Visual Behavior Analysis of Human Performance in Precision Tasks

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Abstract. In this paper we have presented a pilot study done on seven subjects for analyzing the variation of human task performance on precision manual tasks by changing the visual distance. A trivial screw fastening task was performed at sitting and standing posture. It was observed that as long as components remained properly visible and within hand reach, the subjects were able to perform faster at a longer visual distance. We performed two additional laboratory experiments that consisted of tasks comprising of block duplication and visual peg-hole search and observed the same results. For recording the visual activity, a head-mounted binocular eye-tracker was used that captures first person view of scene along with gaze vector and fixation time. The data generated was analyzed for all three tasks and results are shown that justify our observations.

Keywords: Vision analysis · Eye tracking · Precision tasks · Human performance · Visual behavior

1 Introduction

Manual tasks where human skill and accuracy precedes over power can be called as precision tasks [9]. In common scenarios these tasks can be electronic or mechanical assembly, jewelery design, medical procedures, etc. Often it involves working with small size tools and components (only the term 'component' will be used from now onwards that signify both). Operators performing such tasks largely depend upon high visual feedback which is required to maintain continuous accuracy over assembly clearances and motor controls that are characterized by hand-eye coordinated movements [19]. Occasionally they call for manipulation activities in artificial visual environment such as a microscope or eye loupe which induces restrictions on posture and vision.

According to Li and Haslegrave [15] the industrial guidelines designed for studying ergonomics and human factors mostly focus on the physical arrangement of the workspace. Most production planning systems rely on predetermined

time standards based only on task characteristics and the above mentioned characteristics are usually not considered [12]. Since visual demands required to perform precision tasks are difficult to predict during real product and production development the overall planning can produce erroneous results. Hence understanding of visual behavior induced by tools and components is relevant for precision task planning and it requires appropriate research.

A typical manual assembly task comprises of several activities where eye lead the hand for a goal directed movement (like picking a component). The most common activity involves searching and locating a component of interest [5]. During this activity, a saccade to the component is initiated prior to the start of the hand movement. This follows visual fixation over the target till the hand reaches the target [4]. Gaze behavior like this, brings the target in central high acuity vision (Binocular Convergence) that is known for providing detailed information about location and characteristics of the target. On the basis of depth perception, the relative position of hand and target is computed by visual system that guides the hand for goal directed reach [17]. For predicting and optimizing the human performance, it is important to take in account the time taken by visual system in such scenarios.

The aim of this pilot study is to understand that up to what extent human performance is correlated to operator's working visual distance with respect to components while performing precision tasks. To begin with, we started with examining human performance and visual behavior in a simple manual assembly task of fastening screws on a board using screwdriver performed by seven subjects in two different visual distances (Sect. 2). It was observed that as long as components remained properly visible and within hand reach to all the subjects, the task performance time improved at higher visual distance. The subjects were able to perform faster. For verification and validation, we performed two laboratory experiments under constrained scenarios (Sect. 3) and observed same behavior. The results of our observations and experiments are presented in Sect. 4 followed by discussions and future work in Sect. 5. Conclusions in to our study presented in Sect. 6.

2   Manual Screw Fastening Task

2.1   Setup

Seven subjects with normal vision and similar height of 160 cm, were seated on a chair of height 60 cm. A wooden table of height 90 cm was kept in front of the subjects for resting the arms in comfortable position. Components required to perform tasks were kept over table within the hand reach envelope. The subjects were explained with the procedure to be followed and were given ample time to get accustomed with the workspace. The eye movements were monitored using Arrington Research's Viewpoint eye tracker. Its an eye-frame mounted, camera-based, IR dark pupil reflection based binocular eye tracker [18]. While performing the tasks, tracking speed was kept at the maximum sampling frequency of 60 Hz under which the accuracy of the device was approximately $0.25°$ to $1°$ of visual

