

Evaluation of an Augmented Reality Supported Picking System Under Practical Conditions

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Abstract

Order picking is one of the most important process steps in logistics. Because of their flexibility, human beings cannot be replaced by machines. But if workers, in order, picking systems are equipped with a head-mounted display, Augmented Reality can improve the information visualization. In this paper, the development of such a system—called Pick-by-Vision—is presented. The system is evaluated in a user study performed in a real storage environment. Important logistics figures as well as the subjective strain were measured. The results show that a Pick-by-Vision system can considerably improve industrial order picking processes.

Keywords: Augmented Reality, order picking, evaluation

ACM CCS: 1.2 [User/Machine Systems]: Human factors; H.5.1 [Multimedia Information Systems]: Artificial, augmented, and virtual realities; H.5.2. [User Interfaces]: User-centered design

1. Introduction

Over the last decade, globalization has led to an increasing division of labor along the value creation chain. Companies focus on their core competences and the trend is moving towards outsourcing processes and tasks. Because of this, the domain of logistics and most of all, order picking as one of its core functions are becoming more and more important. Order picking is the gathering of goods out of a prepared range of items following some customer orders [VDI94]. As such, it is the last process step before the goods are delivered to the customers. Mistakes arising from manually performed processes have a strong influence on the quality of delivery and the relationship between clients and suppliers. The business confidence will be negatively influenced, possibly leading to financial consequences. Thus, zero defect picking is one important goal of order picking. But this will not be achieved, no matter which technologies are used [GK07]. One way to minimize errors is complete process automation. Due to the high variety of goods in order picking applications, machines usually cannot replace human being with his flexibility and fine motor skills [GK07]. Flexibility is needed because the

product range and thus the variety of items increases while, by contrast the size of orders is decreasing. For example, the e-commerce company Amazon has a product range from books over clothes to electronic devices. Normally you only buy one or two products so that the orders in the distribution centre comprise one or two order lines. Human beings and flexible storage environments are often the best solution for picking in such big storages. Accordingly the aim is to optimally support workers by technical devices during their task fulfillment. In this paper, we focus on the provision of information for order pickers.

Since 4 years, the Department for Materials Handling, Material Flow, Logistics (fml) of Technische Universität München (TUM) is working on a research project on visual information assistance—the Augmented Reality (AR) supported order picking system Pick-by-Vision. The order picker wears a head-mounted display (HMD) that visualizes all the required data directly in his field of view. Hence, he does not have to move his head, which leads to a decrease in dead times caused by looking, for example at a mobile data terminal (MDT), or a paper list used in conventional

storages. In combination with a voice system for data input, the application is hands-free and the worker can use both hands for his real task.

First in this paper, possible order picking environments for Pick-by-Vision are worked out. There are special requirements mainly for the hardware for the use of a mobile AR system in real storages. After selecting the important hardware components, the test bed at the Department fml, is presented. This configuration was used for an evaluation of the Pick-by-Vision system. The experimental setup, the execution of the test and its results are presented in the next chapter. This evaluation is the basis for some optimizations and for the second system, which includes a tracking device and which is displayed next. The last chapter gives an outlook on future fields of application of the Pick-by-Vision technology.

2. State of the Art

2.1. Order picking

The basic conditions in the field of logistics have changed rapidly over the last years. The market is demanding customized products. As an example, 20 years ago, automotive manufacturers offered three-model series, while nowadays they are offering nearly ten. According to this, the variants within one series increase steadily. Thus, production and logistics systems as well as the workers within these systems have to become more flexible to fulfill the customers' needs. A lot of different techniques exist for order picking in warehouses [GK07]. Conventionally, workers execute their orders with paper lists, which are intuitive for human beings but laborious to handle. Modern systems go without paper work. They include mobile data entry devices still having a high handling effort but which are usually connected online to the warehouse management system (WMS) processing the data [GK07].

