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Beyond being there? Evaluating augmented digital records

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Abstract

Technological advances have made possible a new generation of digital *prosthetic memory* devices (or memory aids). Yet we currently know little about when, how and why these devices might be useful. We evaluated two novel *prosthetic memory* devices in naturalistic and controlled learning settings. Both devices provide controlled access to annotated *digital records* of lectures, potentially freeing students from taking detailed notes, allowing them to re-access lecture recordings whenever they choose. *Digital records* had benefits over traditional learning aids (e.g. handouts/personal notes): Students were more accurate in answering class quizzes using *digital records*, and spontaneous *digital records* usage outside lectures showed strategic access during important aspects of the course. Native speakers who used *digital records* performed better on coursework, and non-native language speakers used *digital records* extensively. Despite being a verbatim record, *digital records* did not substitute for attendance: students who had attended lectures performed better on quizzes and final coursework and few students listened to lectures from beginning to end. *Digital records* are thus a highly promising teaching tool, but *prosthetic memory* devices are best understood as working in synergy with current tools to aid human memory, rather than replacing it. We conclude by discussing potential theory and design implications.
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1. Introduction

Human memory is fallible, and we all rely on various prosthetic devices (or memory aids) such as diaries, notebooks, sticky notes and calendars to remind us about things that we would otherwise forget. However, recent advances in storage, networking and sensor technologies have now made it possible to capture huge amounts of digital data relevant to our everyday lives. We can potentially record every experience we have, and every piece of information we touch. One potential benefit of these *digital records* is that they might address the limitations of fragile human organic memory. We use the term *organic memory* to refer to those occasions when people rely on what they can remember without the use of a memory prosthesis. This general term organic memory encompasses the use of more specific memory subsystems such as semantic, working or long-term memory.

Various ‘Lifelogging’ visions, have been proposed, starting with Bush's Memex (Bush, 1945) and including the influential MyLifeBits (Gemmell et al., 2006). These visions have led to the development of large numbers of proof-of-concept *digital record* demonstrators that are intended to support our fallible memories (Lamming and Flynn, 1994; Dumais et al., 2003; Dickie et al., 2004; Karger and Quan, 2004; Cutrell et al., 2006; Gemmell et al., 2006; Sellen et al., 2007). However, uptake of *digital records* has been slow, and few working applications have been deployed outside the laboratory. One challenge we address here is to find domains where there are strong memory requirements, where there are strong incentives to use *digital records*.

One domain of considerable promise for *digital records* is education, where there are high memory demands. In many pedagogic situations there is a need to master and reflect on

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complex novel information delivered verbally in real-time. Prior research has documented the cognitive problems that students experience in determining what is critical (and hence important to record) while simultaneously processing complex new information (Brown, 1987; Bransford et al., 1999).

Digital records might therefore be useful in freeing students from the pressures of 'not missing anything important', while trying to simultaneously comprehend novel ideas or contribute to class discussion (Brotherton and Abowd, 2004; Munteanu et al., 2008). *Digital records* also potentially allow students to be more self-directed during lectures, allowing more time for personal reflection about what they have just heard (Brown, 1987). The ability to re-access material after the lecture may also be of benefit to particular populations, e.g. non-native students who experience additional challenges of trying to master new material delivered in an unfamiliar language (Robertson et al., 2000). Furthermore, exploration of multimedia recording tools is timely, technologies such as MP3 players are now readily available, making it straightforward for students to re-listen to podcast recordings at their convenience, and many institutions are now actively experimenting with lecture recording for asynchronous learning (Hiltz and Goldman, 2005; Walker and Moore, 2005). Finally, multimedia access tools are mature, with well understood techniques developed for controlled access to complex multimedia recordings (Stifelman et al., 1993; Whittaker et al., 1994; Brotherton and Abowd, 2004; Munteanu et al., 2008).

Despite these arguments, the benefits of *digital records* in education have not yet been demonstrated. Although early studies (Brotherton and Abowd, 2004), found that *digital records* were well liked by students, there was no evidence that they led to measurable pedagogical benefits. There are also potential disadvantages to *digital record* deployment. *Digital records* may change students' learning strategies, making them less likely to attend classes, hence failing to benefit from social learning opportunities (Johnson, 1981; Hiltz and Goldman, 2005). Given these potential drawbacks, the increased deployment of these techniques make it crucial to establish whether *digital records* have direct pedagogical benefits (Hiltz and Goldman, 2005; Walker and Moore, 2005) and how they might be used most effectively in educational settings.

We therefore set out to test the benefits of *digital records* in an education setting. We developed two novel UIs that provided straightforward access to *digital records* of lectures, using student-generated handwritten or photo annotations (Figs. 1 and 2). We collected naturalistic data about *digital record* use from 98 students over the duration of a course, as well as more controlled data from 35 more students who used *digital records* to answer class quizzes. We addressed the following research questions:

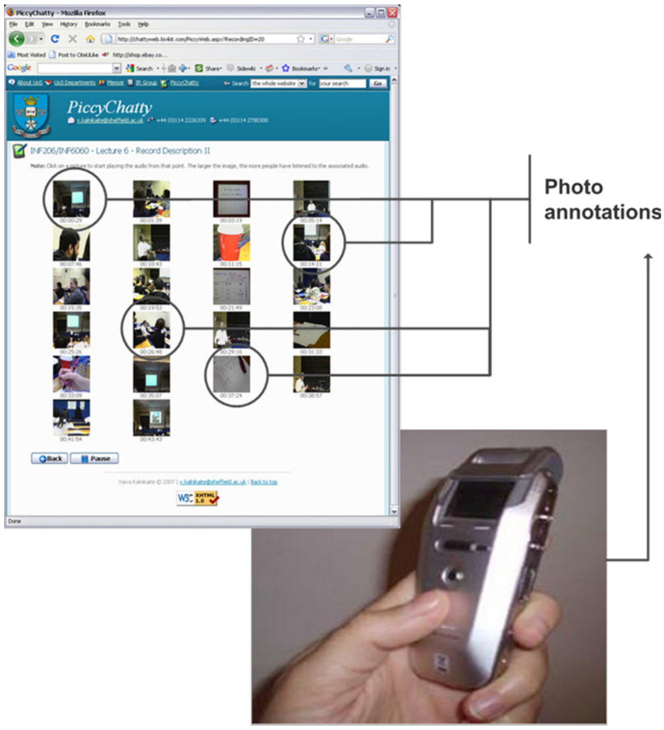

Fig. 1. Sony recorder device for capturing speech and end user photo annotations, along with PiccyWeb UI for retrieving speech using these annotations. Clicking on a photo annotation initiates playback of the speech recorded when that photo was taken.

