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Library inventory using a RFID wand: contribution of tag and book specific factors on the read rate

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Abstract

Purpose – Low read rates are a general problem in library inventories. The purpose of this study is to examine the factors that contribute to the success of library inventory by means of a radio-frequency identification (RFID) inventory taker. The factors investigated were tag position, tag orientation, book thickness, tag density (related to thickness of a sequence of books) and position on the shelf.

Design/methodology/approach – A total of 210 books were placed in eight random permutations on three fixed book shelves. For each configuration, the RFID tags were read forty times. The resulting data were analysed by means of a generalized linear model, relating the combined contribution of tag position, tag orientation, book thickness and position on the bookshelf to the read rate.

Findings – The tags positioned directly next to the spine were always read, but those near the opening of the book (far from the spine and inventory reader) were not always read. Considering only books with tags near the opening, tag orientation and position on the shelf appeared not to be related to the read rate, while book thickness, thickness over three books and spine tag density appeared to have a small positive contribution to the read rate.

Practical implications – Low read rates during a library inventory can be prevented by placing the tags near the book spine – the other book specific factors (listed in the previous paragraph) are of little influence. When not scanned during a first sweep, repeated scanning can increase the read rate with 0.15.

Originality/value – This paper is one of the first to analyse the influence of tag location and book specific factors on the read rate of RFID tags in library books. The experimental approach sets an example for future work.

Keywords Library inventory, RFID wand, RFID read rate, Tag location, Tag position, Book thickness, Book position, Kernel smoothing

Paper type Research paper

Introduction

Library inventory has changed since the introduction of radio-frequency identification (RFID). The physical work load of inventory taking has reduced dramatically compared to the visual or barcode reading methods. By using RFID tags the books can stay on the shelf while the inventory reader (RFID wand / antenna / interrogator) is swept along the spines of the books. Not much is known however about how conclusive read rates of RFID tags are in books on the shelf in a library, which may lead to an underestimation of the absolute number of books on the shelves. RFID read rate performance testing is common in supply chain

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management, livestock management, courier services (Rafiq, 2004) and from retail applications (supermarket chain) to army applications (Grider). However, the library environment is different from other areas: books are to be read at the item level, books are stacked on the shelf and only from one side approachable and the tags are positioned "perpendicular" to the inventory reader. Our assumption is that this perpendicular position makes the tags harder to read. Another difference between most of the library RFID systems and the supply chain environment is the frequency band which is used. In supply chain the UHF frequency is used whereas in the library environment the HF frequency is paramount. In general, the distance at which tags can be read is overestimated for the HF-frequency systems by using free space calculations. Golding and Tennant (Golding and Tennant, 2011) are (one of) the first to publish an experiment with RFID tagged books in a "real world" library environment and did find read rates of 99% for a library inventory.

The rationale underlying the purpose of this this study is the initially disappointing performance of the inventory reader in the library at the University of Amsterdam (UvA), the Netherlands. During inventory taking using the RIFD wand, low read rates were obtained.

The purpose of this paper is therefore to investigate the factors contributing to the performance of the collection inventory in a library environment. The factors considered are tag position, tag orientation, book thickness (number of pages) and location on the shelf as independent variables and the read rate as dependent variable.

In the subsequent sections we first give an overview of the know performance factors in RFID inventory taking, next we describe the methodology of our experiment in detail. Subsequently the experimental results are presented and those results are discussed. The final section is the conclusion.

Review of performance factors

The performance of an inventory reader is dependent on a variety of factors. These factors can be classified into characteristics of the environment, properties of the antennas (tags and inventory reader) and process properties of inventory taking.

Most shelves in libraries are made of metal because of its strength / load capacity. Metal can detune and reflect the RFID signal which can result in poor tag read range or no read signal at all (Bovelli *et al.*, 2006; Qing and Chen, 2007). Shelf material is a hard to change factor and therefore excluded in this experiment (the shelves in this experiment were made from metal). Besides metal shelves, libraries tend to use metal separators to keep the books in place (to prevent slipping down of books). Books near metal separators have a large chance to be misread (Golding and Tennant, 2008).