In modern warehouses, worker support based on a usual paper list is often replaced by MDT with or without scanners, Pick-by-Voice (PbV) or Pick-by-Light (PbL) systems (Figure 1). All these technologies have specific advantages as well as disadvantages. PbV supports the worker by giving him all instructions through the computer's speech output. Unfortunately, these systems face difficulties in noisy industrial environments. Furthermore, it is questionable whether the warehouseman, as the user of such a system, likes it when he is bossed by a monotone voice the whole day. Compared to voice support systems, PbL offers the worker visual aid by installing small lamps on each storage compartment. PbL systems have the problem that the displays and lamps have to be elaborately integrated into the shelf construction and are thus very expensive and inflexible towards rebuilding. Besides, continuous functional tests of the lamps are needed, so that maintenance costs rise. PbL is suitable for order picking stations with a high throughput because the display addresses



Figure 1: Usual order picking technologies: scanner (1), Pick-by-Light (2) and Pick-by-Voice (3).

the human optical sense, the favored sense for the provision of information. This is the premise for quick reaction. Another common system is a MDT, but there is a lot of handling time for this device. Normally, it is attached to the waist belt of the worker. On the one hand, he has to move it into his field of view for information reception and on the other hand, he has to move it for scanning barcodes on the goods or the storing compartment.

2.2. Augmented Reality

Augmented Reality is a technology that can support the human visual sense. Following the definition of Azuma we define AR as a combination of the real and virtual world with 3D registration and which is interactive in real time [AZU97]. This definition requires a tracking system for positioning virtual objects. For order picking, the support with static data-like pictures, or text information via an HMD could be enough.

AR has many possible fields of application in industrial environments. In the ARVIKA research project, AR applications for development, production and service were implemented. One example was AR supported order picking [FRI04]. Assembly, maintenance and production planning are also often mentioned. The first industrial application was the wire bundle assembly project carried out by Boeing in the 1990s [MIZ01]. The use of AR, for maintenance of a printer, was introduced by Feiner *et al.* [FMS93]. Production planning is another field where AR is used productively in industrial applications. AR allows comparing virtually planned facilities to the realities of manufacturing layouts, for example to identify interfering edges [DSAP03]. In this paper, we

focus on supporting the operative staff. One productive application is an intelligent welding gun for experimental vehicle construction [ESK*04]. With AR the workers found the welding points four times faster than with the common technology because the process steps searching the point with a measurement equipment and welding can be done in one go with AR. Tang *et al.* [TOBM04] showed in a user study that AR can improve manual assembly tasks. The subjects were faster and made fewer errors using a HMD and a tracking system for dynamic data visualization instead of static information on a paper list, monitor or HMD. One example for assembly, maintenance or service applications is the mobile service application for machine tools developed by Weck *et al.* [WHH*04]. Training of the operative staff is another field [WAL07; ZLGB03]. AR has advantages because the information is displayed directly in the user's field of view thus speeding up the information provision and the training curve.

The biggest potential of AR is the parallelization of information gathering with secondary employment. Hence, dead times can be minimized and the time for information search can be reduced when the data are displayed in the user's field of view. This is an interesting factor for order picking. Some other work on AR picking was done besides ARVIKA. In the research project ForLog (Bavarian Research Cooperation Supra-Adaptive Logistics Systems), an evaluation for information visualization in storage environments was performed [KFPS06]. Besides a PDA and spatial displays mounted at the entrance of every aisle, an AR system with an optical see-through (OST) HMD was tested. The small field of view and the bad depth perception of this non-stereoscopic HMD caused problems. Most of the subjects could not clearly identify the real spatial position of the 3D arrows pointing on the storage compartment. Therefore, they often grasped into the storage compartment above or below the right one. This was the main reason for the worse performance when compared to the other display technologies especially the PDA. The Department fml also evaluated a first prototype of a Pick-by-Vision system [RW07]. The results and the consequences are mentioned later in this paper in Section 5. Unfortunately, all the very first experiments did not include the integration into practical logistics processes.

3. Selection of Possible Picking Environments for Pick-by-Vision

Before beginning to develop a novel order picking system based on the AR technology, it must be checked which applications offer the biggest savings potential. Basic order picking scenarios were worked out depending on the VDI guideline 3590 [VDI94]. Systems with automatic grasp processes and the use of industrial trucks were not regarded. The use of HMDs on fork lifts is problematic due to reasons of labor safety. Most of the purchasable HMDs limit the field of view increasing the risk of accidents. Furthermore, the fixed displays available in the fork lift can be used for the

AR visualization instead of the HMD. But this is no topic in the research project.

The first step was selecting the data that can be displayed in each picking scenario. The following four kinds of information were identified:

- static data: picking information (article, stock location, amount, etc.), pictures, description of the articles;
- optical marking of the stock location or the picking container using 2D maps or spatial 3D geometries;
- wayfinding to the stock location; and
- optical marking of the storage area (if several orders are picked in parallel).