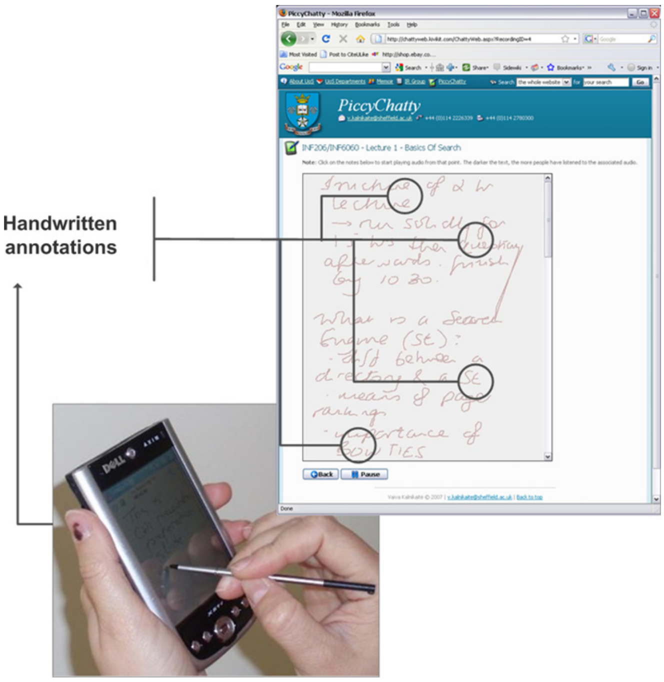

Fig. 2. ChittyChatty device for capturing speech and handwritten annotations, along with ChattyWeb UI for retrieving speech using annotations. Clicking on a digital note accesses the speech occurring when the note was taken.

Overall benefits: Will people make use of *digital records* in real-world settings? What are the main *advantages* of *digital records*? Do *digital records* help students to perform better on class assignments compared with more traditional instructional techniques such as

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handouts or personal notes? And do students prefer *digital records* to traditional tools such as handouts or personal notes?

Users: *Which* students use *digital records*, and *why* do they do so? Who benefits most from them? Do non-native speakers exploit *digital records* to re-access material they might have found initially hard to understand, or are *digital records* used as a 'catchup' device by absentee students to listen to material that they initially missed?

Exploitation processes: If *digital records* do help memory, *how* do they do so? And *when* are they used? Do students use them to answer specific course questions or to remind themselves about the gist of an entire lecture? And what types of retrieval indices are most useful in accessing *digital records*?

2. Related research

Many recent systems support multimedia capture in lecture settings. eClass (Brotherton and Abowd, 2004) integrated traditional and multimedia methods to support learning. The system supplements the regular learning experience with digital video recordings of lectures, slides, digital whiteboard activity, and personal digital notes. Evaluation surveys showed students felt access to the *digital record* recordings allowed them to participate more effectively in classes. More quantitative learning benefits were not so clear however. eClass users performed no better on assignments than those using regular teaching materials. Other similar systems have also not found huge benefits for annotated lecture recordings (Grudin and Bargeron, 2005).

Similar classroom tools that combine *digital records* with active student sharing of information include Active Class (Ratto et al., 2003), Debbie (Berque et al., 2001), Classroom Presenter (Anderson et al., 2004; Wilkerson et al., 2005), and DyKnow (Berque et al., 2004). A more traditional approach supporting handwritten annotations, NoteNexus (Harvel et al., 2005), showed increased access for materials directly related to assessments. Other research has focused on developing advanced search and browsing to provide remote access to lecture materials (He et al., 2000). The Personal Audio Loop (Hayes et al., 2004) was found to be useful in the social context of recording everyday conversations on a ubiquitous device. Yet none of these studies demonstrated extended use of access tools, or strong learning benefits.

Recent educational theory has emphasized the importance of cognitive monitoring, self-paced learning and self-direction (Brown, 1987). A *digital record* of classroom interaction can allow students to engage in more reflection about their understanding, and more active learning. As multimedia records, they might also support different learning styles (visual and auditory) (Bransford et al., 1999), as well as the possibility of seeing material in different contexts—encouraging cognitive flexibility (Spiro et al., 1992).

In addition many institutions are actively experimenting with lecture recording, either using standard recording software such as Camtasia (2008), or dedicated recording tools (Walker and Moore, 2005). Tools such as Wimba (2008), iLinc (2008), Elluminate (2008) MRAS (LeeTiernan and Grudin, 2001) or SUNY (Shea et al., 2001) are being actively deployed to support asynchronous learning. These tools offer ways for learners to remotely 'attend' lectures as these are broadcasted and provide them with interfaces to access recordings for later revision. The tools we study here are incremental extensions of these deployed technologies, providing straightforward ways for learners to access recorded lectures. Other research is now beginning to explore the implications of such deployments (Hiltz and Goldman, 2005; Walker and Moore, 2005), making our study timely.

3. Creating digital recordings

3.1. Tools

3.1.1. Creating annotated digital recordings

Prior research has demonstrated the benefits of time-indexed user annotations in supporting *digital record* access (Stifelman et al., 1993; Davis et al., 1999; Kalnikaite and Whittaker, 2007). We therefore used two access tools to capture end-user annotations: (a) the Sony Recorder (Fig. 1) which takes digital *photographs* to serve as annotations, and (b) ChittyChatty (Fig. 2) a pen-based UI that creates *handwritten* digital annotations. Every user annotation is time-stamped. Both tools also record speech, and end-users' annotations are automatically temporally co-indexed to that recorded speech (see Fig. 3), allowing those annotations to be used for controlled access to the speech. Both tools are extensions of this prior work, and we deploy these to test specific hypotheses about memory and learning.

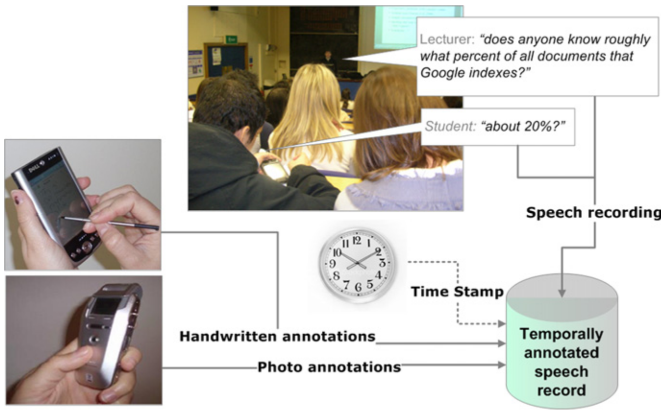

Fig. 3. Temporal co-indexing technique—the speech recording is time indexed using handwritten or photo annotations.

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3.1.2. *Accessing digital record through photo and handwritten annotations*

We developed two retrieval UIs: one for *digital record* access using photo annotations[1] PiccyWeb (Fig. 1), and one for *digital record* access using handwritten annotations: ChattyWeb (Fig. 2). Access is straightforward. Temporal co-indexing of annotations and speech means that clicking on an annotation plays back what was being said at the time that the annotation was made (see Fig. 3). Notes/photos therefore serve as high-level index to the underlying speech.

For example with PiccyWeb, if users want to access the part of the *digital record* associated with a specific topic, they visually scan for a relevant photo annotation (e.g. a photo showing a slide relating to that topic — Fig. 1). Clicking on that photo causes the system to play what was being said at the time that the photo was taken. This allows users controlled access to different parts of the verbatim content of the lecture — without having to listen to the entire recording.[2] Of course for the annotator there is a delay between hearing information and constructing the index relating to that information. After extensive piloting, we therefore introduced a short offset, so that playback starts 1.5 s before a given index was made.

3.2. *Context*

Our study ran over 13 weeks, during an Information Storage and Retrieval course. The course was introductory, covering different types of information retrieval indexing methods, search engines and how they operate. Lectures explained Boolean vs. Free text search, web search techniques such as Pagerank, search interfaces, metasearch, cataloguing methods, and the future of search. Students were a mixture of second and third year undergraduates and masters students. The lecturer uploaded to the web a powerpoint presentation of the lecture, making this available for students to access prior to the lecture. One of the authors was an instructor on the course.