arc. Eye-frame of this device holds a miniature scene-camera at its center, aimed directly at the scene. While recording, the tracker generated a video stream of the scene from the subject's perspective on the scene-monitor, along with a circular dot indicating the intersection of the subject's gaze with the working plane along with time stamp. Because the scene-camera moved with the head, the eye-in-head signal indicated the gaze point with respect to the world. All the experimental data was additionally stored in the form of text file for further off-line analysis using the supplied software. For each subject, the device was calibrated using standard 9 point calibration procedure before each trial. For the experiments performed in Sect. 3, similar setup was used. The tasks were intended to be performed at two visual distances, for which two postures viz. sitting and standing were considered. For sitting posture, eye to table distance was approximately 30 cm (Fig. 1a) with wider field of view for arranged components as shown in Eye-tracker's frame in (Fig. 1c). In standing posture, eye to table distance was 60 cm (Fig. 1b) with components appearing in narrower field of view (Fig. 1d).
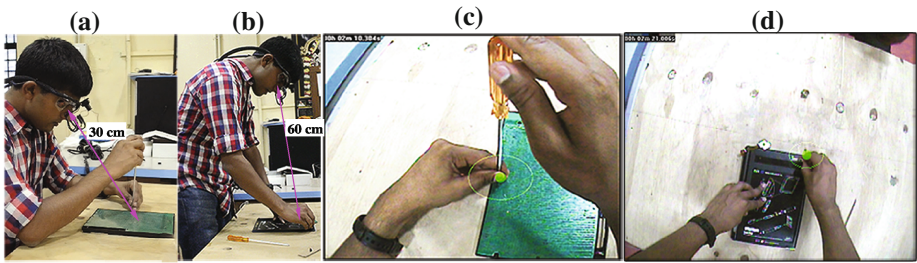

Fig. 1. Experimental setup showing subject wearing an eye tracker performing tasks in (a) Sitting posture at 30 cm and (b) Standing posture at 60 cm visual distance. Eye-trackers scene camera frame showing the fixation point as smaller green solid circle while performing the task in (c) Sitting posture and (d) Standing posture (Color figure online)

2.2 Procedure

Most manual precision assembly involves fastening screws as the most common task [16], hence we considered the same task for analysis. This task involved assembling an electronic device (a scrap Seiko Smartpad2) that mainly consisted fastening metal screws in screw holes using a Philips screwdriver with simple to understand assembly instructions. The disassembled parts were kept in front of subject that included a board, a set nine screws and a Philips screwdriver as shown in Fig. 2. The hand workspace size was limited to 45 cm. Size of all the screws were roughly 5 mm. The subjects were given following instructions and were instructed to maintain precision wherever possible.
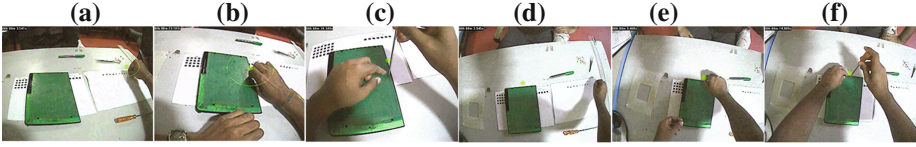
Fig. 2. Setup used in manual assembly task. While performing the manual assembly in sitting posture, eye remains constantly fixated at the target while (a) picking a screw, (b) inserting the screw into screw-hole, and (c) fastening the screw using screw-driver. Similar behavior is observed in standing posture shown in (d), (e) and (f) (Color figure online).

 i. Pick one screw each time starting from right
 ii. Place it over the hole starting from top left in clockwise direction
 iii. Pick the screw driver and fasten the screw
 iv. Place the screwdriver back.

2.3   Observations

Upon analyzing the visual data obtained from eye tracker, it was observed that all the subjects visually fixated at three main locations, where the component of interest were present during the following three behavioral activities.

 i. Pick - This involved saccadic search to locate a screw, followed by fixation at the location the screw till the hand reaches the target (Fig. 2a and d).
 ii. Insert - This involved pre-searching for the screw hole and locating its position followed by inserting the screw (Fig. 2b and e).
 iii. Fasten - This involved picking the screwdriver, aligning it with screw head and fastening it (Fig. 2c and f).

For above mentioned three visual activities, the eye fixation time was calculated for each of the nine screws. While performing activity (i), the eye always preceded hand and in most cases eye moved to activity (ii) even before actual pick happened with hand. Hence we considered the time only till eye remained fixated on the screws. In activity (ii) we omitted the time spent after the screw was aligned with screw hole, just before actual insert operation performed by hand. This was done because all the subjects had different pace of fastening the screw where vision did not played active role. Similarly for activity (iii) we omitted the manual fastening time spent after screw-driver was aligned with screw head.

