Human Factors in Mechanized Cut-to-Length Forest Operations

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Cover: Logging operations with a harvester operator wearing eye-tracking equipment. (photo: Skogforsk)

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Abstract

Although forest operations research has a more than 50-year-long tradition in the field of human factors, there is a current decline in resources put on continuous and systematic human factors research. Therefore, the overall aim of this thesis was to contribute new knowledge on working conditions in mechanized cut-to-length logging operations and their relationship to system performance. Findings from four different studies, each using different research methods and approaches, were compiled and discussed based on their relevance to operator working conditions and logging system performance in a Nordic context and with a broader international outlook.

A human, technology and organization (HTO) framework was used in Study I to scrutinize the problems that exist in the interactions between these three aspects. The body of knowledge on the H, T and O aspects was extended in Studies II, III and IV based on problem identification Study I.

In study II, it was emphasized that most Swedish logging contractors were relatively small enterprises working purely with machine operations. Consequently, with the exception of between harvester and forwarder, task rotation has limited potential to be implemented within most companies.

In Study III, forwarder crane work was essentially ruled out as a major source of harmful levels of whole body vibration (WBV). The results also indicated that the choice of grapple may prove important with respect to avoiding costly growth losses for the landowner and environmental concerns.

In Study IV, gaze behaviour was investigated in an observational field study. By comparing operators in first thinning, second thinning and final felling, a task-dependent information search pattern was identified. Specifically, the information on the bucking monitor and the tree being felled was less frequently attended to, i.e. less interesting, during first thinning than during the other operation types.

Taken as a whole, much of the forestry literature focuses on individual aspects of the work environment, as in studies II-IV, and a systems perspective is less frequently applied. A hindrance to applying a systems perspective is that it demands transdisciplinary research teams and interdisciplinary research. However, this should be seen as an opportunity and not a hindrance to successful future research.

Keywords: contractors, cut-to-length, ergonomics, eye tracking, forwarder, harvester, logging, mechanized forestry, MTO, whole body vibration

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Writing is easy: All you do is sit staring at a blank sheet of paper until drops of blood form on your forehead.

Gene Fowler

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Carola Häggström
Umeå, May 2015

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Carola Häggström & Ola Lindroos. Human, technology, organization and environment – A systems perspective on human factors in forest harvesting. (*Manuscript*).

II Carola Häggström, Akie Kawasaki & Gun Lidestav (2013). Profiles of forestry contractors and development of the forestry-contracting sector in Sweden. *Scandinavian Journal of Forest Research* 28(4), 395-404.

III Carola Häggström, Mikael Öhman, Lage Burström, Tomas Nordfjell & Ola Lindroos (In press). Vibration exposure in forwarder work: effects of work element and grapple type. *Croatian Journal of Forest Engineering*.

IV Carola Häggström, Martin Englund Ola Lindroos (accepted with minor revision). Examining the gaze behaviors of harvester operators: an eye-tracking study. *International Journal of Forest Engineering*.

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The contribution of Carola Häggström to the papers included in this thesis was as follows:

I Planned and designed the study in cooperation with main supervisor and co-author. Carried out the literature search, developed the extended the framework and wrote the majority of the manuscript.

II Contributed to the study design. Performed the analysis of the material and wrote the majority of the manuscript.

III Contributed to the study design. Performed the statistical analysis of the material and wrote the majority of the manuscript.

IV Designed the study jointly with the co-authors and main supervisor. Performed the majority of the material analysis and wrote the majority of the manuscript.