Lectures took place once a week and for each 2 h lecture, one volunteer used the Sony Recorder (Fig. 1) to record the lecture — annotating the speech with relevant photos. Another volunteer used the ChittyChatty application (Fig. 2) to create a speech record of the same lecture, annotated with their own personal digital handwritten notes. Example annotations are shown in Figs. 1 and 2, respectively. While photo annotations are novel, other work has shown that digital handwritten annotations are similar to those taken using pen and paper (Kalnikaite and Whittaker, 2008).

In the first lecture, we explained the *digital record* access tools to the whole class, describing how to use them. Before each subsequent lecture, we reminded students about the existence of the *digital records* and re-described how the PiccyWeb in Figs. 1 and 2 and ChattyWeb access systems worked. Volunteer annotators were also given a brief reminder tutorial about how to generate annotations, before they began their note/photo-taking. After the lecture, the recording and annotations were uploaded to both ChattyWeb and PiccyWeb where they could be accessed by anyone in the class via the internet. Links to the annotated *digital records* were prominently displayed on the class webpage.

4. Study 1: Naturalistic analysis

4.1. *Method*

We collected *naturalistic* data about *digital record* usage for 98 students for both *handwritten* and *photo* annotations. The students were aged 19–35, 42 were women and 56 men. Sixty-two students were native English speakers and the remaining 32 were non-native. They attended the lecture once, but they could access *digital records* of each lecture as many times as they wished, throughout the course using the ChattyWeb and PiccyWeb interfaces. We logged details of access sessions for all participants, including their frequency, duration, as well as when they occurred and which types of annotations (photo/handwritten) were used for access.

We analyzed logs to understand the basic characteristics of access sessions and how participants used the *digital record* recordings: did they focus on one part of the recording, e.g. to answer *particular questions* about a *part* of a lecture, or did they typically have longer sessions to get the *gist* of the *entire* lecture? We also collected data about students' *native language* to determine whether non-native speakers used the system more. We also recorded class *attendance* to determine whether non-attendees relied more on the digital record to compensate for missing a class. Finally, we wanted to determine the learning benefits of accessing recordings. Did students who accessed recordings more often obtain better *final grades* for the course? We collected informal feedback via an email site, and through anonymous surveys circulated to the students to gather their opinions of the *digital record* system.

4.2. *Results*

Overall users were very positive about the system. People were happy to volunteer for the role of official 'note-taker' — whether this was to generate handwritten or photo annotations. Participants found it straightforward to use the system to access the *digital record*, and generally anonymous survey comments were enthusiastic.

[1]Note that we use the term '*photo annotation*' to refer to the fact that the photo serves to tag/index the underlying speech. This form of annotation is not to be confused with many digital photography applications that allow users to add textual descriptions that serve to tag a photo.

[2]The practice of using cameras to generate visual reminders is becoming increasingly common, e.g. people photographing important slides in a presentation using phones or digital cameras. Unlike our application, these photos are standalone reminders and do not provide controlled access to what was being said at the time the slide was shown.

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Several users pointed out that *digital records* encouraged active exploration of the lecture, the annotations helped jog their memory and allowed them to discover information they had originally missed. They also used the controlled access supported by temporal indexing to access different aspects of the lecture:

"*[Digital records] Gives you the chance to move around … in the lecture, as well as jog your memory in some cases by seeing the pictures of the lecture at different points.*"

"*After listening to some of the audio there were things that I missed and it has been a useful review.*"

Others felt that *digital record* information was more compelling and engaging than standard handouts or notes, because materials were multimedia. Powerpoint slides or personal notes were enriched by accompanying audio, and listening to audio was thought to be more engaging than simple slides or notes. Some students made additional notes while listening to the speech recordings. *Digital records* therefore provided support for different learning styles offering the opportunity for verbal as well as textual revision:

"*Digital record is much nicer to listen to rather than staring at loads of text. It is easier to make notes while listening rather than looking back and forth at a computer screen. Using digital record is much more interactive than just looking at standard notes so does tend to help keep my attention, as I prefer to be doing something interactive, than just reading through notes.*"

Even when students had missed a lecture they felt that *digital records* provided a sense of 'being there' that traditional handouts did not afford:

"*[With digital record] You have a sense of being in the lecture even if you missed it.*"

Some participants also pointed out the implicit *social* learning benefits of *digital records*: *digital records* provided insights into what the annotators thought was important. By scrutinizing the notes or photos, students could understand and reflect on what others had thought was critical, which may differ from their own views of what was important:

"*I also feel that with other people making notes you get an insight in what they think, more than one opinion is very useful.*"

However, there were suggestions that *digital records* might induce changes in learning behaviour: various students speculated that *digital records* led them to attend fewer lectures, or to pay less attention during lectures they were at:

"*The availability of [digital records] has made me much less worried about missing lectures as, especially [with] textual annotations, you can listen and make your own notes by listening as it's just the same as being in the lecture.*"

"*In parts [of the lecture] digital records encouraged me to not pay as much attention as I knew that I would be able to look through them at home after the lecture.*"

4.2.1. Session characteristics

Our basic unit of analysis was an *access session* — defined as an unbroken interval spent accessing a specific lecture. If a student accessed another lecture or logged off, that session was deemed to have ended. We excluded sessions longer than 3 h, containing fewer than 5 clicks. Here it was assumed that participants had moved away from their machine and forgotten to close the browser.

There were large differences in access patterns between participants. Some accessed *digital recordings* multiple times during the course, others less so. However, out of the class of 98 people, we had 54 actively accessing the system, i.e. for more than one session (making 59% uptake of *digital record* technology). These active users had 7.74 sessions on average, overall spending 44 min on average using the system (see Table 1).

First we analyzed the *types* of sessions for active users, as this offers clues about what functions the system served (see Table 1). The predominant pattern was to access a particular lecture multiple times for relatively short sessions, rather than listening to an entire lecture without interruption. This pattern of multiple operations occurring within a relatively short session, suggests the main use of the system was to access specific material *within a lecture* rather than to get the *gist of an entire lecture*.

4.2.1.1. When do students access the system?. We next looked at what *points in the course* students most accessed the system. Fig. 4 shows the total number of system accesses for all lecture recordings during each week of the

Table 1
System usage for active users (students with more than one access session) showing access behaviour for native and non-native speakers.

