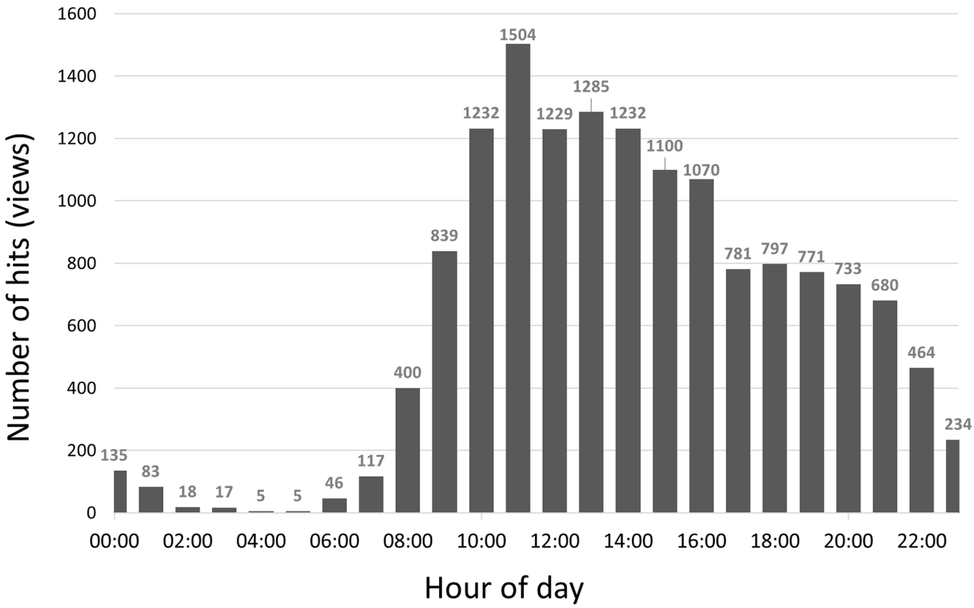

Figure 2 Frequency distribution of the digital resource usage. The statistical tracking feature of the university VLE enabled the number of student views ('hits') for all histology sessions (subjects) to be totalled for each hour of the day and night across the academic year.

The distribution of hits across the day are shown in Figure 2; almost two-thirds (59%) occurred between 10:00 a.m. and 4:00 p.m. including access on weekends. The remainder (41%) occurred outside timetabled (contact) hours, before 10:00 a.m. and after 5:00 p.m., including weekends.

Student evaluation of digital vs light microscopy

The survey included statements which enabled us to directly investigate comparisons between digital and light microscopy (Figure 3). The following (rounded) percentage proportions are the result of summing across both the 'disagree' and 'strongly disagree' categories and both the 'agree' and 'strongly agree' categories. Almost three-quarters of students (72%) felt that using microscopes alone did not allow them to achieve the LOs in histology (statement 2, Figure 3) whereas the majority (93%) agreed that using digital slides, either alone or in combination with lab microscopes, did allow them to

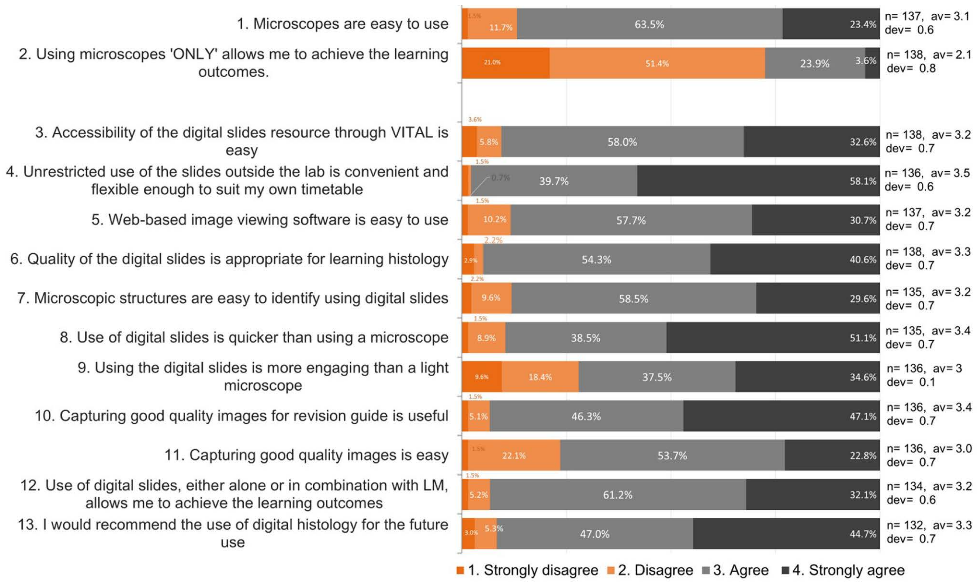

Figure 3 Survey of student opinions on digital vs light microscopy approaches. The number of responses (n), mean (av), and standard deviation (dev) are shown on the right. Data are presented as percentage in agreement (grey) or disagreement (orange).