Compared to real industrial order picking applications, these scenarios were specified regarding the storage setup, the loading aids, the range of items, the order structure or the order picking strategies. A general order picking process was worked out and the AR process was compared to different processes using usual picking technologies like PbV or using a MDT to identify differences in the general process flow. AR showed no serious differences, but some process steps are not necessary in an AR system while other steps can be parallelized. After a final rating, the use of Pick-by-Vision has its biggest potentials in three order picking scenarios (Figure 2):

- A classical man-to-goods system where the order picker moves through some aisles of a compartment shelving system.
- A gravity-storage warehouse where each order picker works along one shelf; this is a system for fast-moving goods and normally supported by a PbL system.
- A goods-to-man system where the order picker is seated at a fixed workstation; conveyors transport the goods to him and his task is distributing the goods to the different orders.

4. Important Hardware Components for a Pick-by-Vision System

An AR system consists of some typical hardware devices: the visualization, the interaction and the tracking system. In this paper, only mobile systems with HMDs as visualization medium are considered. Other components like mobile computers, servers or data transfer technologies are not presented in the following chapter.

4.1. Head-mounted display

The HMD is the most important hardware for Pick-by-Vision because it is the interface between the human and the technical system. Its task is to display the necessary information

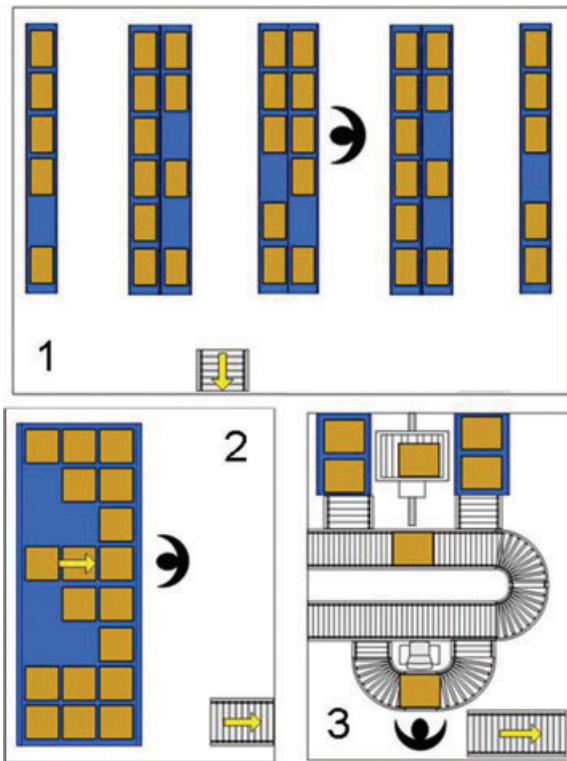


Figure 2: Possible order picking scenarios for Pick-by-Vision: (1) a classical man-to-goods system, (2) picking along one shelf, (3) goods-to-man system.

to the order picker. The visualization of the necessary data is one aspect; the other aspect is ergonomics and the physiologic harmlessness of the device. Furthermore, aspects concerning the use in industrial environments should be considered. The most significant requirement is that the worker has to wear the HMD over a shift of 8 h. Because of that, the HMD should be light and ergonomically designed, but also rugged and with an 8-h battery operation. Another critical point for the operational use is that the field of view must not be limited due to reasons of labor safety.

In this project, more than 40 HMDs were considered and evaluated in terms of suitability but only ten have the potential to be used in storages. VST was a knock-out criterion because a power failure leaves the worker completely blind. Other problems were a too small field of view, the weight or the costs. Virtual Retinal Displays (VRD) like the Nomad from Microvision suit best for order picking applications [MIC08; TJMF95]. They do not limit the field of view because of their construction based on a semi-permeable mirror. The mirror is used to project the image with a laser beam directly into the eye. The HMD is the decisive factor towards user acceptance of Pick-by-Vision. The Nomad HMD was presented to some order pickers employed by some industrial partners, in this



Figure 3: An adjusting knob from Griffin technologies [GRI08] (left) and an infrared camera from metaio called ARLiveCam (right).

project. The feedback was predominantly positive. But the workers did not wear the HMD for more than 15 min. So, the time dependent effects did not have any influence on their opinion. Most of them can imagine working with an HMD for 1 day or even longer for further evaluation. But there are also workers who generally dislike the HMD. Thus, it is essential to involve the workers from the beginning in order to attain a high user acceptance of new technologies.