Abbreviations

AOI	Area of interest
CTL	Cut-to-length
HTO	Human, Technology and Organization
r.m.s.	Root mean square
RTA	Retrospective think aloud interview
VDV	Fourth power vibration dose value
WBV	Whole body vibrations
WE	Work element

1 Introduction

Forest operations research has a more than 50-year tradition in the field of human factors. The main focus of this research has been on forestry workers' abilities, physical workloads, work satisfaction and the workers' exposure to various environmental stresses, such as noise, vibration and non-ideal lighting conditions (Gardell, 1976; Teljstedt, 1974; Hellstrøm & Andersen, 1972; Hansson, 1965). Ager's (2014) detailed and personal description of this research and the long-term development of forestry work in Sweden exposes a current lack of systematic and continuous human factors research in Sweden. The scientific discipline of human factors is concerned with understanding how humans relate to the world around in order to optimize human well-being and performance of the system. Health and safety in forestry has been the subject of many reviews (e.g. Albizu-Urionabarrenetxea *et al.*, 2013; Jack & Oliver, 2008; Kirk *et al.*, 1997; Slappendel *et al.*, 1993). In the present study, the focus is on issues related to the forest machine operator's work environment and the operational performance. While the specific focus is on operator and performance, safety and health are recognized as important aspects within this domain, and those aspects are thus also briefly discussed.

Production performance and resulting economic performance are key factors in most production systems. However, the term performance has a wide range of definitions in the literature (see Tangen, 2005) and can be applied to the entire supply system (Audy *et al.*, 2012; Beamon, 1999), company (Tangen, 2003) and production unit levels (e.g. Eriksson & Lindroos, 2014). Naturally, these factors are of great importance within forestry in terms of competitiveness and value-adding (Rådström, 2014). To date, value adding has been mainly addressed on the manufacturing side (e.g. saw and pulp mills), whereas the supply side (logging and hauling) has mainly focused on competitiveness through improved cost-efficiency. In the face of continuously increasing (e.g. labour) costs, productivity improvement has been key to maintaining and even decreasing costs per produced unit (e.g. USD/m^3 roundwood). However, lately concern has been raised, for example in Sweden, that the trend of continuous productivity improvements has stagnated, and even declined somewhat (Rådström, 2014; Nordfjell *et al.*, 2010). Hereafter, the term productivity is used in reference to the relation between produced goods (output) and the resources used (input), whereas performance is used to encompass productivity and other more qualitative aspects of how well work is executed. The performance of the logging system is affected by performance shaping factors (PSFs), commonly categorized as internal PSFs, external PSFs and stressors (Osvalder & Ulfvengren, 2008). External PSFs for harvesting can, for example, be divided into physical environment, machine related and organizational factors. Internal PSFs are related to personality and behaviour and also the physiological properties of the body. The knowledge and abilities of colleagues, superiors, and the operators themselves are also important internal PSFs. Stressors are related to pressure at work, such as work pace and lack of feedback, and to physiological stressors, such as fatigue, vibration and heat stress.

The work organization of Swedish forestry workers changed drastically during the 1980s as machines became commonplace. Large-scale forestry companies began subsequently to outsource mechanized forestry operations in order to reduce costs. The first tasks to be outsourced were mechanized operations in terrain transportation, harvesting, and soil scarification (Lidén, 1995; Lidén, 1994; Bostrand, 1984), later followed by manual and motor-manual silvicultural activities, mainly planting and pre-commercial thinning (Eriksson, 1999). However, silvicultural machines, such as planting machines and pre-commercial thinning machines, are still rare (Ersson, 2014; Ligné, 2004; Lidén, 1995). As a result of the ongoing outsourcing of processes, forestry contractors now hold a key position in the timber supply chain in many European countries, as well as in some American, African, and Asian countries (see Kastenholz *et al.*, 2011; Kawasaki & Kohroki, 2009; Baker & Dale Greene, 2008; Westermayer, 2006; Bigot *et al.*, 2005; Louw, 2004). Nevertheless, there is a lack of systematically gathered data on Swedish logging contractors.

Large scale forestry now determines the planning horizon and many of the preconditions for the contractors' work (see Eriksson et al. 2015; Vik, 2005). If the cooperation between client and contractor is dysfunctional it can induce a negatively charged organisational culture characterised by dissatisfaction, stress and higher costs for the logging operations (see Vik, 2005; Pontén, 2000).