	Mean	Std. deviation
All active users		
# Sessions	7.74	3.24
Views/session	1.48	0.78
Clicks/session	12.10	5.36
Mins/session	7.80	5.45
Native speakers only		
# Sessions	2.59	1.54
Views/session	0.12	0.33
Clicks/session	5.59	6.77
Mins/session	1.75	4.98
Non-native speakers only		
# Sessions	9.88	14.37
Views/session	0.16	0.37
Clicks/session	14.80	20.37
Mins/session	10.31	32.17

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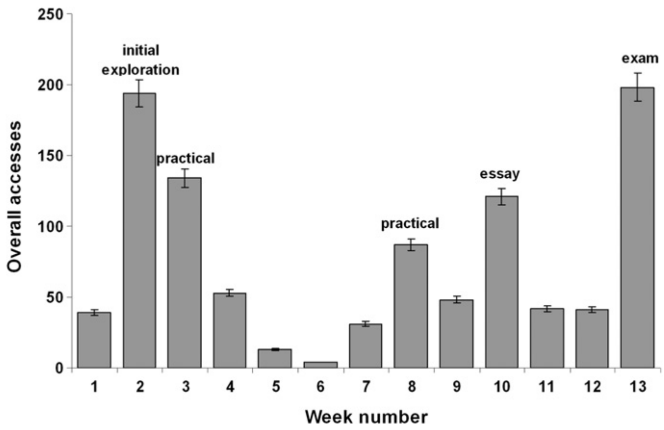

Fig. 4. Overall frequency of system access over the duration of the course, showing the relation between course evaluations and increased access behaviours.

course. Thus in week 13, there were 193 accesses of all course lectures. There is a clear relation between active system usage and coursework evaluations. There was an initial period of exploratory system activity in week 2, just after the system was introduced. Coursework evaluations occurred in weeks 3, 8, 10 and 13, and on each occasion, we saw greater system use. These data support the view that the system was being actively and repeatedly used to prepare for coursework evaluations. User comments support this: "*I mainly used [digital record] in order to do the tutorial and other coursework.*" The importance of the system as a revision aid was further demonstrated by the fact that a system failure during week 13 (just before exams) led to a flurry of emails requesting that the system be reinstated as soon as possible.

4.2.1.2. Who uses the system and why?. For all students, not just active users, we next examined whether *non-native speakers* made more use of the digital record. The results (see Table 1) are striking and confirm our hypothesis: non-native students make far greater use of the system. They both had a larger number of sessions (one way ANOVA: $F(1,96) = 6.35$, $p < 0.01$), and also a greater number of accesses ($F(1,96) = 5.41$, $p < 0.02$). Because of these large differences between native and non-native students we analyze the two populations separately in our subsequent analyses. It seems that non-native students made greater use of the system because it allowed them to revisit information that they had missed during the lecture because of their lack of fluency in English. One overseas student commented:

> "*When [digital records] are used in lectures, I find I can concentrate more than with traditional methods, because I know that if I miss something important, the lecture can be listened to again. This is also a benefit if I've not fully understand what was being said as I can listen to the lecture at my own pace.*"

Next we looked at the relationship between *attendance and system usage*. We expected that students who attended fewer lectures would make much greater use of the system. As expected, there was a strong correlation between the number of lectures missed and the number of access sessions. However, this was true only for native students ($r(35) = 0.36$, $p < 0.03$). There was no overall difference in attendance between native and non-native students ($F(1,96) = 3.1$, $p > 0.05$), so non-native students' greater use of the record does not seem to result from greater absenteeism.

4.2.2. Effects of system use on course performance

We then explored the relationship between system usage and overall student performance on the course. Given the large differences in access behaviours between native and non-native students, we conducted two separate linear regression analyses: one for each population.

We included the following independent variables to characterize system use: # sessions, # access clicks/session, # views/session, total time using the system, session length. We also included a *general measure of student ability* (their last year's general score for their entire degree) as another independent variable. This was to control for the possibility that more able students might be more motivated to use the system, making their higher marks on this course the result of their inherent ability rather than system use. These variables were regressed against the dependent variable of overall mark for this particular course.

The overall regression model for native students is shown in Table 2. It is highly significant (R squared = 0.744, $p < 0.001$), showing that the independent variables in the model combine to strongly predict course mark. However, only two of the independent variables (degree score and # sessions, both bolded) are individually significant. As expected, students' overall ability/motivation (as measured by last year's degree score) predicts their final mark for this course ($p < 0.001$). More importantly, when we factor out this ability/motivation, the number of *digital record* sessions still predicts their mark for this course ($p < 0.05$). Thus for native students, we can conclude that greater system usage promotes

Table 2
Regression model showing user behaviours and general ability as predictors of final course mark for native students. Significant variables in bold.

Independent variable	Standardized coefficient, β	t	Sig.
(Constant)		−3.340	0.002
Last year's degree score	**0.879**	**8.178**	**0.000**
# Sessions	**0.439**	**2.118**	**0.043**
Clicks/session	−0.148	−1.010	0.321
Views/session	0.751	1.132	0.216
Minutes	−1.024	−1.024	0.245
Mins/session	0.577	1.151	0.223

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higher coursework scores, when we control for overall ability.

We conducted a second regression with the same variables for non-native students. There was no relation between system usage and overall course scores, even when we controlled for overall ability. Several overseas students suggested a possible reason why the system may not have directly improved scores. Despite being positive about the system, they noted that the audio quality of the recordings was not high, which made it hard for them to understand what was being said in the recordings. Another possible reason for the lack of effects is that the extensive use of the system may have led to a ceiling effect for non-native students, as they accessed it more frequently and spent a lot more time using the system than native speakers.

4.2.3. Which indices are used most, photos or handwritten text?

On average users annotated using 174 words and 60 photographs. As in prior work, digital handwritten notes seemed to be very similar in character to pen and paper notes — capturing key points and terms from the lecture (Kalnikaite and Whittaker, 2008). When we talked to annotators, they described three main motives for taking photos: (a) key slides to capture verbal discussion associated with these; (b) people who asked questions; and (c) images of surrounding people or the lecture theatre to record the context of the lecture.

We compared use of the two types of indices. Overall, people accessed *handwritten annotations* more than photo *annotations* (means 4.41 vs. 2.49, one way ANOVA $F(1,96) = 2.32$, $p < 0.03$), and they spent more time listening using *handwritten annotations* than with *photo annotations* after clicking (means 16.95 vs. 7.98, one way ANOVA $F(1,96) = 2.56$, $p < 0.01$).

This behaviour is consistent with subjective user feedback. People felt *handwritten annotations* provided more fine-grained indices when scanning for relevant information. With *photo annotations* it seemed more difficult to find an appropriate visual index to the underlying speech. In addition, certain photos such as contextual images were not directly useful for accessing specific parts of the lecture:

> "*The [photo annotations] were not very visible and sometimes only showed photos of the slides so just the set of slides would have been preferred. However, the [handwritten annotations] was very useful as they were practically an in-depth look into the slides as the lecturer is explaining the slides.*"

We thought that non-native students' lack of linguistic fluency may make it harder for them to interpret others' scribbled annotations making them more reliant on photo indices. However, the opposite was true: non-native speakers were more reliant on *handwritten* annotations than native speakers ($F(1,96) = 5.95$, $p < 0.02$), possibly because they used the system more overall.

5. Study 2: Controlled quiz

The naturalistic data offered strong evidence of when, how and who made use of the *digital record* system. In our next study we wanted to *quantify* these effects under more controlled conditions, and to identify the *mechanisms* by which the effects were achieved. We did this by assessing student performance with and without *digital record* on a series of specific class quiz questions that probed knowledge of material delivered in previous lectures. The previous study had also suggested that non-attendees made more active use of *digital record* for lectures they had not attended in person. We therefore wanted to determine whether non-attendees used *digital record* in a different way from attendees and the extent to which they were able to compensate for their absence by directly accessing information from the *digital record*. In this study we focused on native students as they had shown greater benefits of system use in the previous study. The specific research questions we addressed were therefore:

- To what extent does *digital record* improve student performance compared with traditional tools such as handouts and personal notes?
- Can *digital records* compensate for missing a lecture, i.e. can non-attendees use the *digital record* to access information from lectures they missed?
- Which annotations provide better retrieval indices, photos or handwritten text?
- Does having a *digital record* lead students to change the strategies they use for accessing course information, and if so how?