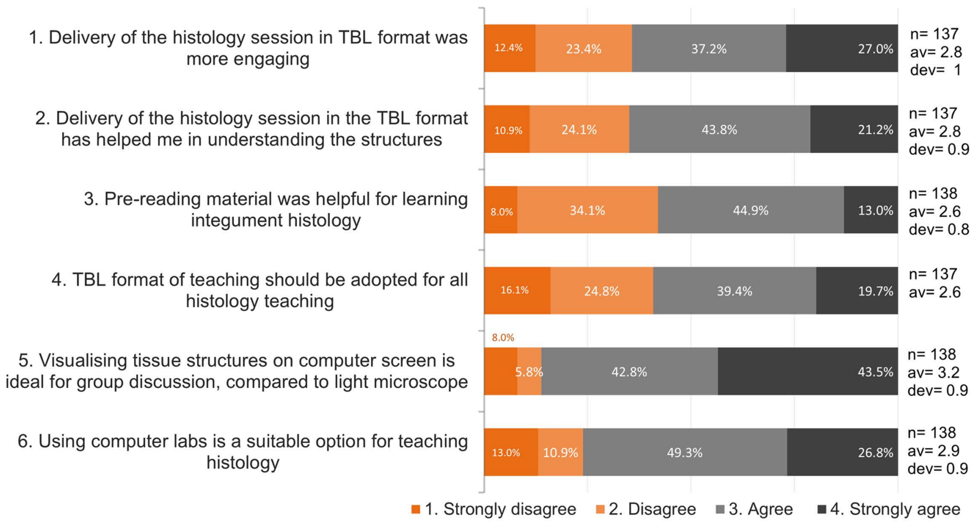

Figure 4 Survey of student opinion on the team-based learning (TBL) approach to histology teaching. After reading related study material (pre-reading) prior to each session, students were able to view digital histology slides in computer-assisted learning (CAL) spaces and discuss them in teams during the instructor's demonstration. The number of responses (n), mean (av) and standard deviation (dev) are shown on the right. Data are presented as percentage in agreement (grey) or disagreement (orange).

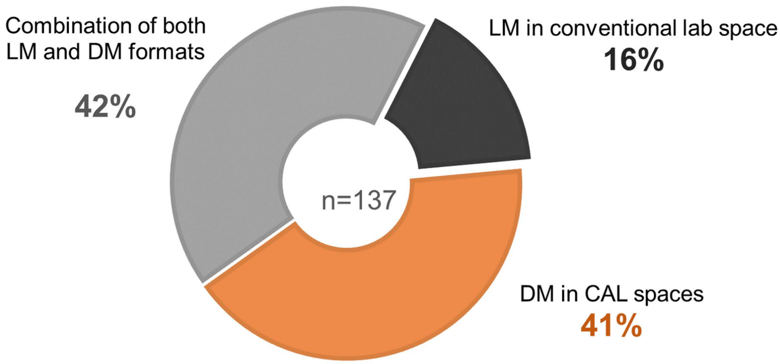

Figure 5 Survey of student preference for practical histology teaching formats. Students were asked to provide their views on the use of digital slides in computer-assisted learning (CAL) spaces compared to that of conventional light microscopy in a traditional teaching laboratory setting.

achieve this (statement 12, Figure 3). Indeed, a substantial proportion (42%) of students expressed a preference for combining the two approaches in future (Figure 5). Figure 3 also shows that the majority of the students (88%) generally agreed that, in comparison to LM, DM enabled microscopic structures to be more easily identified and that using this method was quicker (90%), more engaging (72%), appropriate for learning (95%), and allowed them to capture good quality images for their own learning (93%). Similarly, the majority of students agreed that the accessibility of the digital slides was easy (92%) and that unrestricted use outside teaching hours was convenient, allowing them to study according to their own timetable (98%). As a result, 92% of students recommended the use of DM in the future.