The physical nature of the work also changed fundamentally with mechanization. Although the physical intensity of the work fell dramatically, it also became highly repetitive and workers became exposed to associated stresses for longer durations (Axelsson & Pontén, 1990). Interacting stressors typically associated with repetitive stress injuries include, for example, whole body vibrations (WBVs), repetitive hand and arm movements, non-neutral body postures and manual lifting (Burström *et al.*, 2014; Lis *et al.*, 2007; Okunribido *et al.*, 2006; Punnett & Wegman, 2004). Consequently, operators of forestry machines have a high prevalence of musculoskeletal symptoms in the lower back, neck and shoulders (Jack & Oliver, 2008; Rehn *et al.*, 2002). It is suggested that the high prevalence of neck pain among forestry machine operators is associated with exposure to shock-type vibration, although the association between WBV exposure and neck and arm pain has not yet been clearly established (Rehn *et al.*, 2009). Shocks may also be more important than sinusoidal vibration with regard to low back pain (Okunribido *et al.*, 2006). Reduced WBV should therefore improve the work environment for forestry machine operators.

Today, the cut-to-length (CTL), or rather bucking-to-value procedure is fully (machine) automated, but the harvester operator is expected to determine tree qualities and species and to visually identify stem defects. However, the increase in work-related data yielded by advanced sensors and computers in forestry machines provides rapidly increasing opportunities to produce decision support systems and automate processes. Upcoming decision supports will most likely utilize graphical user interfaces due to problems in using tactile or advanced auditory stimuli in vibrating and noisy environments. Thus, thorough understanding of workers' visual behaviour will become important for developing safe, efficient forestry machines and work procedures. Research is ongoing in areas such as decision support for route planning of logging sites (Mohtashami *et al.*, 2012), intelligent boom control and automated functions (Ortiz Morales, 2015; Hansson & Servin, 2010; Löfgren, 2009; Attebrant *et al.*, 1997), teleoperated forestry vehicles (Milne *et al.*, 2013; Westerberg & Shiriaev, 2013; Bergkvist *et al.*, 2006), and unmanned self-navigating vehicles (Ringdahl *et al.*, 2011; Hellström *et al.*, 2009; Vestlund & Hellström, 2006). Autonomous vehicles are lighter and drive faster, and relieve the operator of harmful WBV exposure. However, concerns remain regarding the safety and the cognitive work needed to monitor and control such vehicles (see Sarter *et al.*, 1997; Bainbridge, 1983). Human factors engineering thus offers a way of minimizing the risk of unwanted outcomes from product design. Moreover, poor usability engineering may prove costly for the company producing the product (Bias & Mayhew, 2005). The cost of customer support for a poor product may become high, leading, in the worst case, to its failure and withdrawal from the market. According to Stanton *et al.* (2001), automation in aviation has taught us to expect a shortfall in expected benefits; it becomes more costly, causes equipment to become less reliable, increases the need for training in skills and maintenance, and may induce human error. With increasing automation operators receive less on-the-job training in manual procedures, thus impoverishing the operator's knowledge and, specifically, their skilled expertise. Moreover, insufficient operator knowledge and ability to override the automation when necessary can lead to major consequences in terms of both safety and performance (Amalberti & Deblon, 1992). These expected shortfalls can be compared to early mechanization when logging costs increased and worker health was severely compromised by immature systems (see Ager, 2014; Axelsson, 1998; Väyrynen, 1984). Thus, the next generation of automation is likely to introduce a system change comparable to that brought by the introduction of mechanization to forestry work. As the nature of the work continues to evolve, old "truths" about safety, health and performance will need to be re-examined and revised in light of both new and old methods. Consequently, there is a need to include human factors specialists in product design and to conduct research that is relevant to practitioners in this field.

1.1 Mechanized CTL operations

Mechanized CTL harvesting is most often associated with harvester and forwarder operations, which is also what is considered here. Although the logging operation is rather straightforward in terms of how the two machine types are used to do the work of transforming trees to logs placed at roadside, there is nevertheless some variation in the tasks and decisions that are taken by the machine operators. In some regions the operator takes the majority of operative forest management decisions (see Hultåker 2006, Eriksson et al. 2015), whereas in other regions operators are expected to follow detailed instructions from foresters (e.g. drive on pre-marked strip roads and harvest pre-marked trees). The former case is most common in the Nordic countries, and will therefore be the main point of view in this thesis. For a thorough description of roles and the principal organization of Swedish industrial forestry, see Hugosson (1999).