Humidity and temperature are two other factors of the environment of influence on the RFID performance (Saarinen and Frisk, 2013).

The medium between the antennas has a huge impact on the performance. Traditionally performance experiments are done in air. In maritime circumstance application of RFID tags require other methods and perform totally different from free air. RFID inventory, taking in settings with proximity of water (Dobkin and Weigand, 2005), results in a sharp decline in read range.

The output power of the inventory reader determines the read range. The higher the output the longer the read range is, although this relationship seems not valid at all distances (Daim and Lee, 2009). The output power is limited by legal limits for health and safety reasons (TagSys, 2006), the higher the output the larger the battery needed or shorter the battery life.

In library environments two frequencies are used. The high frequency (13.56 MHz, HF) is much more used than the ultra-high frequency (915 MHz, UHF). This is mainly a result of the longer availability and higher acceptance of the HF RFID as the performance of UHF RFID is equal or higher (Ching and Tai, 2009).

Small distance between tags (or high tag density) can result in cancelling signals (Boss and American Library Association, 2003). Values of critical minimum spacing between the tags in books are however not described in the literature.

The read distance is the distance between the inventory reader and the tag. The read distance increases when a tag is placed further from the spine (as the spines face the outdoor world). The amount of energy decreases with 1 /d2 where *d* is the distance from the transmitter, RFID wand.

The RFID tag can be attached to the book on several places. Tags are almost always attached inside the books. This can be inside the front cover or back cover. Mostly the back cover is chosen, although there appears to be no difference between the two according to Golding and Tennant (Golding and Tennant, 2010). In a more recent article by Golding and Tennant (Golding and Tennant, 2011) no influence on performance by the position of the tag in the book (top, middle and bottom) was found. 3M, a manufacturer of RFID tags, advices to place the tag as near as possible to the spine. Even the spine itself is suggested as a possible place for the tags. This option decreases the distance between the interrogator and the tag and optimizes the orientation. (FABBI, 2002) Tag orientation, horizontal or vertical placed tags, has influence on the read range, at least in free space (Hoong, 2007).

The RFID tag and the inventory reader are both antennas. The area of the antenna (and hence the size of the tag) have a significant impact on read range (Dobkin and Weigand, 2005). The tags used in the UvA libraries have an antenna size of 45 × 76 mm (credit card size).

A higher number of sweeps results in a higher read rate. Golding and Tennant found with a distance of 1 inch by 1 sweep 93% read rate and by three sweeps 99%, but this difference was not statistically significant (Golding and Tennant, 2011).

The sweep direction (from left to right or right to left) appears to have no influence on the read rate (Golding and Tennant, 2010).

The orientation of the two antennas relative to each other determines the amount of magnetic flux to pass through. Two antennas facing each other perform better than two antennas in a perpendicular position. The inventory taker can influence the performance by putting the wand in a certain angle where the performance is best.

The speed by which the RFID wand (inventory taker) passes the tags (books) is of influence on identification performance. In supply chain situations speed testing is common, mainly in conveyer belt experiments / testing (Buffi *et al.*, 2014; Fabbi *et al.*, 2002; Satyavolu *et al.*, 2016; Wang and Wang, 2010; Zhao *et al.*, 2017). However, no experimental studies area known where the speed of passing is investigated in the context of a library.

Based on these findings we decided to investigate the influence of book and tag specific factors as well as the number of sweeps on the read rate.

Methodology

Design

Two hundred and ten books of the lecture notes on mathematics (LNM) series from Springer publisher were selected for the experiment. The books in this series had more or less the same properties in paper used, were all soft covered and had all the same dimension (but varying thickness). The position and orientation of the tag, the number of pages and the thickness of the books were recorded. Thereafter the books were put on three shelves, randomly but at a known position (the randomization was done by an Excel VBA script). This position was used to analyse the influence of the neighbouring books (tag density among others) and influence of the shelf side proximity. No metal separators were used during the experiment. Only at the shelf side there was an open metal support.