4.2. Interaction device

The second important piece of hardware is the interaction device. Order picking processes vary slightly from one company to the next. But the acknowledgement of the pick, the input of the zero crossing (if there are not enough items in the storage compartment) or the input of errors are necessary for every order picking system. These interactions are implemented in the fml Pick-by-Vision system. Different input devices were evaluated in terms of their suitability. The interaction device should be robust and should not limit the worker's freedom of movement. For example, arm keyboards do not suit order-picking applications. They are too heavy because the order picker has to move his arms the whole day long. Besides, they are too dangerous because they can catch the shelf construction during picking and hurt the worker. Two devices were chosen for Pick-by-Vision. An adjusting knob (Figure 3) and speech input can be used best for this application. The degrees of freedom of the adjusting knob (turning left and right and pushing) can be transfused easily to the user interface, and it is rugged enough for use in storages. Speech input is the most intuitive form of interaction for humans and it is the only technology that allows hands-free interaction. These advantages shame the problem of the operability in noisy environments.

4.3. Tracking system

Another important hardware component is the tracking system. Besides the HMD the tracking system is the most problematic hardware component of a mobile AR application, especially in industrial environments. A lot of different factors like degrees of freedom, accuracy, resolution, update rate and range characterize tracking systems [RDB01]. If these technical issues are suitable for an industrial application,

there is still another important factor: the price. On the one hand, an AR system must work robust and safe in practical operation. On the other hand, it must have a better performance than the system used before so that a short return on investments can be achieved.

There are many different functional principles for tracking systems like electromagnetic, inertial, mechanical, optical, radio-based or ultrasonic systems [RDB01]. They all have their specific advantages and disadvantages. Electromagnetic, ultrasonic or radio-based systems have problems in storages because of the high proportion of metallic structures like shelves. Magic Map is a WLAN-based technology that is used in storages to locate devices and loading aids [ISLW05]. The position can be measured well but this system gives no orientation. Ubisense developed a tracking system based on the ultra wideband technology that works in metallic environments [UBI08]. In most publications, optical tracking systems are seen as the best choice for use in industrial environments. After an evaluation optical tracking systems were also chosen for Pick-by-Vision. Three different variants are possible:

- An inside-out system with a video camera and paper markers mounted in the storage, for example on the shelves or selected points in the environment.
- An inside-out system with infrared sensors and active LEDs on the ceiling like the Hi-Ball system [WBV*01].
- Markers on the HMD and infrared cameras in the environment like the ARTtrack from A.R.T. [ART08] or the ARLiveCam from metaio [MET08] (Figure 3).

Paper markers are always crucial if they are used in industrial applications because they can become dirty and perform more poorly. In our application it was not possible to implement LED on the ceiling. Hence, we decided to use the outside-in system with infrared cameras with spherical reflective markers mounted on the HMD.

It is questionable if a tracking system is needed for a Pick-by-Vision system. In the evaluation of Tang *et al.* [TOBM04] the tracking system leads to a better performance especially to less error. But is the performance in order picking systems with tracking as much better than without so that the additional costs amortize in an acceptable time? This is one question that should be answered in this project. Therefore, the first Pick-by-Vision system was installed without a tracking system. This system will be explained and evaluated in the next chapters. The system with tracking is introduced in chapter 7.

5. Setup of Pick-by-Vision without Using a Tracking System

The first Pick-by-Vision system was implemented in close collaboration with our industrial partner CIM GmbH, which



Figure 4: Used system in this setup: a Microvision Nomad HMD, a head-set for the speech input and a possible visualization (little picture).

is the developer of Prolog World™, the WMS used in this application. The information of the WMS, which is normally shown on a fork lift terminal is displayed on the Microvision Nomad VRD (Figure 4).

One of the most important things about this system is the Graphical User Interface (GUI), because the virtual information must be displayed at the right time and at the right position. A GUI was implemented following special AR guidelines [BKIV*05] [FRI04]. For his daily work the order picker needs essential text information about the orders, for example stock locations, article number, goods description or required quantities. The data input, for example the acknowledgement, is done by the order picker with a rudimentary speech input system based on the *speaKING*™ software from MediaInterface Dresden GmbH. Only a small vocabulary is needed for order picking. In this case, the system can be operated with ca. 20 words. The system must function properly independently of the speaker. This is very important for an industrial application with changing workers (especially temporary workers) or for an evaluation with several test persons. Only then, every user can work with the system without a special familiarization.