Students' response to TBL format and the use of PCs for practical histology

We selected one practical teaching session, on the subject of integument system histology, to combine a TBL/flipped classroom approach with use of the digitized resource (i.e. a blended learning technique). Preparatory reading material ('pre-reading'; Young, O'Dowd, & Woodford, 2014) had been provided one week prior to the session via the VLE. The session was delivered in a CAL space rather than the traditional laboratory space, fostering a social constructivist approach (Hrynchak & Batty, 2012), team work, and formative assessment, both on an individual and group basis. Using computer spaces allowed students to learn actively individually, as well as in groups where they could sit together and discuss the complex tissue structures observed and manipulated on-screen by using digital microscopic files. A key advantage was that the instructor could gain control over individual PCs at any point during the session to resume the role of lab demonstrator, ensuring that correct structures were viewed by all learners simultaneously.

Figure 4 shows students' feedback on this dual strategy. Over two-thirds of the cohort agreed or strongly agreed that delivery via TBL was more engaging than by a traditional lecture format (64%) and that it helped them understand microanatomy (65%). Although a similar proportion agreed that the TBL format should be adopted for all histology sessions (59%) and found the pre-reading material to be helpful (58%), a significant proportion (41%) were reluctant to embrace it fully. More marked proportions of the cohort were positive about the use of CAL spaces as an alternative to lab microscopy: Three-quarters (76%) of students agreed that using computer labs is a suitable option for histology teaching and more than four-fifths (86%) were in general agreement that visualizing tissue structures on a computer screen is ideal for group discussion. When asked which of the two formats, LM or DM, most helped their learning (Figure 5), equal proportions (42%) preferred the use of both formats or of CAL spaces alone, with the remainder (16%) preferring traditional lab microscopy alone.

Student learning, engagement with course material, and exam performance

Students also had the opportunity to expand on their opinions with free-text comments. The majority expressed a high degree of enthusiasm for learning with DM and computers. Below are some illustrative examples:

> 'It may be easy to use microscopes to find certain structures but not always able to identify the same structures as on the large screens. Digital slides show much more identifiable examples of the structures.'

> 'Using the microscopes is valuable in terms of improving my ability to use a microscope which I can see the value of for use in practice. However, I found the new session far, far better for my learning than the conventional ones. With the microscopes, it's great if you manage to find the structures shown on the screen, however they're not as clear as with the digital slides, and if you can't manage to find the structures with the microscope, it can take 10 minutes to get help from the staff, which then means I lose focus and my learning is interrupted as I waste time. It's much harder to stay focused with the conventional way of learning and I think it is harder to benefit from it.'

> 'In theory, teaching using the digital slides is much better because it is easier to see the structures the lecturer is referring to and easy to navigate and look yourself. Less hassle than trying to focus microscopes. However, I liked having the lecture slides to fall back on and check my understanding.'

> 'Found this session really engaging and interactive which suits my learning style. It is easier to just concentrate on the slide rather than adjusting microscope/ looking around for slides/ adjusting light etc, thus I believe you get more out of it.'

> 'I found it much easier to engage using the digital histology session and that the session was more efficient as time didn't have to be taken up to focus microscopes/ find the right slides etc.'

'It's good to be able to annotate the slides with lines so that we can see where one section of cells starts and another finishes, and then to "print screen" and save as a picture so that we can come back and see exactly what we were trying to describe… "A picture is worth a thousand words". Also, by doing it ourselves rather than using pre-labelled pictures from books and lecture slides, it sticks in the brain a lot more.'

'Really useful for revising histology at home, especially for the SPOT examination.' (It is noteworthy that *this was remarked on by sixteen students*)

'Using the digital slides allows for easy group discussion which in turn keeps you more engaged and also makes it easier to learn as you can work through the slide together and ask questions.'

Engagement with the course material and exam performance

To assess the impact of DM on learning performance, we analysed resource usage and exam results data for any correlation between these two variables. The results of exam performance appeared to have a symmetric distribution while a non-symmetric distribution was observed in the pattern of resource usage (data not shown). Thus, to determine whether or not there was in fact a relationship between exam scores and resource usage, we applied the Spearman's rank correlation coefficient and identified a modest, though significant, positive correlation ($R = 0.35$, $P<0.001$): Figure 6 shows that the more students accessed (and presumably used) the digital resource, the higher the scores that were achieved in the practical histology ('spot') examination.