The inventory for a specific ordering of the books was taken forty times by sweeping alongside the spines of the books. A sweep in our experiment is a back and forth movement of the interrogator. Thereafter the books were reshelved randomly over the three shelves again to repeat the 40 readings. This procedure was executed eight times. The choice for the 40 repetitions was made to obtain a resolution in calculating the probability of detection to multiples of 2.5%. The number of repetitions (eight) was maximized with the available time and resources for this experiment, and considered as sufficient for the expected variability (based on the experiment by Golding and Tennant (Golding and Tennant, 2011))

The tags in the books were read with an inventory reader by sweeping from left to right and back from right to left. All three shelves were inventorized this way. The angle of interrogation was optimized by trial and error: moving the interrogator along the back of the book in a curved way with direct contact: the interrogator touched the backs of the books. Illustrations of the experimental setup of the books, the sweeping path and the interrogator are given in Figure 1.

The tags in the books were all on the inside back cover but not all at the same place. Six positions were distinguished: (1) tag at the upper side near the spine, (2) upper opening side, (3) middle spine side, (4) middle opening side, (5) spine lower side and (6) lower opening side.

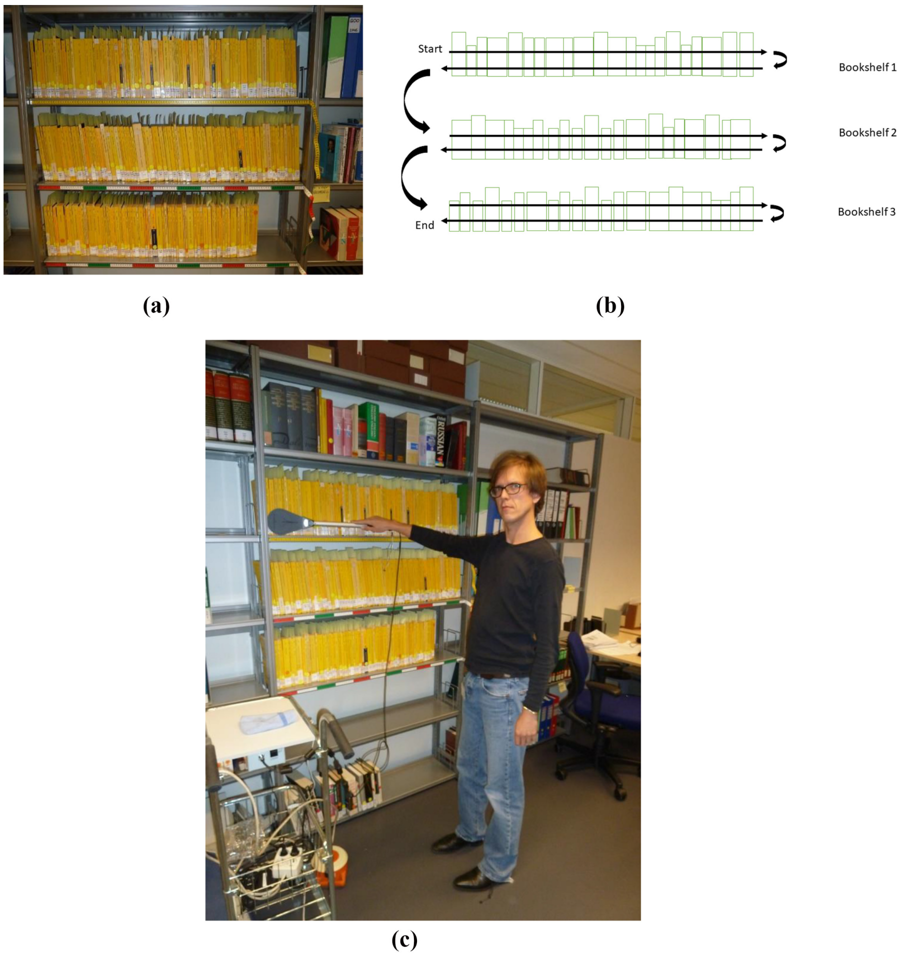


Figure 1.
(a) The experimental setup (210 Springer books on three shelves). (b) Schematic illustration of movement by the RFID interrogator along the three bookshelves, representing a single sweep. (c) RFID interrogator that was used

Figure 2 illustrates the position, and also lists the frequency of occurrence of each tag location in our experiment. Clearly, the large majority of the tags were in position 5 and 6.