The task was performed at sitting and standing posture. According the analysis results, the fixation time for all three activities and the total activity time was reduced when subjects performed tasks in standing posture as compared to sitting posture. The results are further discussed in Sect. 4.1. It was observed that while size of hand workspace was same in both the cases, the size of visual workspace was less at standing posture as compared to sitting posture. In sitting posture, although the components were visually located near the subject, but they were projected in wider visual field of view. This can also be observed in

eye-tracker scene frame in Fig. 2(a), (b), (c). Hence while sitting, we observed that both head and eye moved for locating the components followed by gradual hand movements. In standing posture the components were visually located twice as far as sitting posture, the complete visual workspace was visible in narrow visual field of view. We observed only eye movements and head remained still most of the time. The hand movements were faster probably due to faster visual estimation of target locations and hand trajectory. In both sitting and standing posture, the subjects did not faced any visual strain in seeing the components, however some subjects reported back strain while performing the task in standing posture due to bending forward. For further experimentation following observations were hypothesized for further validation with a constraint that components should be properly visible and placed well within hand reach envelope:

1. Working from farther visual distances may reduce the task completion time since most details are visible in central field of vision that helps in better estimation of hand and tool-component location.
2. Searching and matching one component (like screw) with the other (like screw hole) involves comparison or recognition either on the basis of stored features in memory or visually comparing the size. Performing such activities from longer visual distances may lead to reduction in task completion time.

3   Experimental Tasks for Hypothesis Verification

We performed two simulated task experiments aimed specifically to understand the hypothesis derived in previous section. "Pick" and "Insert" behavior of assembly task was simplified to "Pick" and "Place" in first experiment where subjects were asked to create duplicate copy of alphabets block. We observed that visual search can be of two types viz. search to find the target on the basis of features in memory, like searching for a screw driver and search to recognize a target by comparing size tolerances of two or more components, like searching for an appropriate size screw on the basis of size of screw hole. First experiment was targeted searching of alphabets blocks on the basis of memory and the second experiment was targeted towards searching of multiple targets on the basis of size comparison with a given source. The experiments are described in following sub-sections.

3.1   Block Duplication Task

Setup. This task involves the assembly of a copy of a pattern made of alphabetical blocks similar to experiments done by Ballard et al. [1] and Hayhoe et al. [10]. The setup is shown in Fig. 3a (without measurement markings) was printed on a A4 sheet of paper and glued on tabletop for performing this task. A total of 15 pair of plastic blocks with English characters imprinted on sides (making a total of 30 blocks) were divided in 2 groups. As shown in Fig. 3a, group towards
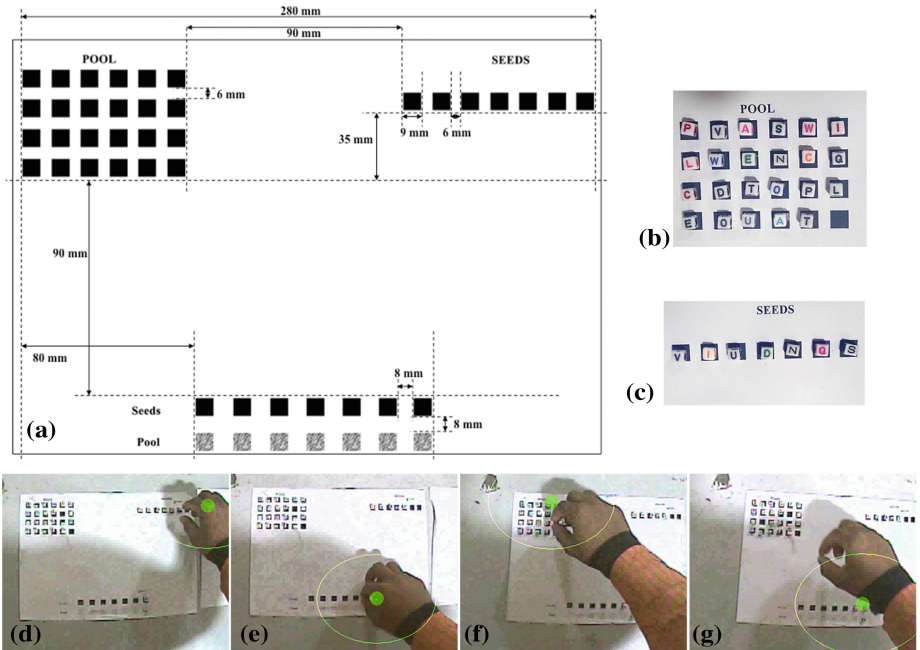
Fig. 3. (a) Setup used in Block Duplication task. (b) Plastic blocks placed over "Pool" and (c) "Seeds" group. (d) Eye is fixated at the target before the actual pick by hand from seed group, (e) eye is fixated at the target before placing the block over white sheet on green circle, (f) eye involved in searching while hand is preceding to pick the target (g) eye is fixated at the target before placing the duplicate block over white sheet on grey block (Color figure online).

right side, called as seeds, consisted of 7 randomly selected blocks (Fig. 3c) and group in left side, called as pool, consisted of remaining 23 blocks (Fig. 3b). The size of each square block was roughly 8 mm. Two rows were printed separated by a distance of 8 mm. Each row consisted of 7 solid square cells of size 9 mm separated by a distance of 25 mm. Cells in top row were colored as black and the bottom row cells were colored gray.