1.1.1 Harvesting

The harvester operator is expected to position the machine for harvesting, to select and reach the tree to be felled, to fell and move it to the chosen location where it is processed (i.e. delimbed and bucked), and put into log piles where the logs, sorted by assortment, can be easily collected by the forwarder. Delimbing is done by feeding the stem through the harvester head. A delimbed stem section is cross-cut (i.e. bucked) into a log of suitable length before delimbing the next section and bucking the next log. The bucking is aided by decision support systems which suggest value-maximizing log lengths and assortments (Malinen & Palander, 2004; Olsen *et al.*, 1991). This process is repeated for each tree, with around 100-200 trees cut per hour (Eriksson & Lindroos, 2014).

Forest harvesting has been described as joystick-intense, mentally demanding work in which visual information and supervision are important (Gellerstedt, 2002; Hansson, 1990). As partly described above, the harvester operator's work tasks include, among other things, controlling both the crane and the machine, evaluating ground conditions, determining tree species and quality, detecting approaching people, and supervising the equipment. Riding a bike or driving a car soon becomes an automatic behaviour, and the same applies to manoeuvring a forestry machine (see skill-based behaviour Rasmussen, 1983). Many automatic behaviours rely on implicit knowledge, and thus harvester operators are typically unable to describe the functions of the joysticks without physical demonstration (see Gellerstedt, 2002). Nevertheless, visual supervision is involved in the performance of automatic tasks due to the complexity of coordinating the actions – even when the operator not is consciously aware of it (Land *et al.*, 1999). Thus, apart from the traditional methods of cognitive task analysis, eye movement analysis may prove valuable by facilitating the difficult process of extracting implicit knowledge.

1.1.2 Forwarding

The forwarder operator is tasked with collecting the pre-sorted logs from the forest and transporting them to the roadside. Terrain driving is therefore an essential part of forwarding, whereas driving is only required for short distances during harvesting, such as when repositioning to reach new trees. As a consequence, the work pace is normally lower in forwarding compared to harvesting. In forwarder work, productivity is benefitted by as fast driving as possible. However, the work also includes the complex logistic problem of determining how to allocate the correct number and proportion of assortments in the various loads in order to forward a given stand efficiently.

The work of the forwarder operator also includes many tasks similar to those of the harvester operator, such as controlling both the crane and the machine, evaluating ground conditions, detecting approaching people, and supervising the equipment. An important logistic, problem-solving aspect of forwarder operation is the ability to identify and separate wood assortments among logs on the ground as well as in the bunk. Similar to harvesting, crane work and driving soon become highly automatic for the operator.

Driving in terrain is the major source of WBV during forestry operations, and the type and amount of vibration transmitted to the driver is mainly determined by speed and ground roughness in combination with chair and vehicle design (Rehn *et al.*, 2005a; Hansson, 1990). Much research has therefore been put into various dampening systems for vehicles, chairs and cushioning (Baes, 2008; Cation *et al.*, 2008; Sherwin *et al.*, 2004; Mansfield *et al.*, 2002; Gellerstedt, 1998; Sankar & Afonso, 1993; Boileau & Rakheja, 1990). Nevertheless, WBV persists as a major challenge in forestry, and knowledge of when and why shocks occur remains scarce. Shock-type vibrations have been identified while loading the forwarder (Rehn *et al.*, 2005a), but to my knowledge no previous study has examined WBV exposure in sufficient detail to differentiate exposure levels during crane work and during driving.

1.1.3 The physical environment

The performance of the human operator is affected by the physical environment. The outdoor setting in which forest operations are conducted offers limited possibilities to influence the work environment of the operator compared, for instance, to industrial settings. Forest work is thus affected by the characteristics of the forest stand in which the work is carried out. For instance, tree species composition, stem size, distance to roads, stand size, terrain slope, type of felling (e.g. thinning or final felling) and environmental concerns delimit and define the boundaries of forestry machine operation (see e.g. Eriksson & Lindroos, 2014; Hiesl & Benjamin, 2013). Moreover, difficult terrain, such as poor carrying capacity, slippery ground or steep slopes, hinders work (see e.g. Kolodny & Kiggundu, 1980; Andersson *et al.*, 1968).