Therefore we decided to distinguish between tags which were located near the spine (locations 1, 3 and 5–99 in total) and near the opening side (locations 2, 4 and 6–111 in total). This decision is supported with the finding by Golding and Tennant (Golding, Tennant, 2011) that tag location (top, middle or bottom) has no influence on the read rate.

The majority of the tags had a standing (vertical) position, 188 books of the 210. The average book was 14 mm thick, the thinnest 4 mm, and the thickest 47 mm. The number of pages (of course highly related to the thickness) ranged from 69 to 806 pages with an average of 242.

The RFID tags were identified with a ten digit integer identification code. The tags were HF RFID tags manufactured by UPM RAFLATAC (ISO 15693). The inventory reader was a TAGSYS' L-W1 Antenna with a maximum power of one Watt, operating at a frequency of 13.56 MHz (HF). The software used to record the results (barcodes programmed on the RFID tag) from the inventory reader was Vscan from Autocheck Systems B.V.

Statistical analysis

The experimental data were ordered in a data matrix which summarizes for each book: an identifier for each book (categorical; unique 10-digit integer), the spatial arrangement (1–8), the number of successful reads (0–40), the number of failed reads (0–40), successful

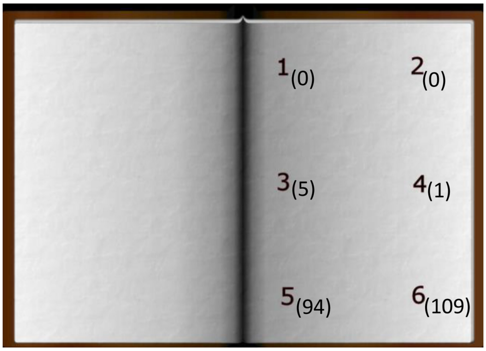


Figure 2.
The six possible locations of the tags on the inner back cover of the books in the experiment. The frequency by which each tag-location was present in the experiment is given by the numbers between brackets

Table 1.
Description of the data used in this study. Variables to identify the experimental units and repetitions are distinguished from the response variable, and variables used to predict the success rate in RFID reading. The measurement levels and accompanying class definitions or units of the variable are given between brackets

Name	Description
Variables to identify experimental units and repetitions	
bar	identifier for each book (categorical; unique 10-digit integer)
run	identifier to indicate the arrangement of the books (categorical; 1 to 8)
rep	identifier to indicate the repetition, i.e. the number of sweeps (categorical; 1 to 40)
Response variable	
s	number of times that a tag was successfully identified (count; 0 to 40)
f	number of times that a tag was not identified (count; 0 to 40, by definition f = 40-s)
r	success ratio (ratio; r = s/40)
Predictor variables	
tpo	Tag position (binary; near spine or near opening side)
tor	Tag orientation (binary; standing or laying)
sdi	Distance to nearest shelf side (ratio; cm)
bth	Thickness of book (ratio; cm)
bt3	Thickness over three books (ratio; cm)
std	Spine tag density, determined by kernel smoothing (ratio; nr/cm)

identification rate (the fraction out of the 40 times that a book is correctly identified) and the five predictor variables (see Table 1). The pre-processing steps to establish all predictor variables, except for spine density, were all trivial. To calculate spine density, a kernel smoother with automatic bandwidth selection was applied (Silverman, 2018).