5.1. Quiz questions

We asked our participants to individually answer four specific questions from each of four previous lectures. The lectures had been presented by the same professor, who also generated the quiz questions. We conducted a pilot to ensure the questions could be easily understood, were of comparable difficulty and did not contain any unfamiliar or unusual terms. Questions were chosen so that they could not be answered directly from lecture notes (to prevent participants from answering questions simply by reading the lecture handouts). An example question was: "*How do search engines match a document to a query?*"

5.2. Procedure

The quiz was run using a custom built website. Students were first given a general description of the quiz, the questions and the ChattyWeb and PiccyWeb systems. We then gave them a brief hands-on tutorial on how to use each interface.

Participants had access to *handwritten annotated digital records* using ChattyWeb for half the quiz questions and for the other half access to *photo annotated digital records*

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using PiccyWeb. The annotations had been generated by two students who did not participate in this study. Order of presentation of these user interfaces was counterbalanced across students. For all questions, they also had access to *traditional reminders:* we provided them with the relevant handouts for each lecture and they were asked to bring their own personal lecture notes along to the quiz. Of course students who had missed specific lectures did not have personal notes for those lectures. Participants were also told which lecture the questions were generated from. They answered quiz questions on web-based forms. After the quiz they rated the interfaces and compared them with traditional reminders (such as handouts/personal notes) along various usability and efficiency dimensions.

5.3. Measures and variables

We collected the following data:

Quiz score: Accuracy for each question was scored in the following way. We first generated a target answer for each question, by having two graders, blind to the experimental hypotheses, listen to the lecture recordings and read the relevant lecture notes. The graders agreed on the target answers, specifying keywords and context that needed to be present in each answer. Quiz scores ranged from 0 to 5 depending on how much of the target answer the user specified. For instance, if an answer included all target keywords (or their synonyms) and context, it received a maximum score of 5. Partially correct answers received a proportion of the score depending on the number of keywords and context answered. Scoring was carried out independently by the judges, and disagreements were referred to a third judge for resolution.

Retrieval strategy: We identified three retrieval strategies. Students could answer questions using: *digital records*, traditional reminders such as lecture handouts or personal notes (*traditional reminders*), or their unaided *organic memory*. We use the term organic memory to refer to those occasions when people rely on what they can remember without the use of a memory aid. This general term organic memory encompasses the use of more specific memory subsystems such as semantic, working or long-term memory. After each question, we asked students to note which of these strategies they had used to answer it. *Organic memory* was interpreted strictly as involving neither *digital record* nor *traditional reminders*, and if students used both *digital record* in any way (such as combining it with *traditional reminders*), this was classified as *digital record*.

Attendance: We noted whether each student had been present at the lecture related to the specific quiz question — allowing us to examine the effects of attendance on performance and response strategy. This information was available from class attendance lists.

Index type: For each question, users either had access to *handwritten* or *photo digital record* annotations.

Subjective evaluation: After the quiz, we gave participants a brief survey, asking them to compare retrieval with *digital record* versus *traditional record*. They were asked questions about (a) Benefits, (b) Preferences, (c) Interest, (d) Attention and (e) Attendance. Responses were generated as 5-point Likert scales. In addition, we asked open-ended questions about what participants perceive to be the key differences between the tools they had used and why they preferred one to the other.

5.4. Users

Thirty-five student volunteers took part (10 females and 25 males, aged 19–35). They had no prior knowledge of the project or our research hypotheses. The volunteers took the same class. None had prior experience using handwritten or photo annotations, but obviously all had extensive experience of traditional reminders and their own organic memory. All were native speakers of English.

5.5. Hypotheses

We had four hypotheses.

H1: *Effects of digital recording use on performance*: We expected more accurate responses when digital record was used, compared with traditional reminders or organic memory. This is because digital records provide controlled access to a verbatim record of what was said.

H2: *Effects of attendance on performance*: We expected students to perform better when they attended the lecture. This should be independent of the retrieval strategy used.

H3: *Index utility*: we expected people to perform better using handwritten indices because these offer more fine grained access to the digital record than photos.

H4: *Effects of attendance on digital record use*: We expected people who did not attend a lecture to be more reliant on digital record because they would have no recollection (organic memory) of the information presented, nor would they have access to traditional reminders such as personal notes. In contrast, attendees should be more likely than non-attendees to use both organic memory and traditional reminder.

5.6. Results

H1 and H2 both concern performance, so we evaluated both in a single ANOVA with Response Quiz score as dependent variable, and Retrieval Strategy and Attendance as independent variables.

One concern with this analysis is a potential confound of *self-selection*, i.e. stronger students are more likely to attend lectures and to get higher marks on the quiz because of ability, regardless of the tools used. We therefore included in this analysis only those students who had attended *some but not all* of the relevant lectures. We were therefore able to compare the effects of attendance as a *within subject variable*. The analysis thus compares the

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performance of *the same student* for lectures they had attended versus lectures they had missed, and thus avoids this confound.

H1: Does access to a digital records increase performance compared with other retrieval strategies?

For users who had attended some but not all lectures, we compared retrieval quiz scores: (a) when they used *digital record*, (b) when *traditional reminders* were used (i.e. people used handouts or their personal notes), (c) when they relied on their own memory (*organic memory*). The results are shown in Fig. 5.

The ANOVA showed a main effect for Retrieval Strategy ($F(2,47) = 8.62$, $p < 0.001$). Planned comparisons confirm H1 showing benefits for *digital record* over *organic memory* ($p < 0.0001$), and for *digital record* over *traditional reminders* ($p < 0.02$). There were no differences between *traditional reminders* and *organic memory*. Providing a *digital record* therefore helps students better than traditional access tools, with students performing 16% better overall using *digital record*. Not only does this show the utility of *digital record* it also shows the potential value of others' note- or photo annotations; people are able to exploit annotations taken by someone else to navigate to an important part of a lecture.

H2: How is performance affected by attendance and retrieval strategies?

The above ANOVA also showed a main effect for Attendance ($F(1,47) = 15.22$, $p < 0.0001$). As predicted, students performed better when they attended a lecture. Planned comparisons also confirm that when students attended they remembered more using *organic memory* ($p < 0.05$). There was also a suggestion that attendees were better able to exploit *traditional reminders* ($p < 0.07$). Finally, even though *digital record* provides access to a verbatim record, attendees were still better able to exploit this than those who missed the lecture ($p < 0.01$). User comments support this: "*I felt less need to go to lectures because the recordings were available, however, I feel there is still a greater benefit from attending the lecture.*"

One question arising from the results is why the non-attendees should use *organic memory* at all. Post hoc interviews with participants showed that non-attendees' frustration at being unable to answer questions using either *digital record* or *traditional reminders* led them on occasion to guess likely answers — behaviour they classified as *organic memory*.

Overall the results show clear benefits to a verbatim record. Whether students attended or not they performed better with the *digital record*, than either *traditional reminders* or *organic memory*. However, attendees were better able to exploit both *digital record* and *traditional reminder* to respond more accurately to questions. As one user commented: "*I liked [digital record] to find out what I missed.*"

H3: Does index type affect retrieval?