The forest itself can range from natural forest to plantation. Natural forests vary depending on the local conditions, and plantations also vary greatly in appearance. Some plantations are similar to prepared agricultural fields (crops), while others are managed to preserve as much of the forest’s natural features as possible (Sands, 2013).

Weather is also a key source of variation in work conditions, especially as the work is often conducted round the clock and year-round. In the Nordics, an operator might be working in bright daylight at +25°C one day, and a few months later in pitch dark and snow at -25°C. The weather can impact performance through, for instance, impaired visibility due to rain, snow or sun glare, and physical exposure to heat or cold during repair and maintenance work or when entering or exiting the cabin (Wästerlund, 1998; Gellerstedt, 1993). Maintenance may also expose the worker to harmful oils and solvents (Väyrynen, 1984).

Some environmental conditions may be alterable, if permitted according to national legislation and certification schemes. For instance, some countries may permit the levelling of rough terrain, whereas in others a minimum impact policy may be enforced. However, many environmental aspects, such as climate and weather, are impossible to alter but their effects can be managed. Forest work conditions are thus largely determined by environmental factors, and human operators are required to adapt their choice of technology, work methods and work organization accordingly.

2 Aim

The overall aim of this thesis was to contribute new knowledge on working conditions in mechanized cut-to-length logging operations and their relationship to system performance by examining aspects of the operator, the machine, and the work organization. Findings from four different studies, each using different research methods and approaches, were compiled and discussed based on their relevance to forest machine operators and logging system performance. Study I, presented in Chapter 4, provides a background to human factors research applied in Forestry. The study introduces some key problems identified in the interactions between human, technology and organization (HTO), and provides an HTO perspective with which to approach studies II–IV. The following chapters 5-7 address the aspects of HTO. Accordingly, Chapter 5 aims to elaborate the understanding of the organizational context of Swedish contract forestry, and especially the structures of logging contractors (Study II). Chapter 6 addresses specific logging technology (grapples) and human reactions with respect to vibration and performance (Study III). Chapter 7 addresses aspects of human (visual) behaviour and human–technology interaction (Study IV). The study concludes with suggestions for future research and comments on implications for forestry researchers and practitioners.

Specific aims of papers I-IV:

Paper I: To provide an updated description of human factors research relevant to the production performance of the harvesting system and to scrutinize problems that exist in the interactions between human, technology and organization.

Paper II: To describe and discuss forestry contractors' company structure and development, including an evaluation of who they are, how many there are, how many workers they employ and who are hiring them.

Paper III: To assess the contributions of specific crane work elements to overall vibration exposure in small forwarders and possible effects of three grapple and brake-link combinations on whole body vibration exposure.

Paper IV: Firstly: to obtain information on harvester operators' visual behaviour and categorize it in relation to existing literature on natural vision. Secondly: to evaluate an eye-tracking system as a diagnostic tool in real-world harvesting work in terms of data quality, precision and accuracy, and the data analysis process in terms of ease of analysis.

3 Conceptual framework

The International Ergonomics Association (IEA) defines human factors and ergonomics as: *the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance* (retrieved 2015-02-06, http://www.iea.cc/whats/).

Human factors and ergonomics are often used as synonyms. However, in many countries ergonomics is closely associated with physical ergonomics. Thus, the term human factors is mainly used in this thesis. Similar to the concept of human factors and ergonomics is HTO (Human, Technology and Organization; in some literature referred to as MTO). This concept has been introduced to facilitate a comprehensive socio-technological view (system thinking) of work in which the three interrelated elements – human, technology and organization – and their relations are brought into keener focus (Karltun *et al.*, 2014; Rollenhagen, 2000). While safety has been the main focus of HTO studies (see Rollenhagen, 2000), HTO has also been successfully applied to increase efficiency and enhance performance (Karltun *et al.*, 2014). The HTO framework (*Figure 1*) and its implications for harvesting system production performance framed and provided the focus for the present thesis.