After explorative analysis it turned out that the successful identification rate was close to 100% for tags at the spine site (see the results section). For the books with tags located at the open side, the effect of the predictor variables on the successful identification ratio was investigated with a generalized linear mixed model (Pinheiro and Bates, 2000). The successful identification ratio was treated as a binomial response variable, hence the model used a binomial error model and logistic link function. The repeated observations on the same books were incorporated in the model as a random effect on the intercept. Before model fitting, the predictor variables were standardized by a z-transformation, so that effects by the different predictors could be compared. Models up to three explanatory variables (using variables tor, sdi, bth, bt3 and std) were evaluated and ranked by the corrected Akaike information criterium (AICc) (Anderson, 2007; Akaike, 1998). For the selected model the marginal and conditional R-squared were reported, as well as parameter estimates with their p-values.

All analyses were conducted in the R data analysis system (R Development Core Team RFFSC, 2011).

Results

Of all the 67,200 tag reading attempts (210 books x 40 scans x 8 rearrangements) 55,029 tags were identified successfully, i.e. a read rate of 81.9%. When considering only the books with a tag near the spine, 16 of the 31,680 attempts appeared to be unsuccessful (a read rate of 99.9%) and only 8 books were not identified after 40 scans in one of the 8 rearrangements. When we focus only on the books with the tags at the opening side, 23,353 of the 35,520 attempts appear to be successful (a read rate of 65.7%) with no book identified 100% of the time in each of the 8 repetitions.

With repeated scanning (for a fixed arrangement) it is possible to detect considerably more books than through a single scan. The increase in read rate with repeated scans for books with the tags at the opening side is shown in Figure 3a. It highlights how at each repetition (representing a random reordering of the same books) the non-linear curve of increasing read rate with the number of sweeps may be quite different (differing up to 0.15). However, given a certain ordering of the books, the detection rate accumulates over a comparable range for each repetition - on average a detection is 0.13 (95% conf. interval: 0.097 to 0.169) higher at the 40th sweep compared to the first. Even though this finding shows that book ordering (i.e. how different tags occur in each other's neighbourhood) has a large impact, our research set-up cannot disentangle the exact physical mechanism behind this phenomenon beyond the factors that we investigated (see the predictor variables in Table 1).

In Figure 3b the average increase over the number of sweeps is shown with the 95% confidence interval. This curve shows how an average read rate of 0.75 is f.i. reached at 5 sweeps. However, beyond this point, the detection rate only increments slowly.

For a fixed arrangement of the 210 books (run A), Figure 4 shows the successful identification ratio (at the y-axes) as a function of several predictor variables (the values for tpo, tor and std are shown explicitly, while sdi, bth and bth3 are shown implicitly) for all the books that were used in this study over three shelves. While it highlights the main result reported in the summary statistics reported earlier: the reading rate differs dramatically between books with tag position near spine (closed symbols) versus those with a tag position near the opening side (open symbols), it also highlights the large variability in read rate for books with tags near the opening side. Based on the visualization in Figure 4 it is hard to identify the effects of the variables bth and std on read rates – in any case it evident that there