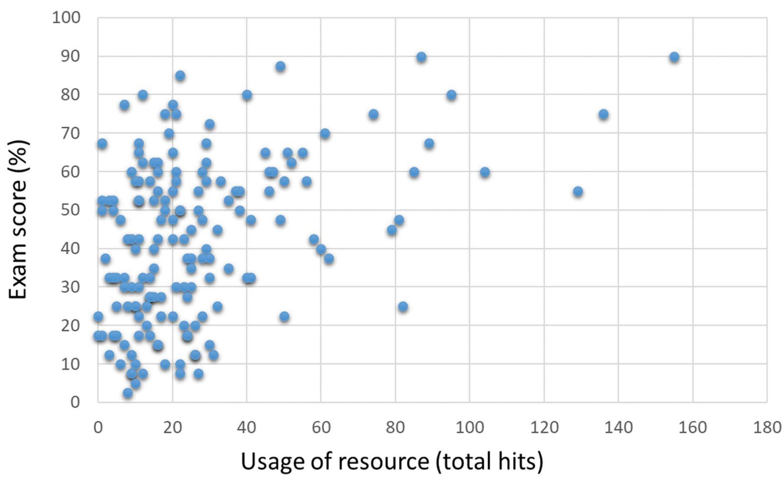

Figure 6 Scatter plot of digital slide resource usage by students against histology practical examination ('spot') score (n=162). A modest though significant positive correlation was found between the two variables ($R = 0.35$, $P<0.001$).

Discussion

Histology is an integral part of the pre-clinical veterinary curriculum, providing necessary skills in recognizing the microscopic features of normal cells and tissues and thereby forming the basis for identifying pathological changes in the para-clinical and clinical years. Current veterinary curricula take an integrated approach which involves reduced contact time for didactic teaching in favour of innovative teaching and self-directed learning. In the authors' experience, the exclusive use of conventional microscopy tools to teach practical histology has posed several pedagogical problems leading to student disengagement with course material, especially where there are limited resources (microscopes and slides) to facilitate learning in large groups. Similar issues have been highlighted previously (Blake et al., 2003; Kumar et al., 2006; Paulsen, Eichhorn, & Bräuer, 2010) and here we discuss points to consider with a view to more widespread adoption of our findings.

With the advancement of technology many institutions have moved away from the sole use of conventional microscopy in favour of DM to enhance the student experience of histology (Bloodgood, 2012; Fonseca, Santos-Silva, Lopes, de Imeida, & Vargas, 2015; Heidger et al., 2002; Hortsch, 2013; Tian et al., 2014; Weaker & Herbert, 2009). Several reports have been published to highlight the benefits and general acceptance of DM in a variety of life sciences disciplines (Krippendorf & Lough, 2005; Merk et al., 2010; Mills, Bradley, Woodall, & Wildermoth, 2007); however, little information is available to evaluate its actual impact on student learning, exam performance, or capacity for integration with TBL and supplementary digital assessment tools. Our pilot study has met its aims by providing initial insights into these areas.

Student survey results confirmed how unrestricted access to a DM resource is exploited extensively to facilitate learning, including revision and consolidation of knowledge, which otherwise must take place in designated teaching suites outside of normal timetabled laboratory sessions. It was fully endorsed by students for future use and from the staff perspective works towards overcoming constraints associated with limited physical resources and large-group teaching. Going forward, it would be useful to analyse student endorsement more carefully: Expanding surveys to include more probing, refined statements and examining relationships between resource usage and assessment results over a number of cohorts/academic years would allow us to determine whether learning outcomes were being met consistently by DM alone, or whether the additional option of the more traditional methods of LM remained an asset and preference of students.

The benefits of combining TBL with a DM resource (in CAL spaces) were also valued by students: This blended approach in a physically flexible learning environment was fluid enough to give students the choice to engage more closely with course material on an individual or cooperative group level and back again at any given moment (Cabrera et al., 2002; Felder & Brent, 2007). However, the risk of institutional computer system failure in this setting is not inconsiderable and requires additional TEL staff to be on standby. Indeed, in future we intend to distribute digital slides through a shared drive in CAL spaces which can be easily accessed through the university network and which should reduce reliance on the remote server which hosts the slide images. Again, a more thorough dissection of student endorsement of the TBL format would clarify the somewhat ambiguous findings of the study: What they do not tell us is whether students would have engaged equally well with TBL in a purely traditional LM setting. This was not trialled as the particular layout of teaching laboratories at the University of Liverpool (adjoining separate rooms) is not conducive to the open discussion required of the TBL format.