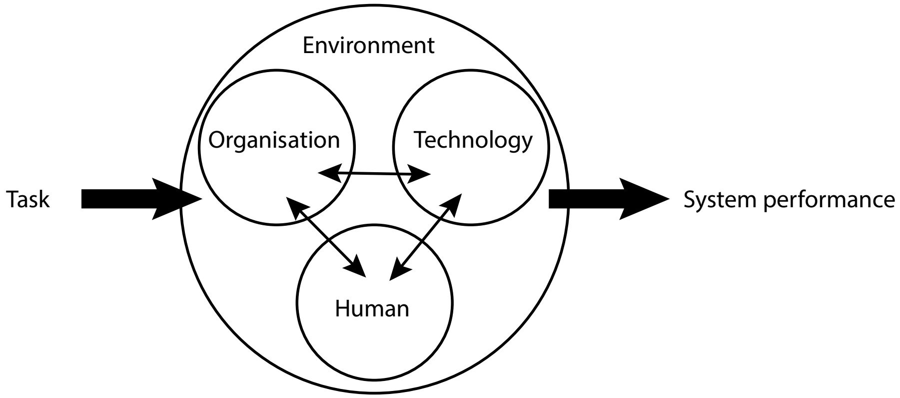

Figure 1. The HTO framework showing the interactions between human, technology, organization and environment (context) affecting system performance (Paper I).

4 Study I – HTO in mechanized CTL forestry

This chapter introduces some key problems identified in the interactions between human, technology and organization, and their implications for the production performance of the harvesting system. Moreover, Study I positions the other three studies within the HTO framework. For this purpose, a selective literature review was conducted. Most literature for the review was found in the Web of Knowledge and Google Scholar databases, or as a consequence of the snowballing approach also applied. In addition, local libraries and papers encountered during previous research projects were also used. Literature addressing the operation of machines in the harvester-forwarder system was prioritized. Moreover, mainly papers published in English or Swedish were included.

A literature search was conducted using various terms closely related to human factors (e.g. ergonomics, human engineering, human factors engineering, usability engineering, and user-centred design, Beith, 1999), as well as variations of following terms: Human-Machine-Interaction/interface (HMI), Human-Computer-Interaction/interface (HCI), organization, cognitive, cognition, (Hu)man-Technology-Organization (HTO), sociotechnical system and system perspective in relation to forestry, forestry machines, harvester, harvesting and logging.

4.1 Human: skills and abilities

It has been argued that operator performance is becoming a bottleneck for increased productivity (e.g. Westerberg & Shiriaev, 2013; Löfgren, 2009; Gellerstedt, 2002; Gellerstedt, 1997). The importance of specific human abilities to forestry work performance has been (somewhat moderately) researched for over 60 years (Ager, 2014; Andersson *et al.*, 1968; Hansson, 1965). Concentration, decision making, memory, motivation, motor coordination, pattern recognition, planning capacity, logic reasoning, and spatial perception are abilities that have been described as important for successful harvesting work (Tervo *et al.*, 2010; Ovaskainen & Heikkilä, 2007; Parise, 2004; Gellerstedt, 2002; Andersson *et al.*, 1968). However, the importance and validity of ability testing for identifying skilled or talented operators has yet to be proven (see the results of Ovaskainen & Heikkilä, 2007; Garland, 1990; Andersson *et al.*, 1968). In addition to the challenge of finding and testing relevant performance indicator(s), selection processes involve an abundance of applicants. However, in many areas of the world it can be challenging to find even the minimum number of forest workers required and future labour shortages are expected (Bernasconi & Schroff, 2011; Baker & Dale Greene, 2008; Egan & Taggart, 2004). Thus, training and usable, user-friendly, machines are and will be crucial in the future, and will require adaption to general, as opposed to narrowly selected, users.