Procedure. The procedure involved two steps. In first step, the subject had to pick up a block from seeds group sequentially starting from left most and place it precisely over first black square cell in the bottom region. In second step, the subject had to look for the matching block (based on character imprinted) from the pool group, pick up and place it over first grey cell. Hence each block placed over black cell had a duplicate block places over grey cell. The task should continue till all seven blocks were kept on white strip along with the seven matches. The experiment was performed in sitting and standing postures.

Observations. It was observed that while performing block duplication task, the eyes fixate for longer duration and at distinct locations for the activities that were motor dependent. Hence this task was divided into following four activities for analysis:

   i. Pick Seed: Eye-fixation before and during the picking if the block from seed group (Fig. 3d).
  ii. Place Seed: Placing the block over white sheet on black square (Fig. 3e).
 iii. Search in Pool and Pick Duplicate: Searching and picking the duplicate block from pool group (Fig. 3f).
 iv. Place Duplicate: Placing the duplicate block over white sheet on grey square (Fig. 3g).

Fixation time was computed for each activity and we noticed that subjects were able to perform better from distance. However there were cases when subjects accidentally dropped a block or forgot to place it in correct position. Those cases were not considered for analysis.

3.2   Visual Peg-in-Hole Task

Setup. A 22 in. LCD Monitor (DELL2209W) was placed on the table in front of the subject at a distance of 30 cm as shown in Fig. 4a. The display was inclined at an angle of 15° from surface of the table. The brightness and contrast were set to 50 % of maximum value such that whites and blacks appear at same light intensity. The subjects were shown several images one at a time on the display. Left half of image consisted of a white solid circle of a specific size on a black background, representing a hole. Right half of image consisted of 17 black solid circles over white background, representing pegs as shown in Fig. 4b and c. The size of pegs varied randomly from 8 mm to 46 mm. For preventing crowding effect, the arrangement was made in such a way, that only top area was kept crowded as compared to bottom. For the purpose of experimental analysis, a total of three images were shown to the subject by keeping the size of hole as 24 mm, 33 mm and 49 mm. For preventing subjects from memorizing the correct sizes at each trial, as a distraction, two more sizes of holes were added in between each trial, one of which was largest of all (56 mm) and another smallest (16 mm). They were not considered in analysis.

Procedure. The task is inspired from trivial peg-in-hole assembly task. At each trial, the subject had to look for white hole in left and point out the black pegs that may fit into hole using his index finger (Fig. 4c). The size comparison has to be done solely on visual basis. The subjects were asked to follow the above-mentioned procedure and perform the task as precise as possible.

Observations. This task mainly involved comparing the pegs located in right half with the hole on the basis of the size. The tasks were performed at sitting
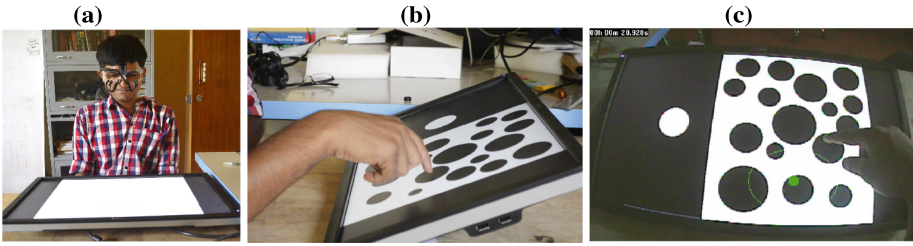
Fig. 4. (a) Setup showing LCD Monitor kept in front of subject. (b) Monitor displaying peg-hole image to the subject. (c) Eye-tracker camera output showing that subject is pointing a selected peg while his eye is fixated at next target peg (Color figure online).

and standing posture. Based on the obtained data, for each given hole, task completion time was calculated. Also the frequency of comparisons in terms of saccades for a given hole with each peg was also noted. For the cases where more number of pegs were closer to given hole in terms of size, had more frequent size comparisons and took more time in task completion irrespective of distance. Number of comparisons between hole and pegs and accuracy of task remained almost same (80 %) in both sitting and standing posture. Holes that very closely resembled pegs in terms of size were missed probably due to bleeding effect of black-white contrast. All the subjects took less amount of time in completing the task in standing posture as compared to sitting posture.