The workflow of this Pick-by-Vision system includes all important tasks found in the general order picking process. In real order picking applications there are more company specific tasks but for our system the following workflow is sufficient. First, there is a short login dialog (user name, password). After choosing the next order the user has to take a picking trolley where he sets down the picking container. Then, the system shows him the next stock location. During his way to this stock location, he can already read the picking information (article number and amount). After acknowledging the pick, the next order line is displayed. When the last order line is completed, he is told to go to the delivery station to finish the order by putting the picking container on a conveyor. Every command is confirmed with the same simple speech input—except for the case where



Figure 5: The experimental setup with the compartment shelving system and the starting point (left) in the Kühne + Nagel distribution centre.

the picking amount also has to be acknowledged by repeating the amount. Because of the small number of speech commands, the user becomes familiar with the system in a little while.

6. Evaluation of the Pick-by-Vision System

A first simple Pick-by-Vision system was evaluated in 2007 [RW07]. The users' acceptance was high but the measured logistics operating figures were worse when compared to the paper list. Several factors were responsible for this. The speech input system was of a worse implementation, the GUI could use improvement and the test storage at the Department fml was too small. After improving the system, a new evaluation was carried out in a bigger storage.

6.1. Experimental setup

In this experimental series, the Pick-by-Vision system was compared to a usual paper list in a compartment shelving system in a distribution centre hosted by our industrial partner Kühne + Nagel (AG & Co.) KG. The storage consists of eight shelves with four aisles with more than 600 stock locations (Figure 5). Over 75% of the stock locations were filled with goods.

Each subject had to finish 14 orders using both techniques. The orders had between two and six order lines with one to six items each. Altogether there were 52 order lines with 119 items (average 2.3 items per order line). The items were boxes in different sizes and with different weight. Normally, the boxes could be handled with one hand but some were so big or heavy that two hands were needed. Other items were booklets or sweets, which were also the reward for the test persons. Most of the items were stored in loading aids. Some were lying in the shelves without one. The orders were picked

in the same sequence with each technique. This means that each subject started with order 1 and finished with order 14. For every order, the WMS optimized the route through the storage.

Sixteen subjects took part in this test series. Most of them were male (13); the average age was 27.6 years (between 20 and 52 years, standard deviation 8.13). Among them were students or researchers, but also non-academic people like skilled workers. Six had experience with 3D visualization, for example from computer games, less than from Virtual Reality applications. Five were familiar with order picking processes. The data for this analysis was collected in personal questionnaires. The subjects had also to fill out a special questionnaire for each technique after picking with it to measure the subjective strain.

6.2. Null hypotheses

During the test series, two very important logistics operating figures were measured: order picking time and errors.

- Order picking time is important for the throughput time of the orders in the storage. It is a part of the reaction time between the order of the customer and the delivery to him. This time is getting shorter and shorter and it is an essential factor of success for a company. Besides, the order picking time can be used to calculate the order picking performance. The performance is the average number of picked order lines per hour.
- Picking errors can have a big effect when they are not recognized before shipping. They can result in high contract penalties, for example when the customer has to stop his production. The picking errors are translated in an error rate. That represents the amount of errors within all picked order lines.

The order picking time for the whole trail was measured with a common stop watch. The times for the separate orders were read off in between. The errors were counted after the delivery of the picking container with the corresponding order.

Normally, both technologies should not equally perform. For the statistical proof it is hypothesized that the tested figures for both are equal. This null hypothesis is proofed and accepted or if necessary discarded. For these figures some null hypotheses can be introduced comparing Pick-by-Vision to a paper list based system. The first null hypothesis is that the picking time t for both techniques is equal:

$$H_{0,1} : t_{\text{Pick-by-Vision}} = t_{\text{paper list}}$$

For Pick-by-Vision little training is needed. So the order picking times for Pick-by-Vision can be different between the subjects who started with Pick-by-Vision and who started the

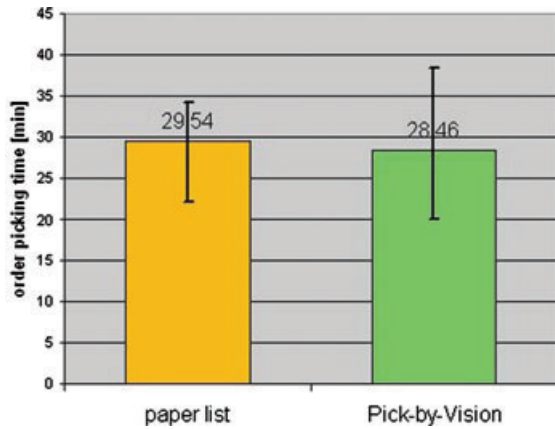


Figure 6: Mean values, maximum and minimum of the order picking times with paper list and Pick-by-Vision over all 16 subjects.