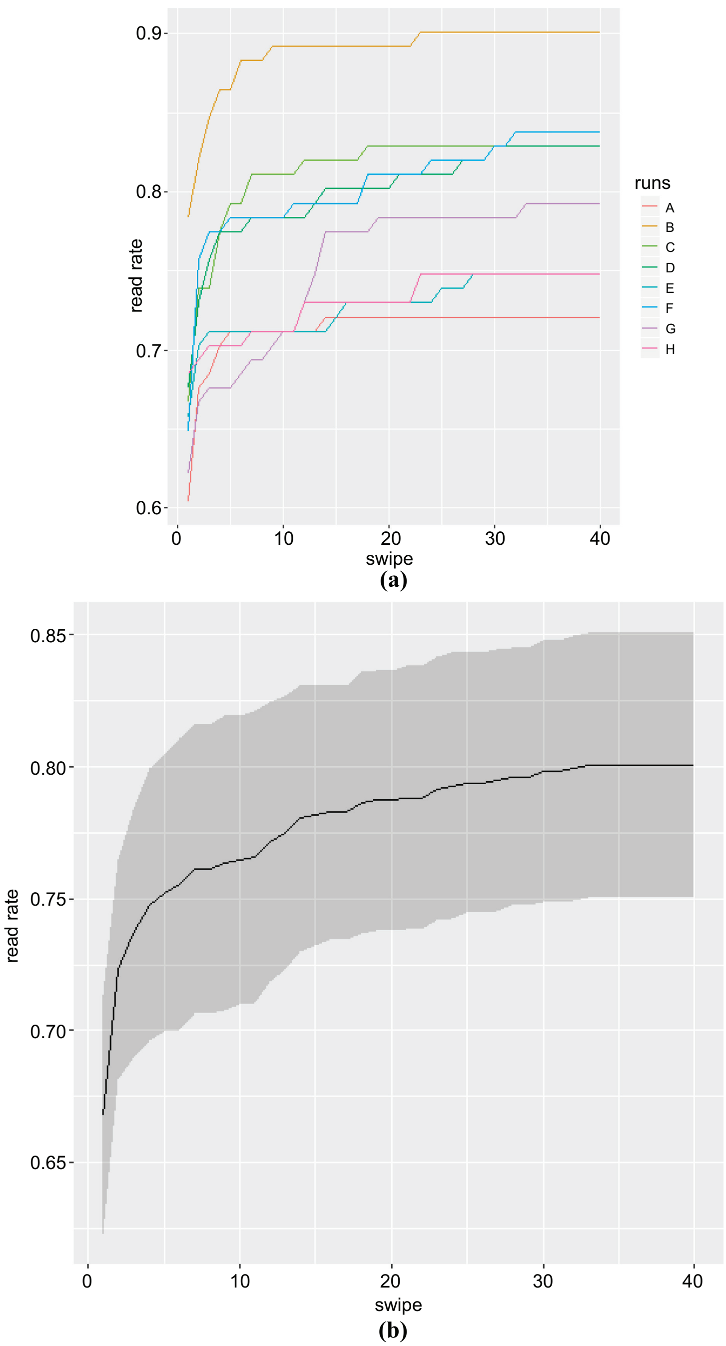
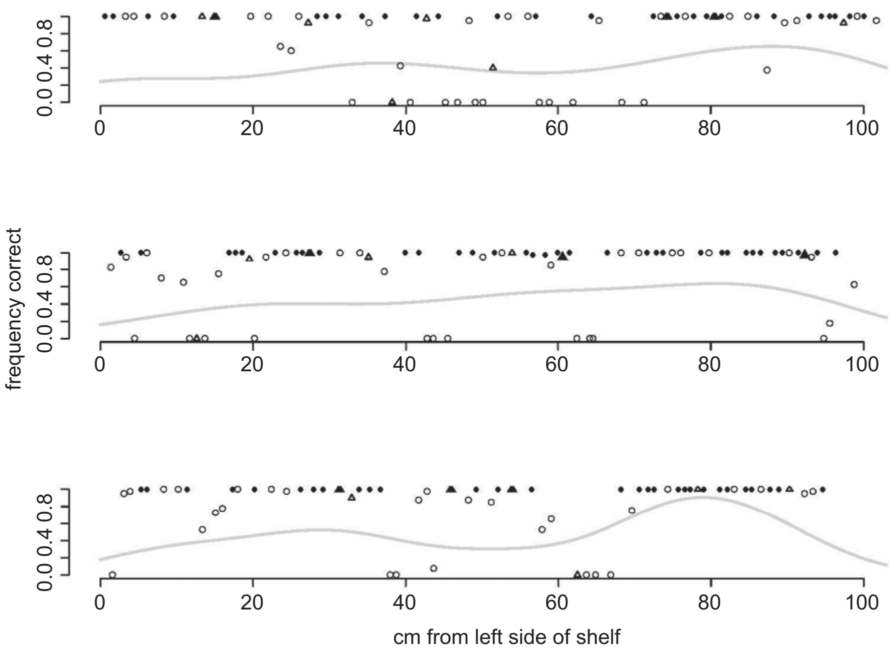


Figure 3.
The read rate as determined by the number of consecutive sweeps. (a) In eight different repetitions (runs), representing different re-orderings of the 210 books. (b) Averaged over the 8 runs with a 95% confidence bound for the mean (grey shaded area). For each book ordering, the read rate increments with an increasing number of sweeps in a similar way, a steep increase over the first 10 swipes, followed by a slow increase later on. The ordering of the books itself appears to have a large impact on the read rate: a difference of more than 15% exists between the ordering with the highest (B) and lowest (A) read rates

are no large effects on read rates (also when only considering the tags located at the open side of the books).