4   Results

4.1   Manual Screw Fastening Task

For visual distance of 0.3 m (sitting posture), the subjects spent an average 1.19 s for fixating over screw before picking with hand (activity [i]). Before inserting they spent an average of 2.60 s fixating over screw hole till the screw was properly aligned with hole (activity [ii]). Fixation time spent before fastening over screw till the screwdriver aligned with the screw head was 4.25 s (activity [iii]). While performing the same task at a distance of 0.6 m (standing posture), the fixation time reduced to 1.04 s, 2.28 s and 3.83 s for activity [i], [ii] and [iii]. Figure 5a shows the graph comparing time spent for each activity at sitting and standing posture. As shown in Fig. 5d, the total visual fixation time dropped by 9.5 % in standing posture. Paired two-sample t-test gave a p-value of 0.03, that shows that obtained results are significant.

4.2   Block Duplication Task

The visual fixation time was averaged for each of the four subtasks mentioned in Sect. 3.1 based on values obtained for seven blocks for all seven subjects. For visual distance of 0.3 m, the average time for sub-task (i), (ii), (iii) and (iv) was 1.11 s, 1.60 s, 2.95 s and 2.11 s, and for the distance of 0.6 m, the average time was reduced to 1.00 s, 1.41 s, 2.49 s, and 1.84 s. Figure 5b shows the graph
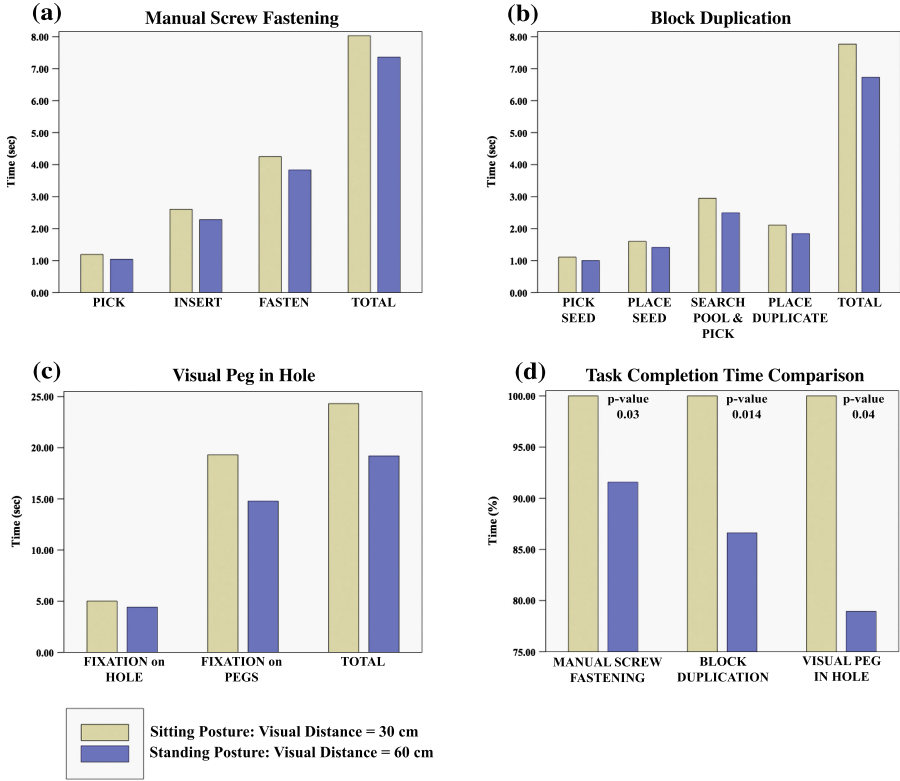
Fig. 5. Plots (a), (b) and (c) show the comparison of average time taken under each task for different activities and total task time taken at two different visual distances. Plot shown in (d) shows percentage of reduction of total task completion time in standing posture as compared to sitting posture (Color figure online).

comparing time spent for each sub task at sitting and standing posture. As shown in Fig. 5d, the total visual fixation time dropped by 13.4 % in standing posture. Paired two-sample t-test gave a p-value of 0.014, that shows that obtained results are significant.