H3 was not confirmed. Users performed no better using handwritten than pictorial indices ($F(1,22) = 0.22$, $p = 0.64$), even though many users felt that handwritten annotations provided more detailed indices than photos.

H4: How does attendance affect access behaviours?

We conducted a second ANOVA with Frequency of Access as dependent variable, Retrieval Strategy, Index Type and Attendance as independent variables. We included all students, as we were interested in access behaviour so there was no need to control for confounds of attendance with ability/motivation. The results are shown in Fig. 6. Confirming H4, there were main effects for Attendance ($F(1,99) = 5.53$, $p < 0.02$), and Strategy ($F(2,99) = 25.78$, $p < 0.0001$), and a significant interaction between Strategy and Attendance ($F(2,99) = 25.78$, $p < 0.002$). Planned comparisons showed, as predicted, that attendees were more likely to use *organic memory*

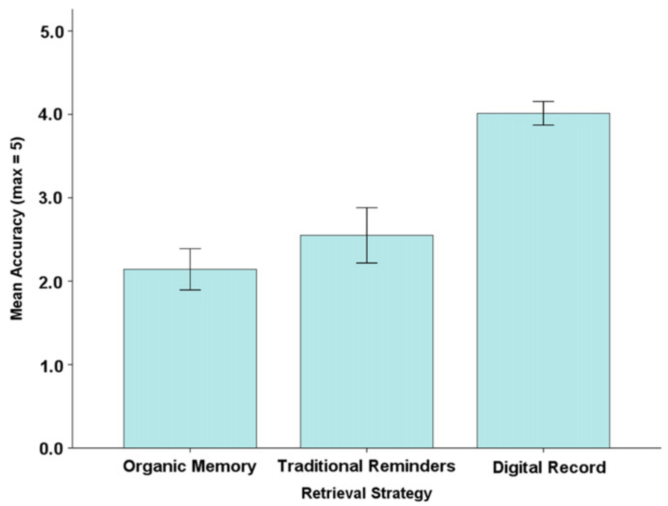

Fig. 5. Quiz Accuracy score for different Retrieval Strategies (OM = organic memory, TR = traditional reminders and DR = digital record).

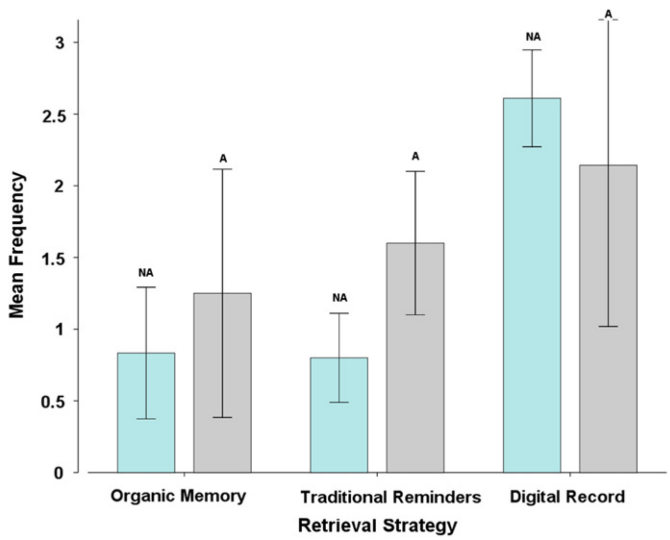

Fig. 6. Mean frequency for non-attendees (NA) and attendees (A) per Retrieval Strategy.

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($p < 0.05$), and to use *traditional reminders* ($p < 0.0001$) than non-attendees. However, contrary to our expectations, non-attendees were no more likely to use *digital record*. This may have been because non-attendees were unclear about which parts of the *digital record* to access, leading them to have relatively few, but long, access sessions. Overall the results show that attendance affects strategy use, with non-attendees being forced to rely on *digital record* to access information.

5.7. Subjective user feedback

We also analyzed students' subjective feedback about *digital record* tools and how they compare with *traditional reminders*, as illustrated in Fig. 7. The results are highly positive. For various Likert judgments, users judged that *digital records* were more useful than *traditional reminders* ($t(36) = 2.47$, $p < 0.02$). They also expressed an overall preference for using *digital record* to access lectures ($t(36) = 3.90$, $p < 0.0001$). They judged that *digital record* made lectures more interesting: ($t(36) = 3.85$, $p < 0.0001$), but felt they paid equal attention in lectures regardless of whether they could later use *digital record* or *traditional reminders* ($t(36) = 1.45$, $p > 0.2$). People also felt less worried about missing a lecture knowing that it was recorded on *digital recordings* ($t(36) = 3.07$, $p < 0.004$).

6. Study 3: Quiz replication

A problem with the quiz study 2 is that some of the results are ambiguous, and certain predicted effects did materialise. One interpretation of Fig. 5 is that *digital record* is superior to *traditional reminders*, and *traditional reminders* do better than *organic memory*, but this could simply follow from the way that we measured *digital record* and *traditional reminder* usage. In the quiz, people were recorded as using *digital records* whenever they used any combination of memory strategies (*digital record*, *traditional reminder*, *organic memory*) that included *digital record*. In other words, using *digital record* with *traditional reminders*, or *digital record* with *organic memory*, *digital record* with *traditional reminders* and *organic memory*, as well as *digital records* alone were all scored as *digital record* responses. In the same way people recorded as using *traditional reminders*, when they used *traditional reminders* alone, as well as *traditional reminders* with *organic memory*. Our results showing that *digital records* outperformed *traditional reminders* could therefore be a simple artefact of the fact that people had more resources available to help memory in the '*digital record*' situation (i.e. any combination of tools including *digital record*) than in '*traditional reminders*' (any combination of tools involving *traditional reminders*), and more in both conditions than the *organic memory* condition. We therefore conducted a replication of the quiz study where we changed the way that we recorded and measured strategy use in order to tease out these competing explanations. We classified as *digital record* use, those cases where only *digital record* was used. We defined *organic memory* and *traditional reminder* use in the same way. We distinguished these 'pure' cases from those in where multiple strategies were used: e.g. any combination of *traditional reminders*, *digital record* and *organic memory*, and again tested the effects of memory strategy on retrieval.

In addition our first quiz study indicated that notes based indices did not outperform photos. Again there may have been an error in the way that we measured actual strategy usage. One possible explanation for this is that we compared photos versus notes by *condition* rather than by actual strategy use. Some users could therefore have been relying on *organic memory* or *traditional reminders* to answer questions, even though pictures or notes were potentially available. In our replication we therefore compared the effects of picture vs. notes indices based only when *digital record* was actually used.

In our replication we repeated the basic quiz study, but with more refined measurement, in order to control for some of these confounding explanations. We again used student volunteers from the same class (but 2 years later) using the same materials, lectures and lecture order. There were 43 volunteers overall, 7 females and 36 males, aged 19–35. Again all were native English speakers.

We modified the procedure in the following ways:

Students were asked to specify whether they had used *digital record*, *traditional reminders*, *organic memory*, or a *combination* of these to answer the question. We were therefore able to distinguish the separate effects of each tool on memory.

This contrasts with the first study in which the *digital record* response could have meant the use of only *digital record* or *digital record* in combination with *organic memory* and *traditional reminders*. We could also tell exactly when a picture or note was used as an index.