paper list. Thus, the second null hypothesis is that the times t_{start} are equal and do not depend on the starting technology:

$$H_{0,2}: t_{\text{Pick-by-Vision, Start Pick-by-Vision}} = t_{\text{Pick-by-Vision, Start paper list}}$$

The same effect is checked for the paper list. This is the third null hypothesis:

$$H_{0,3}: t_{\text{paper list, Start Pick-by-Vision}} = t_{\text{paper list, Start paper list}}$$

For the error rates f between both techniques it is expected that they are equal. This is the fourth null hypothesis:

$$H_{0,4}: f_{\text{Pick-by-Vision}} = f_{\text{paper list}}$$

6.3. Analysis of the test series

The measurement of the logistics operating figures, is one side, their interpretation is another. Identifying a difference between Pick-by-Vision and the paper list for only one certain value in this test series does not necessarily imply a universal validity of this result. First, descriptive values like the mean value, maximum, minimum or standard deviation are calculated. Based on these results the null hypotheses are proven. For a specific level of significance, the difference is significant. For all analysis in this paper, the level of significance α is 5%.

6.3.1. Picking time

There is only a small difference between the mean values of the order picking times. With Pick-by-Vision the subjects were about 1 min (4%) faster than with the paper list (Figure 6). In both tests the Grubbs' Test for outliers shows no outliers with a confidence level of 99%. The confidence

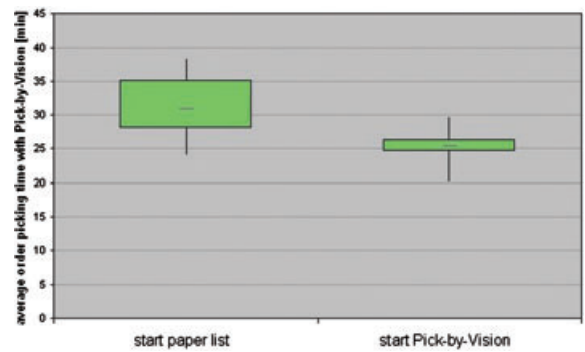


Figure 7: Boxplot with median, maximum and minimum of the order picking time with Pick-by-Vision: left subjects starting with the paper list, right subjects starting with Pick-by-Vision.

interval for the mean value for Pick-by-Vision is 25.81 to 31.11 min, and for the paper list 27.90–31.18 min. So, both samples are very homogenous and are normally distributed (Kolmogorov–Smirnov-test because the amount is smaller than 30). This is the condition for the significance test. A t -test for paired dependent samples is used because the number of values for both samples is equal but the variance is different (Pick-by-Vision: 4.97, paper list 3.08). The difference between the order picking times is not significant and the null hypothesis $H_{0,1}$ cannot be discarded. Remarkable is that the statistical spread is bigger with Pick-by-Vision. The difference between the slowest and the fastest subject is 18 min (ca. 47%) whereas, it is only 12 min (35%) with the paper list. So, the variance is different. With a special test the significance can be proven [BOR05]. The difference is significant. Thus, the null hypothesis $H_{0,1}$ can be discarded. There is a difference between the order picking times due to the variance. Expectedly, with Pick-by-Vision some subjects performed very fast and some needed a lot of time before they were familiar with the new system.

6.3.2. Learning effects

There are always some learning effects, for example concerning the layout of the storage, the workflow or the look of the articles. To minimize these effects the technique with which the subjects had to start was randomized. Hence, eight subjects started with Pick-by-Vision and eight with the paper list. We can notice an interesting effect. When the picking times with Pick-by-Vision are compared, there is a difference of 6 min (ca. 19%). So, the subjects were noticeably faster with Pick-by-Vision when they had picked with the paper list before (Figure 7). This effect is checked for significance. Both samples are normally distributed (Kolmogorov–Smirnov-test). A t -test for paired dependent samples is used again because the number of values for both samples is equal but

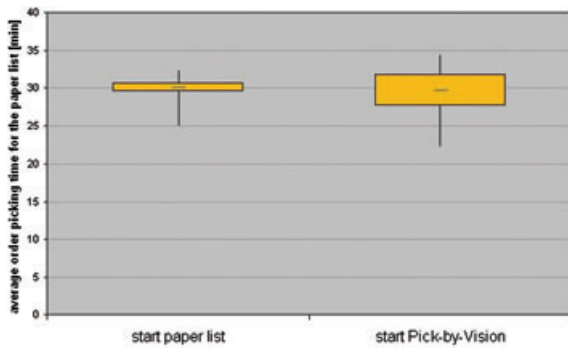


Figure 8: Boxplot with median, maximum and minimum of the order picking time with the paper list: left subjects starting with the paper list, right subjects starting with Pick-by-Vision.

the variance is different (start Pick-by-Vision: 3.90, start paper list 2.23). The test shows a significant difference between the order picking times. Therefore, $H_{0,2}$ is discarded. The explanation for this effect is that the subjects work more confidently with Pick-by-Vision if they know the storage and the workflow. So, they can concentrate on the new AR technology.