For learning the practical side of histology (as opposed to theory), we found most students strongly preferred DM, either alone or in combination with LM, although a minority would prefer to continue using conventional LM alone. This suggests that some students are able to see the value in having their learning mimic the real-life veterinary practice of microscopy for accurate diagnosis in histopathology. Indeed, it would be undesirable to entirely replace practical with virtual microscopy, as basic use of the light microscope is an important clinical competence for veterinary graduates, for example, when examining blood smears or biopsy material to aid in diagnosis. In the event of more widespread adoption of the approaches tested in our study across the curriculum (in particular, histopathology in third year) microscopy per se could be incorporated into clinical skills sessions where teaching occurs in smaller groups and one-to-one assistance from staff gauges competence more closely. This would address the feeling revealed by a small minority of students (8%) that they had not acquired the microscopy skills required for our normal large-cohort lab sessions (as indicated by a short, diagnostic survey conducted online immediately after one of the sessions; data not shown).

In contrast, with respect to theoretical (factual/lecture) material, a preference for didactic teaching persists. At least this early on in the programme (first year), it would seem that students need to build their confidence with the flipped classroom format (Segolsson & Bäcklund, 2017; Taylor, 2015). Nevertheless, the independent learning made possible with the DM resource complements either type of teaching format: Students can take high-resolution 'snapshots' of slide specimens to create their own PowerPoint library of annotated images (Hortsch, 2013; Krippendorf & Lough, 2005; Kumar & Velan, 2010; Kumar et al., 2006; Merk et al., 2010; Ordi et al., 2015; Tian et al., 2014). We observed students making extensive use of this option both during and outside of timetabled practical sessions, i.e. consolidation and coursework, which includes the completion of an assessed drawing task to establish this approach early in the academic year. We encourage the drawing of specimens at the microscope to help develop observational skills and for this reason, as well as embedding general use of the DM resource, we now actively encourage students to access it, alongside their studies at the microscope, via use of their mobile devices (phones, tablets, laptops).

Perhaps the best measure of success has been the confirmation that use of this resource is directly, if modestly, related to exam performance. If possible, it would be useful in future to further mine the statistical tracking data to reveal whether the digital resource 'hits' are spread across the cohort or associated with a subset of students who access it repeatedly, and whether this subset obtains the highest exam scores.

An additional advantage of providing the resource via a VLE is the ability to create formative assessment quizzes related to the material. These short tests, released at the end of each CAL session, have been designed to provide students with immediate feedback on their learning during that session and are also in line with institutional drives eventually to transition completely to electronic assessment. Although we have not yet formally collected data on this approach, we can say anecdotally that the majority of students perform well and that about two-thirds find this assessment method more convenient than previously used methods (e.g. questions and drawing tasks set within paper-based handouts or electronic polling while the practical session is ongoing).

Therefore, the advantages of a DM resource for teaching and learning in veterinary histology (and, by extrapolation, other types of clinical histology) appear to outweigh the disadvantages. They assume the existence of a real resource of slide specimens to begin with, whether having been created in-house by the department or school in question, or obtained commercially. It must be accepted that there is a front-end-heavy workload when the labour-intensive electronic scanning is carried out and the library created and made accessible. However, this pays dividends later in terms of flexibility and efficiency of lesson-planning. The significant self-directed element for students relieves staff workload at the point of full engagement. These findings should be of particular value to university departments interested in following hybrid educational models of mixed face-to-face and online learning. During the current COVID-19 pandemic they are also timely, when remote learning has largely been imposed and when it is, at the time of writing, uncertain when a return to former teaching methods can be considered.

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Statements on open data, ethics approval and conflicts of interest

Further information about the study may be requested by contacting the corresponding author. This study was approved by the Research Ethics Committee of the Institute of Veterinary Science, University of Liverpool and guidelines were followed to ensure anonymity, confidentiality, and secure management of the data. The authors claim no conflicts of interests. The contents of this paper were presented as an abstract and in poster format at the annual international Veterinary Education (VetEd) Symposium, Liverpool, July 2017.