Moreover, in order to keep existing machine operators and attract new ones the work must be considered attractive (see Kolstrup, 2012; Kolstrup *et al.*, 2008; Lewark & Kastenholz, 2007; Åteg *et al.*, 2004). In a small Swedish study, most machine operators stayed within the profession (Bergquist, 2009). However, the general perception both in Sweden and internationally is that it has become difficult to attract new forestry workers (see Ager, 2014; Lewark & Kastenholz, 2007; Egan & Taggart, 2004).

Operator skill clearly has an important impact on operational outcome. However, exactly what skills constitutes this impact is less obvious and less investigated. Various skills have been reported to affect system performance, including technical, maintenance, planning (of how and in what order a stand is harvested and extracted), cooperative, know-how, and automated machine control skills (e.g. Tervo *et al.*, 2010; Gellerstedt, 2002; Kolodny & Kiggundu, 1980). In order to measure skill, the concept has been operationalized as, for example, the number of simultaneous lever or joystick movements (see Tervo *et al.*, 2010; Parise, 2004; Andersson *et al.*, 1968) and the proportion of time spent on various work phases (Palander *et al.*, 2012; Tervo *et al.*, 2010; Parise, 2004). Productivity is also a measure of skill. When there is a discrepancy between operator skill and ability and the conditions and demands of the work task, the workload becomes high. Measures of heart rate variability as an indicator of mental workload have been presented in a few studies on harvester operators (Tynkkynen, 2001; Yamada, 1998; Gellerstedt, 1997; Inoue, 1996), but the measure was excluded from the study of Nåbo (1990) due to immaturity of the technology as a measure of mental workload. Moreover, these studies did not use workload measures as a means to evaluate attempts to reduce (or increase) the workload of a task in the context of given forestry work. Thus, it is difficult to evaluate the magnitude or effect of those measures. Neck and shoulder pains among operators are most likely due to a combination of the mental and physical aspects of the work, physical properties of the operator, task demand, organizational pressure, vibration and cab design (Burström *et al.*, 2014; Jack & Oliver, 2008; Østensvik *et al.*, 2008; Lis *et al.*, 2007; Okunribido *et al.*, 2006; Punnett & Wegman, 2004; Rehn *et al.*, 2002; Hagen *et al.*, 1998; Eriksson, 1995; Bostrand, 1984). These injuries (repetitive stress injuries) furthermore tend to be costly to the employer (as well as the employee and society) due to the high amount of sick leave compared to accidents or acute injuries (Eriksson, 1995). All injuries and ill-health are nonetheless costly to the employer (Bohlin & Hultåker, 2006), and a health and performance guideline have been therefore developed (see Gellerstedt *et al.*, 2005).

One way of working with the human aspect of these parameters (i.e. skills and abilities) is through education and training. Several studies have shown that working methods and techniques matter (e.g. Alam *et al.*, 2014; Ovaskainen *et al.*, 2004) and training has been considered crucial for successful, healthy and safe machine operators (Gellerstedt & Dahlin, 1999; Kirk *et al.*, 1997; Axelsson & Pontén, 1990; Väyrynen, 1984). Moreover, machine operators show continuous productivity improvement for many years after the start of their professional work. For example, it has been suggested that is takes up to five years to reach full potential as a harvester operator (Gellerstedt, 2002), an assumption which is supported by the findings of a three-year study of harvester operator productivity (Purfürst 2010). In the latter study, there was great variation in the number of years of experience and/or specialized machine education among the operators. Half of the studied population initially had, on average, eight months of significant productivity increase (Purfürst, 2010). Furthermore, highly experienced hauling operators have shown continuous productivity improvements over the course of a three-year study period (Björheden, 2001). Thus, the general assumption is that there is much to gain from more and/or better education and training. Nevertheless, education and training systems vary greatly between countries (Bernasconi & Schroff, 2011; Bigot *et al.*, 2005; Vik, 2005; Gellerstedt & Dahlin, 1999). In Finland, effort has been made to develop simulator-based training (Ranta, 2009) and computerized skill evaluation and feedback systems (Palmroth, 2011; Tervo *et al.*, 2010). Simulators have also been successfully used for training harvester operators in Canada for almost 20 years (Lapointe & Robert, 2000). The benefits of using simulators are that they are cheaper than real machines, and training can be standardized, custom-made and performed without concern about environmental disturbance or personal safety. However, the results from Purfürst and Erler (2006) serve as a reminder that simulators are not universal tools and that training tasks must be carefully designed (see Ranta, 2009; Lapointe & Robert, 2000).