With the paper list there was nearly no difference in the mean values of the order picking times (Figure 8). It did not matter if the paper list was the subject's first or second test series and $H_{0,3}$ cannot be discarded. The paper list is very intuitive to handle for human beings because they are familiar with it in everyday life. The subjects had no problems when starting with the paper list. One interesting effect is that the statistical spread is wider when the subjects picked with the AR system before (35% to 23% when starting with the paper list). Normally, the spread should be wider in the first trial. If this is proven with a test for variances [BOR05], there is even a high significance ($\alpha = 1\%$) and $H_{0,3}$ must be discarded. But this is the contrary effect to Pick-by-Vision where the spread within the subjects, who started with the paper list, was wider. Faster subjects in the second trial are normal because they knew the workflow and the storage. The slower subjects are more difficult to explain. Perhaps they were tired or they were bored to do the same task with a simple paper list.

6.3.3. Picking errors

Among other things, the error rate depends on the order picking technology. For a paper list it is normally 0.35%, for Pick-by-Light 0.40% or Pick-by-Voice 0.08% [tHS04]. This means, for example for an error rate of 0.40% that four order items within 1,000 are faulty. There are different types of errors, for example a wrong item was picked, the amount is incorrect or all articles of an order line are missing. Even one error within 1,000 is usually not acceptable to the customers,

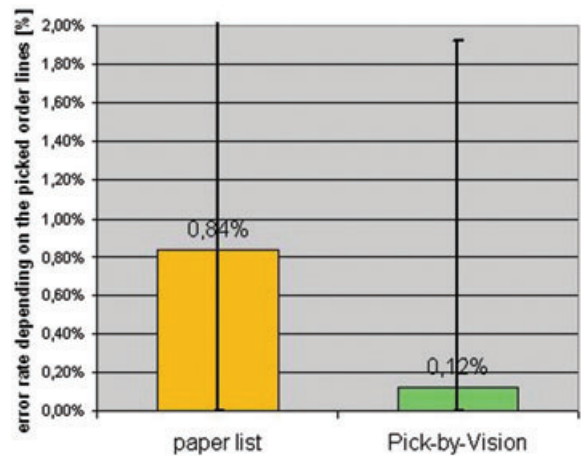


Figure 9: Mean values, maximum and minimum of the order picking times with paper list and Pick-by-Vision over all 16 subjects.

because in extreme case each mistake can lead to halting the production line.

In this test series the error rate for the paper list is seven times higher than for Pick-by-Vision (Figure 9). With Pick-by-Vision only one error was made for each 1,904 picked items. Significance is questionable because of such a small number of errors in the whole evaluation. The confidence interval for the mean value for Pick-by-Vision is 0.03–3.69 errors and for the paper lists 2.77–13.05 errors. Both samples are not normally distributed. Error rates are subject to the Poisson distribution because the error count can only take integer; non-negative values and picking errors are a rare event. Thus, the significance test was made with the Mann–Whitney U -test. The test shows no significant difference although the difference seems to be big enough. The null hypothesis $H_{0,4}$ cannot be discarded. The reasons are that there were only 16 subjects and they made too few errors for a statistical conclusion.

6.3.4. Questionnaires

Besides the logistics operating figures the psychological factors motivation, usability, impression and the cognitive load were measured with questionnaires. The subjects accepted the system very well and the subjective strain is lower than with the paper list. The distinct usability and the low cognitive load lead to a very high motivation to work with Pick-by-Vision. The motivation is the major difference (Figure 10) when compared to the paper list whereas the other examined factors showed no clear differences. There were also free questions where the subjects could state their opinion in their own words. On the one hand, some had problems with the HMD because they could read worse due to