References

Blake, C., Lavoie, H., & Millette, C. (2003). Teaching medical histology at the University of South Carolina School of Medicine: Transition to virtual slides and virtual microscopes. *Anatomical Record. Part B, New Anatomist*, *275*(1), 196–206.

Bloodgood, R. A. (2012). Active learning: A small group histology laboratory exercise in a whole class setting utilizing virtual slides and peer education. *Anatomical Sciences Education*, *5*(6), 367–373.

Borg, M. O., & Shapiro, S. L. (1996). Personality type and student performance in principles of economic education. *Journal of Economic Education*, *27*(1), 3–25.

Cabrera, A. F., Amaury, N., Crissman, J. L., Terenzini, P. T., Bernal, E. M., & Pascarella, E. T. (2002). Collaborative learning: Its impact on college students' development and diversity. *Journal of College Student Development*, *43*(1), 20–34.

Chick, N. (2018). Learning styles. https://cft.vanderbilt.edu/guides-sub-pages/learning-styles-preferences/

Coffield, F., Moseley, D., Hall, E., & Ecclestone, K. (2004). *Learning styles and pedagogy in post-16 learning: a systematic and critical review*. London: Learning & Skills Research Centre. http://hdl.voced.edu.au/10707/69027

Coleman, R. (2009). Can histology and pathology be taught without microscopes? The advantages and disadvantages of virtual histology. *Acta Histochemica*, *111*(1), 1–4.

Costa, A., & Kallick, B. (2014). Why we need self-directed learners. *Assessment Strategies for Self-Directed Learning*. https://doi.org/10.4135/9781483328782.n1

Dee, F. R. (2009). Virtual microscopy in pathology education. *Human Pathology*, *40*(8), 1112–1121.

Deniz, H., & Cakir, H. (2006). Design principles for computer-assisted instruction in histology education: An exploratory study. *Journal of Science Education and Technology*, *15*(5), 399–408.

Duffy, T. M., & Jonassen, D. H. (2013). *Constructivism and the technology of instruction: A conversation*. https://doi.org/10.4324/9780203461976

Felder, R. M., & Brent, R. (2007). Cooperative learning. In P. A. Mabrouk (ed.). *Active learning: models from the analytical sciences, ACS Symposium Series 970, Chapter 4* (pp. 34–53). Washington, DC: American Chemical Society.

Fonseca, F. P., Santos-Silva, A. R., Lopes, M. A., de Imeida, O. P., & Vargas, P. A. (2015). Transition from glass to digital slide microscopy in the teaching of oral pathology in a Brazilian dental school. *Medicina Oral, Patologia Oral y Cirugia Bucal*, *20*(1), e17–e22.

Foster, K. (2010). Medical education in the digital age: Digital whole slide imaging as an e-learning tool. *Journal of Pathology Informatics*, *1*, 38–40.

Hazel, S. J., Heberle, N., McEwen, M. M., & Adams, K. (2013). Team-based learning increases active engagement and enhances development of teamwork and communication skills in a first-year course for veterinary and animal science undergraduates. *Journal of Veterinary Medical Education*. https://doi.org/10.3138/jvme.0213-034R1

Heidger, P. M., Dee, F., Consoer, D., Leaven, T., Duncan, J., & Kreiter, C. (2002). Integrated approach to teaching and testing in histology with real and virtual imaging. *Anatomical Record*, *269*(2), 107–112.

Hortsch, M. (2013). From microscopes to virtual reality: How our teaching of histology is changing. *Journal of Cytology & Histology*, *4*(3), 3–5.

Hrynchak, P., & Batty, H. (2012). The educational theory basis of team-based learning. *Medical Teacher*. https://doi.org/10.3109/0142159X.2012.687120

Jefferson, R. N., & Arnold, L. W. (2009). Effects of virtual education on academic culture: Perceived advantages and disadvantages. *US-China Education Review*, *6*(3), 61–66.

Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory Into Practice*, *41*(4), 212–218.

Krippendorf, B. B., & Lough, J. (2005). Complete and rapid switch from light microscopy to virtual microscopy for teaching medical histology. *Anatomical Record – Part B New Anatomist*, 285(1), 19–25.

Kumar, R. K., Freeman, B., Velan, G. M., & De Permentier, P. J. (2006). Integrating histology and histopathology teaching in practical classes using virtual slides. *Anatomical Record – Part B New Anatomist*, *289*(4), 128–133.