When using only the tag position (tpo) as predictor, it explains 76% of the variance in read rate (while 83% is explained when including effects by individual books).

To make inferences about the relation between the read rate and these covariables for the books with tags positioned near the open side, a model selection procedure was applied. This led to a logistic regression model that best fitted the data, by using the variables thickness of book (bth), thickness over 3 books (bt3) and spine tag density (std) as predictors (Table 2). This model had an AICc value of more than 130 over the second-best model. All variables appeared to have a positive effect on read rate. The effect size of bt3 was 2–3 times higher than the other variables (see the coefficient estimates in column 1 of Table 2) . Even though the coefficients were highly significant, the model explained only a small amount of the variance in read rate (5%). In contrast with this, the (unidentified) factors related to individual books explain 20% of the variance. Hence, the properties by the individual books that were not captured by the predictor variables explained four times as much variance as the observed predictors.



Note(s): Each symbol represents a book. The height of each symbol (on the y-axis at the left) gives the read rate from zero to one. An open symbol means that the tag position is at the opening side of the book. A closed symbol means that the tag position is at the spine side. A triangle depicts a standing (vertical) tag. A circle is a lying (horizontal) tag. The density of the tags (the variable std) is determined by a kernel smoother and shown by the grey line (the higher the grey line, the higher the density). The figure clearly shows that among thebooks with a high read rate (close to 1) there are those with tags at the opening as well as spine side, but among those with a lower read rate (e.g. smaller than 0.9) there are only books with tags at the opening side

Figure 4. Reading rate in run A for all the books that were used in this study over three shelves in relation to several predictor variables

The edited data were published on figshare and can be downloaded from: http://figshare.com/articles/RFID_library_tag_scan/106924

The raw data were published on UvA figshare and can be downloaded from: https://uvaauas.figshare.com/articles/RFID_raw_data_handheld/8427191

Discussion

In the past RFID library systems vendors claimed almost 100% read rates. However, in daily practice these perfect detection rates are only achieved for books where the tags are placed near the spine. When we take in to account all books, next to the spine as well as at the opening side of the book, we get a rather disappointing read rate of 82% (when applying 40 scans). When we focus only on the books with the tags far from the spine, at the opening side of the book, the read rate with a single sweep drops to 65.7%. These results emphasize that putting tags nearby the spine is off vital importance for inventory taking with a RFID handheld.

Read rates in library settings are not widely available in the literature. Golding and Tennat (2010) found read rates of 93% and less, depending on the variables considered. Buzzi *et al.*, (2011) found read rates of 100% using UHF RFID 500mW technology at lower than 5 centimetres distance. UHF is known for its larger read rang than HF and considering the small read distance of less than 5 centimetres, it is clear that also for UHF the tags in books should be put as close to the spine as possible. Read rates in other environments are more common (Sullivan and Happek, 2005), but the factors of influence in these are so different from books on the shelf in a library, that we will not further discuss this literature. In our experiment we found a surprisingly large effect of book ordering on read rates (see Figure 2) which could only to a very limited degree be explained by the predictor variables considered in our study (see Tables 1 and 2). We would suggest taking this phenomenon as a starting point for follow-up research to disentangle the underlying physical mechanisms, optimize interrogator design or even optimize book placement.

The library inventory taking model of Golding and Tennant (Golding and Tennant, 2010) shows that the read rate is mostly determined by the distance between the two antennas, which is in agreement with our findings: when using only the tag position (tpo) as predictor, it explains 76% of the variance in read rate.