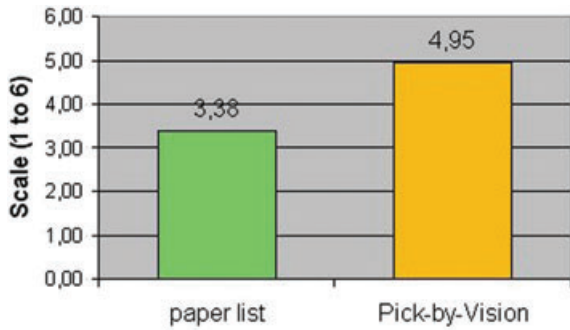


Figure 10: The motivation of the subjects to work with the paper list and Pick-by-Vision.

changing brightness or the shift of the Nomad VRD mounted on a usual baseball cap. Most disliked the monotone speech input and that they had no overview of the size of an order (foremost the amount of order lines). On the other hand, the subjects liked that they could work hands-free and that the information was displayed clear and in their field of view. Another advantage is the acknowledgment of the pick with the right amount. This is the main reason for the low error rate. Altogether, the results are very positive but the subjects wore the HMD only between 30 and 45 min. Therefore, it is hard to make predictions concerning full-time use.

7. Current Work: Pick-by-Vision Including a Tracking System

The second functional model is developed independently from the first one together with the Fachgebiet Augmented Reality (FAR) of the TUM. With the tracking system, it is possible to display 3D information in correct spatial position. For this approach, the same HMD is used but the GUI is different. Besides text information, pictures of the articles or 3D geometries can also be visualized. These geometries are used for wayfinding and for marking the stock location. One important point is to find the right amount of displayed information because it should not occlude too much of the real environment. Labor safety would be influenced negatively if the worker's field of view is occluded with too much with virtual information.

Several evaluations were made at the FARs AR Lab to find the best visualization [SK08]. 2D maps performed worse because they occlude too much of the real environment and the users counted time-consuming the stock location from the beginning of the aisle to the stock location of the current order line. Arrows are usual symbols for navigation tasks. But there is one problem. With the monocular HMD the subjects had problems with the depth perception of the arrows. Often they picked items from the stock location above or below the right one. Hence, we need visualization with a good spatial effect



Figure 11: Tunnel becoming transparent if the right storage compartment is recognized and a frame around the right stock location.

using only one eye. The combination of a tunnel with a frame seems to be the best solution. This is a further development of the attention funnel [BTOX06]. The tunnel consisting of some cycles begins at the eye of the user and ends following a special curve at the stock location. It shows the user in which direction he should look. If his view is towards the right shelf, the tunnel becomes transparent and at its end, the user can see a frame around the marker of the stock location (Figure 11). In the evaluation, the subjects made no errors with the tunnel. It is intuitive to follow and it gives a good spatial effect even with the monocular HMD.

The next step was the transfer of the system to the storage at the Department fml. For the small storage with two aisles of four meters in length more of the A.R.T. infrared cameras were needed than in the FARs AR Lab. Thus, two cameras are hanging above the shelves to cover the whole area. At the end of each aisle, there are a couple of cameras. One at 2.5 m height points diagonally and one at 1.5 m height horizontally into the aisle. With this configuration, the six cameras cover the whole operating area very well (Figure 12). The passive target for the tracking system consists of five self-reflecting balls mounted on the HMD. We also changed the interaction device for this functional model. An adjusting knob is used for interaction because the speech recognition in the other functional model does not work satisfactorily.

With this setup we made some evaluations that will be published soon. One interesting question is the real advantage of using a tracking system. Thus, we made one experiment comparing a Pick-by-Vision system with tracking to the same system without using tracking. We analyzed the logistics operating figures, the different occlusion of the real environment and the objective strain. All our present evaluations were short-term experiments of 15 to 45 min. Therefore,



Figure 12: Pick-by-Vision including an infrared tracking system with targets fixed on the HMD.

we made another middle-term experiment of about two hours comparing Pick-by-Vision with tracking to a common paper-based system. The focus was on the different subjective and objective strain of the subjects.

8. Conclusion

Our results underline the potentials of Pick-by-Vision. We worked out in which order picking scenarios in such a system makes sense and which information must be displayed. Our evaluations show that the users are faster and make fewer errors. We considered more than just logistics operating figures. The user acceptance is high, resulting in a steep training curve. But there are still some problems. The biggest obstacle for porting such systems from the research stage into practical applications is the hardware components, especially the HMD and the tracking system, if required. But there is a continuous further development of these components because the gaming industry slowly discovers AR and HMDs will soon be a part of the everyday life within mobile multimedia applications. Therefore, HMDs will also be used in industrial applications within the next 5 years.

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