Kumar, R.K., & Velan, G.M. (2010). Learning across disciplines using virtual microscopy: new approaches. In Mendez-Vilas, A. & Diaz, J. (eds). *Microscopy: Science, Technology, Applications and Education, Vol.4: 1467–1473*. Badajoz, Spain: Formatex.

Lage, M. J., Platt, G. J., & Treglia, M. (2000). Inverting the classroom: A gateway to creating an inclusive learning environment. *The Journal of Economic Education*, *31*(1), 30–43.

Le, H., Janssen, J., & Wubbels, T. (2018). Collaborative learning practices: Teacher and student perceived obstacles to effective student collaboration. *Cambridge Journal of Education*, *48*(1), 103–122.

Macpherson, B. R., & van der Ven, A. J. a M. (2003). Enhancing the dental histology curriculum using computer technology. *Journal of Dental Education*, *67*(3), 359–365.

McDermott, L. C. (1997). Guest editorial: How we teach and how students learn. A mismatch? *Electronic Journal of Science Education*, *2*(2).

Merk, M., Knuechel, R., & Perez-Bouza, A. (2010). Web-based virtual microscopy at the RWTH Aachen University: Didactic concept, methods and analysis of acceptance by the students. *Annals of Anatomy*, *192*(6), 383–387.

Mills, P. C., Bradley, A. P., Woodall, P. F., & Wildermoth, M. (2007). Teaching histology to first-year veterinary science students using virtual microscopy and traditional microscopy: A comparison of student responses. *Journal of Veterinary Medical Education*, *34*(2), 177–182.

Ordi, O., Bombi, J. A., Martinez, A., Ramirez, J., Alos, L., Saco, A., … Ordi, J. (2015). Virtual microscopy in the undergraduate teaching of pathology. *Journal of Pathology Informatics*, *6*(Cm), 1.

Patel, S. G., Rosenbaum, B. P., Chark, D. W., & Lambert, H. W. (2006). Design and implementation of a web-based, database-driven histology atlas: Technology at work. *Anatomical Record – Part B New Anatomist*.

Paulsen, F. P., Eichhorn, M., & Bräuer, L. (2010). Virtual microscopy-The future of teaching histology in the medical curriculum? *Annals of Anatomy*, *192*(6), 378–382.

Pospíšilová, E., Černochová, D., Krajčí, D., & Lichnovská, R. (2012). Evaluation of a New E-Learning Method of Teaching Practical Histology Using Virtual Microscopy. *MEFANET Report 05, Technology Enhanced Learning in Medical Education. Editors: Daniel Schwarz Martin Komenda Stanislav Štípek Vladimír Mihál Ladislav Dušek*, *5*, 79–87.

Prensky, M. (2001). Digital natives, digital immigrants: Part 1. *On the Horizon*, *9*, 1–6.

Segolsson, M., & Bäcklund, J. (2017). The flipped classroom and student learning at compulsory school in Sweden: A longitudinal, qualitative study. *Journal of Education and Practice*, *8*(18), 77–86.

Smith, L., & Macgregor, J. T. (1992). What is collaborative learning? In Goodsell, A., Maher, M., Tinto, V., Smith, B. L., & MacGregor J. T. (eds). *Collaborative Learning: A Sourcebook for Higher Education*. Pennsylvania State University: National center on postsecondary teaching, learning, and assessment publishing.

Staniszewski, W. (2009). Virtual microscopy, data management and image analysis in aperio scanscope system. *Folia Histochemica et Cytobiologica*, *47*(4), 699–701.

Taylor, A. (2015). Flipping great or flipping useless? A review of the flipped classroom experiment at Coventry University London Campus. *Journal of Pedagogic Development*, *5*(3), 57–65.

Tian, Y., Xiao, W., Li, C., Liu, Y., Qin, M., Wu, Y., … Li, H. (2014). Virtual microscopy system at Chinese medical university: an assisted teaching platform for promoting active learning and problem-solving skills. *BMC Medical Education*, *14*(1), 74.

Weaker, F. J., & Herbert, D. C. (2009). Transition of a dental histology course from light to virtual microscopy. *Journal of Dental Education*, *73*(10), 1213–1221.

Young, B., O'Dowd, G., & Woodford, P. (2014). *Wheater's functional histology: A text and colour atlas*. 6th ed. London: Churchill Livingstone Elsevier, 159–179.