4.3   Visual Peg-in-Hole Task

This task only relied on comparisons on the basis of vision. Hand usage was done only to point that was negligible. Time spent in searching for target among in the group of 17 pegs reduced significantly from 19.30 s to 14.44 s, when task was performed at standing posture. Time spent on fixating over hole for comparison dropped from 5.01 s to 4.42 s with distance while the average number of comparisons remained 11 to 12 per hole at both the postures. Figure 5c shows the graph comparing time spent for each sub task at sitting and standing posture. As shown in Fig. 5d, the total visual fixation time dropped significantly by 21 %

in standing posture. Paired two-sample t-test gave a p-value of 0.04, that shows that obtained results are significant but with higher variance.

4.4   Comparison Across Tasks

Comparing the graphs shown in Fig. 5a and b, it can be seen that average time to pick a screw and a block is almost same since both were of same dimensions. Inserting the screw involved aligning the screw with respect to smaller screw hole and hence fixation time is more in this case as compared to time spent in activity (ii) and (iii) of Block Duplication Task. Fastening a screw involved searching for screwdriver and bringing it closer to screw head for aligning, hence this activity has taken maximum time. Time taken in search for both Block Duplication and Visual Peg in Hole dropped considerably in both the tasks. This effect can also be seen in Insert and Fasten activities of manual screw fastening task.

5   Discussion and Future Work

With a primary objective to minimizing lead time and improving total assembly cost, methods like Manual Design Efficiency by Boothroyd [3], Design for Assembly Calculator by Sturges [11], MTM, MODAPTS, MOST [8] etc., have been designed for the prediction of assembly time and simplification of manual assembly. They have been targeted for the optimization of trivial shop floor assemblies like material handling, lifting weight, etc. Many of them rely on some form of Fitts index of difficulty (ID) as given in Fitts' law that classify any manual task on the basis of distance traveled by hand and size of target [7]. However these methodologies may not work in the case of precision assemblies since movement, speed and accuracy of hand relies mostly on visual feedback.

There are several areas where movements of the eyes have been studied in depth. In [6,13] authors have studied eye movements while reading text and in [14,20] music reading. In this paper we have studied eye movements for manual assembly and correlated visual working distance with task completion time. For the three tasks performed in this study, it can bee seen that between sitting and standing posture, due to depth perception, only the perceived visual distance was changed between hand and component. The distance traveled by hand as well as component size remained same. Hence fitts' law and other automated tools may not work effectively under scenarios like these where there is a chance of improving the human performance lies on visual characteristics and behavior of operators performing the task by changing the visual distance across population. However behavior like these can be simulated on the basis of individual visual attributes, using modern ergonomics assessment tools like digital human models (DHM) that are slowly leading towards the same direction.

We developed a functional vision model that enables one to systematically incorporate human factors like acuity, central and peripheral vision, accommodation, etc. that affect visibility and legibility of components at any given visual distance [2]. On the basis of this model the visual distances (30 cm and 60 cm)

were chosen for the current study, that ensured us the legibility components on which subjects were working. However the model reported only a range of distances were full legibility of components was available. Working on the components very close and very far, both dropped the legibility. In this pilot study we have only shown that withing a permissible range of visual distance, working on a higher range can reduce the task performance time thereby increasing the efficiency. In future we plan to perform the same study across range of distance and with more number of subjects so as to mathematically formulate variation of visual performance with working distance for any component in vision dominated precision task. This formulation can also be used in natural visual behavior simulations like search, reach, etc. and also for evaluating human performance using DHM.

6 Conclusion

In this paper we have presented a pilot study done on seven subjects to study the variation in human task performance with respect to visual distance on a manual precision task of fastening a screw using as eye-tracker. The task was further simplified to pick, place and search behaviors for which two more laboratory experiments were performed. It was observed that as long as components remained properly visible and within hand reach to all the subjects, the subjects were able to perform faster at a longer visual distance. The visual distances were limited to two values of 30 cm and 60 cm for which an improvement in task completion time was observed at higher visual distance. However we believe that on the basis of object type and visual characteristics of operator, there may be a range of working distance under which task performance may improve, beyond which it may start to decline. In future we plan to perform similar study across range of distances by varying components and with large number of subjects. This will help us in formulating a mathematical relationship that can be used for predicting task performances and computer simulations.

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