As already mentioned in the introduction, the orientation of the two antennas relative to each other determines the amount of magnetic flux that is measured by the sensor. In a library setting a parallel orientation between the two antennas (the antenna from the handheld reader is directly facing the book) results in the highest read rate (Golding and Tennant, 2010). The common method of inventory taking in libraries (also used in our experiment) results in a

Variables	Coeff. Estimate	SE	*z*-value	*p*-value
Intercept	0.73	0.09	8.06	0.00
Thickness of book (bth)	0.17	0.08	2.10	0.04
Thickness over 3 books (bt3)	0.34	0.02	19.84	0.00
Spine tag density (std)	0.12	0.01	8.64	0.00

Note(s): For each coefficient estimate the accompanying standard error (SE), zvalue and *p*-value are also given. The model is a logistic mixed effects model with book ID as random effect on the intercept. It was selected from the set of models with all combinations of three additive variables created from the available predictor variables (see Table 1), using the AICc as selection criterion. The variables were ztransformed before model fitting, so that the size of the parameter estimates reflects variable importance. The marginal R-squared for this model is 0.05, while the conditional R-squared is 0.25

Table 2.
Coefficient estimates for the best model predicting read rate for books with tag at open side of book

perpendicular orientation between both antennas, so, while this method it by far the most efficient in terms of labour cost, it is suboptimal in terms of read rates.

The orientation of the tags, horizontal or vertical, had no significant influence on the read rate in our experiment. Hoong (Hoong, (2007) found higher free space read distances for vertical placed tags but these results were also not statistical significant.

In our study we found a strong increase in read-rate (considering books with tags at the open side, see Figure 1) with an increasing number of sweeps. This seems at first sight to be in contrast with the finding by Golding and Tennant (Golding and Tennant, 2011), who found a non-significant increase in read rate when evaluating the effect of one and three sweeps along with other factors. However, we think the marginal impact of this factor (i.e. the impact while not considering variation in other factors) could very well be consistent among the two experiments. Unfortunately it is not possible to single-out the marginal effect of increasing the number of sweeps from the results published in (Golding and Tennant, 2011), so we like to note that the possibility to increase the read rate by simply increasing the number of swipes needs to be looked at in future investigations.

Increasing the output power generally increases the reading distance (Daim and Lee, 2009) for UHF tags. This relation does, however, not apply at certain distances, and the range can decline at increasing power (Hoong, 2007). In our experiment we did not evaluate the effect of power (it was fixed at 1 W). To investigate the optimal output power of the handheld in a library setting (within government / legal limits) further research should be done.

Libraries traditionally used HF RFID but the last couple of years a swift to UHF is visible. UHF tags are smaller than HF tags and have a higher typical read range, and in addition, reading multiple tags goes faster with UHF than HF (Dobkin and Weigand, 2005). However, a disadvantage of UHF is its sensitivity to metal, which is especially relevant in a library where shelves are present. The exact effect of metal shelves on read rates as not been studied in this context and also deserves further attention in follow-up research.

An alternative method for inventory taking of library books is inserting the RFID handheld between the books. This way the distance between the two antennas reduces and the orientation between the two antennas becomes optimal (facing each other). Inserting the handheld between the books is of course a more labour intensive method than sweeping along the backs of the books. Libraries with tags placed at the opening side of the books can consider this alternative method of inventory taking.

Conclusion

Libraries at the start of implementing HF RFID should always put the tags next to the spine of the books. A tag near the spine is almost always read in our randomized experiment (99.9%).

Tags placed at the opening side of books are only read in 65.7% of the cases. An analysis with a generalized linear model showed that for the books with tags at the opening side, the factors of book thickness (bth), thickness over 3 books (bt3) and spine tag density (std) are, in combination, positively related to read rate; whereas the factors of tag orientation, and distance to nearest shelf side do not play a role. However, the overall effects by these factors on read rate are so small that they are not of practical use. In contrast, the number of sweeps is highly relevant for increasing read rate in practice. In spite of a limited read rate when tags are placed at the opening side, it can be increased by approximately 15% when incrementing the number of sweeps from 1 to 15.

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