We tested a simplified set of hypotheses:

H1: *Effects of digital recording use on performance*: We expected more accurate responses when a digital record

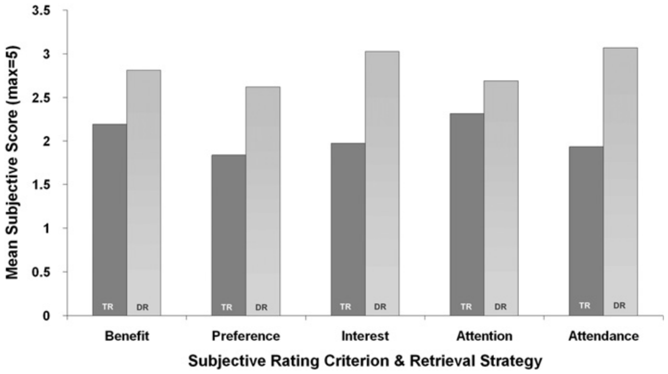

Fig. 7. Subjective user ratings (TR = traditional reminders and DR = digital record).

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was used, compared with traditional reminders or organic memory.

H2: *Index utility*: We expected people to perform better using handwritten indices because these offer more fine grained access to the digital record than photos.

H3: *Effects of attendance on digital record use*: We expected people who did not attend a lecture to be more reliant on a digital record because they would have no recollection (organic memory) of the information presented, nor would they have access to traditional reminders such as personal notes. In contrast, attendees should be more likely than non-attendees to use both organic memory and traditional reminders.

We again analyzed the data using ANOVA with Attendance and Retrieval Strategy (*digital record*, *traditional reminders*, *organic memory*, *combination*) as independent variables and Retrieval Score (Accuracy) as dependent variable.

H1: Does access to a digital record increase performance compared with other retrieval strategies?

The results are shown in Fig. 8.

There was an overall effect of Retrieval Strategy ($F(3,171) = 37.13$, $p < 0.0001$), and all planned comparisons tests between the different strategies were significant ($p < 0.01$) except for that between *traditional reminders* and *combination* ($p > 0.1$). These results clarify the initial quiz study, in showing that when people used pure *digital record* (i.e. *digital record* use excluding cases where this is in combination with *organic memory* and *traditional reminders*), they perform better than pure *traditional reminders* (*traditional reminder* use excluding cases where this in combination with *organic memory*), and both are better than *organic memory*. Using a combination of resources is worse than *digital record* alone, and no better than *traditional reminders*. This may be because both *traditional reminders* and *organic memory* are less accurate than *digital records*, *traditional reminders* are an abstraction, and finally, *organic memory* may include memory errors.

We also conducted a second analysis to look at whether *digital record* alone was superior to a combination of *traditional reminders* plus *organic memory*. We wanted to see whether new *digital recording* technology alone could outperform a combination of old 'technologies'. The results are shown in Fig. 9. Overall *digital record* outperformed the combination of older 'technologies' ($F(1,136) = 109.02$, $p < 0.0001$).

H2: Does index type affect retrieval?

Next, we conducted an ANOVA comparing retrieval scores for each index type, analysing only those situations in which people had actually made use of the *digital record* index rather than using *traditional reminders* or *organic memory*. There was a main effect of Retrieval Index ($F(1,93) = 501.8$, $p < 0.001$). However, contrary to our expectations, users performed better with pictures than with notes: the respective mean for pictures was 3.9 and for notes 3.7.

How can we explain this? Pictures may offer a better global overview of the lecture allowing students to quickly identify relevant parts of the lecture. In contrast they may have to scan through multiple pages of handwritten notes in order to identify relevant retrieval indices.

H3: How does attendance affect access strategy?

We conducted a final ANOVA with Frequency of Strategy Usage as dependent variable and Attendance and Strategy Type (either *digital record*, *traditional reminder*, *organic memory* or *combination*) as independent variables. The results are shown in Fig. 10. Confirming H3, there were main effects for Retrieval Strategy Type ($F(3,171) = 33.00$, $p < 0.0001$), Attendance ($F(1,171) = 6.11$, $p < 0.01$) and an interaction between Attendance and Retrieval Strategy ($F(3,171) = 3.18$, $0 < 0.03$). Planned comparisons looking at the effects of attendance show that as expected attendees do marginally better than non-attendees for *organic memory* ($p < 0.06$) and for *combination* ($p < 0.01$), but as in the previous study *digital record* usage was not affected by attendance ($p > 0.1$). Again this

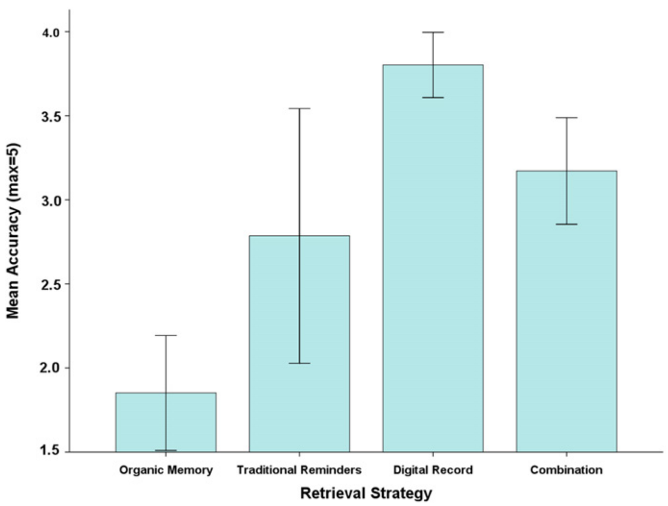

Fig. 8. Quiz accuracy scores from study 3 for different Retrieval Strategies.

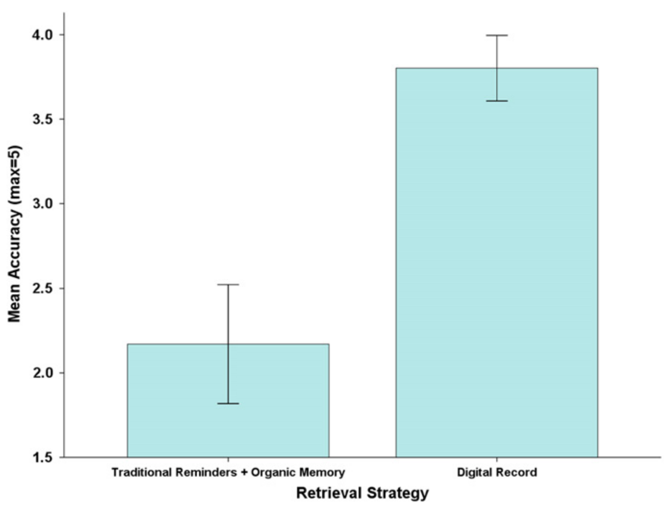

Fig. 9. Quiz replication accuracy scores for old technologies (*traditional reminders* plus *organic memory*) vs. new technologies (*digital recordings*).

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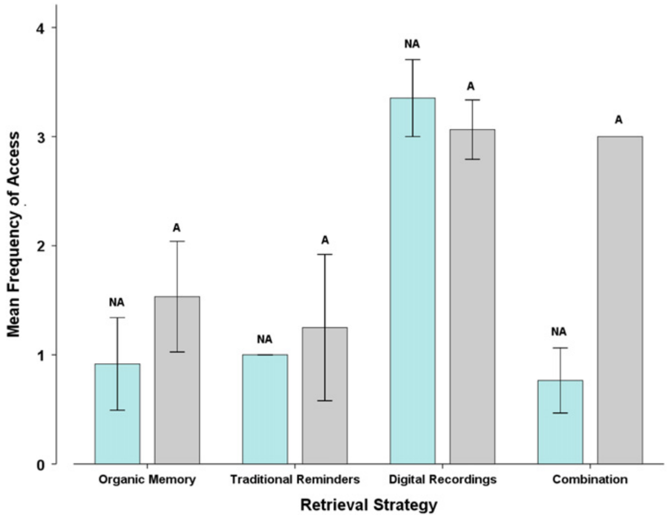

Fig. 10. Mean frequency of strategy usage for non-attendees (NA) and attendees (A) for each Retrieval Strategy in study 3: quiz replication.

may be because non-attendees have longer sessions using *digital records*. Alternatively attendees are exploiting *digital record* because they know that it is an effective way to access information, even though they could use *traditional reminders* or *organic memory*.

7. Conclusions

We evaluated two novel prosthetic memory aids for student learning. In contrast to early work where results were mixed, our results provide strong evidence for the utility of such tools. *Digital records* allow students to perform better on quizzes than existing tools such as *traditional reminder* and *organic memory*, and *digital records* were used strategically throughout the course when students had assignments. They were also accessed extensively by non-native students, and using them helped native students improve their grades. *Digital records* were also considered more enjoyable to use than traditional teaching aids. Students were intrigued by the new tools, and once they discovered their full functionality and benefit, they were motivated to use them, particularly to help with their coursework and exams. The results therefore have significant implications for the deployment of *digital records* as educational technology.

Digital recordings did not serve as a direct *substitute* for attendance. *Digital records* were a verbatim verbal record, making it possible for non-attendees to identify anything that was said from the *digital record* of a lecture they had not attended. But our results showed that although *digital records* allowed non-attendees to answer at least some quiz questions effectively, attendees performed significantly better on quizzes. The naturalistic analysis also confirms that digital records do not directly substitute for attendance. Although non-attendees were more likely to access *digital records* outside lectures than attendees, there was little use of *digital records* to listen to an entire lecture. Instead, confirming other work (He et al., 2000), rather than listening to an entire lecture, naturalistic digital record usage tended to be for specific questions or restricted parts of the lecture. These results suggest that providing *digital recordings* will not lead to students increasingly relying on recordings rather than attending lectures. However, the same results show that care needs to be taken when deploying asynchronous learning technologies so that students understand how best to exploit them — as a valuable adjunct to classroom attendance and discussion, rather than a direct substitute for attending.

As we anticipated, the *digital record* was also used more often by non-native English speaking students to re-listen to lectures. However, only native language speakers performed better in their coursework when they used the *digital record*. User comments throw some light on this. It may have been that audio recording quality was not good enough for non-native speakers to extract enough information from their re-listenings. They may also have experienced ceiling effects in their extensive use of the technology. Given the prevalence of international education, this is an important finding that needs to be better understood and we intend to conduct more studies to explore it further.

One issue is the extent to which the technologies we used could have affected our results. This is a critical consideration as other work has shown that specific properties of a digital prosthesis affect its usage. For example, elsewhere we have shown that use of prostheses is affected by the *efficiency* of the device (the speed at which information can be accessed), as well as properties of the record generated by the device: whether or not the device captures *verbatim* information versus an abstraction of events (Kalnikaite and Whittaker, 2007). Our results may also have been influenced by the lower level properties of the tools we studied here. For example, ChattyWeb indices were handwritten, but we could instead have used tools such as OneNote that allow recordings to be co-indexed to textual notes. Textual indices are more easily readable and searchable which might promote more use of indices. However, this requires that users deviate from their normal practice of taking handwritten notes, and this may alter both the number of type of notes that participants generated. We could also have made notes searchable by using OCR to render notes into text. Again this might have led to greater use of indices. Nevertheless it seems unlikely that these would make a major difference to our results.

Many recent educational applications have incorporated technologies similar to those evaluated here. Consequently our results offer significant information about the practical design of technologies that people are now beginning to use in real situations. There are extensions that might be built onto current technology, that are suggested by our results. In the spirit of Web 2.0 and collaborative tagging, future technologies might combine *multiple* users' annotations of a lecture (Davis et al., 1999; Berque et al., 2001; Ratto et al., 2003). Annotations that are common might be used to provide keyword summaries of lectures, or these could

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be accessed via a tag cloud. Similarly, our retrieval interfaces might be modified to indicate annotation access *popularity*, with more frequently accessed annotations being made more salient, e.g. by increasing the relative size of popular photo images or bolding frequently accessed notes. In other work we have extended our tool to incorporate popularity based indexing, and demonstrated the utility of popularity based access (Kalnikaite and Whittaker, 2008). Finally, content analysis could provide ways to automatically index key lecture events such as main points (Tucker and Whittaker, 2006), or even visual summaries (Foote et al., 1998). These might supplement student annotations, and improve the browsability of the record.

There are important theoretical lessons to be drawn from these results. They are consistent with other prior work (Kalnikaite and Whittaker, 2007; Sellen et al., 2007) which suggests that memory aids are best used *in synergy* with existing tools, rather than as a *replacement* for them. We found strategic use of *digital recordings*. Most students did not stop attending lectures and rely exclusively on verbatim recordings. Instead the naturalistic data suggested many were trying to optimize what they had picked up in lectures, focusing on specific issues or parts of the lecture they had not understood. In particular, they made strategic use of the tool when faced with the course assessments. Consistent with other recent work (Kalnikaite Sellen et al., 2010), *digital recordings* should therefore be seen as acting as *retrieval cues* for partially learned materials, and not as a direct substitute for that learning experience. Finally, our results suggest where *prosthetic memory* technologies might be best deployed. One problem with many early studies of *prosthetic memory* and Lifelogging was that it proved difficult to find practical applications for *digital recording* technologies — where there were real benefits for remembering everyday experiences. Our results here show however that education is an important practical area where people experience significant memory demands, and one in which *prosthetic memory* tools can offer important benefits.

Recordings might mediate and improve memory in various important ways. Students commented that it was more compelling to interact with materials that included spoken information, rather than simple slides or personal notes. Certain learners may also find it more straightforward to understand materials delivered verbally, than the purely visual materials they currently have available. Others we noted were processing information in a multimodal fashion. When revising or preparing coursework, they would simultaneously play the lecture speech, at the same time as browsing though the related slides or their own notes. Thus the same content was being presented in multiple channels simultaneously, which has been shown to be beneficial for memory encoding (Delogu et al., 2009). In addition we provided a rich set of ways for students to retrieve information: they could access spoken information using notes or images, depending on which aspects of the lecture they remembered better. Notes provided a transcription of what was said whereas images could capture the content of slides but also the context of the lecture theatre. Such contextual information might provide different types of memory cues. Having lectures as an external accessible representation might also facilitate various cognitive functions including more explicit encoding of information (Kirsh, 2009).

Finally, by providing *digital recordings*, we might enhance students' learning experiences, reducing current pressures they feel to record all that goes on and allow them to explore new material at their own pace (Bransford et al., 1999; Brotherton and Abowd, 2004). By reducing the need to obsessively prepare for retrieval, we can free students to participate more in classroom discussions, allowing them to focus on important new concepts, rather than attempting to record all that they see and hear.

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