Nevertheless, the right abilities, skills, techniques and training alone are not sufficient for ensuring high performance of the logging system. The operator is affected by and interacts with the machines and technologies, the work organization, and the environment surrounding the system.

4.2 Technology: tools and prostheses

This section focuses on the effects of human–technology interaction in mechanized forest operations. The focus is on two dimensions in which machines and technology act as extensions (see tools or prosthesis, Duchowski, 2003) for the human body: the physical dimension, and the cognitive dimension.

4.2.1 The physical dimension

As the operator becomes proficient in using the machine to perform specific work tasks, controlling the crane becomes automatic (Gellerstedt, 2002; Rasmussen, 1983) and little conscious attention is required. Nevertheless, the interface through which this interaction occurs may affect performance by having an impact on the speed of operation and learning and the amount of sick leave (see Murphy & Oliver, 2008; Gellerstedt, 2002; Attebrant *et al.*, 1997; Grevsten & Sjögren, 1996; Hagberg & Lidén, 1991). It is also possible that the interface may affect work precision, and thus the speed and quality of work (see Hansson, 1990).

Exposure to environmental stresses, such as particles, noise and WBVs, are potential health hazards and thus may induce sick leave, sickness presenteeism and rehabilitation costs. They may also affect stress and cognitive performance, and thus affect system performance and productivity. Much effort has been invested in researching WBV, its physical effects, and ways to minimize exposure (e.g. Paper II, Gerasimov & Sokolov, 2009; Baes, 2008; Cation *et al.*, 2008; Burström *et al.*, 2006; Rehn *et al.*, 2005a; Rehn *et al.*, 2005b; Sherwin *et al.*, 2004; Mansfield *et al.*, 2002; Gellerstedt, 1998; Sankar & Afonso, 1993; Boileau & Rakheja, 1990). The effect of WBV on performance in complex tasks is difficult to assess; however, studies have shown that performance in motor tasks, especially accuracy-based tasks (which are typical to crane work in forest machines) and perceptual tasks with high demand on oculomotor control, is impaired by WBV (Conway *et al.*, 2006;

Wertheim, 1998). However, there seems to be little or no effect on cognitive performance in general (Wertheim, 1998), nor in combination with noise tested at levels typical to forwarder work (Ljungberg & Neely, 2007).

4.2.2 The cognitive dimension

Cognitive work in mechanized forestry has been generally described by qualitative approaches (Zylberstein, 1992), but attempts have also been made to quantify the cognitive work (e.g. Ovaskainen & Heikkilä, 2007; Tynkkynen, 2001), and some studies have combined the two approaches (Gellerstedt, 2002; Gellerstedt, 1997; Nåbo, 1990). Early attempts to increase the performance of the man-machine system have altered decision and information processes in a way that can most easily be described with the concept of function allocation, or Fitts' list (1951). The automation of log length and diameter measurement has increased the speed and quality of work (Malinen & Palander, 2004; Olsen *et al.*, 1991). Intelligent boom control involving various automated functions has been tested or implemented (Ortiz Morales, 2015; Hansson & Servin, 2010; Löfgren, 2009; Attebrant *et al.*, 1997). Despite some interesting concepts (e.g. Brander & Eriksson, 2004), the full effect of implementation of automated boom control systems is yet to be evaluated.

As shown in Paper IV, forestry machine work depends heavily on visual cues and information. Hence, poor visibility may degrade cognitive performance severely. Early research, which focused on artificial lighting and dazzling reflexes, found that brighter and better lighting conditions correlated with higher performance (Teljstedt, 1974), but similar lighting conditions were nevertheless found 25 years later (Nordén & Thor, 2000). Research, in for instance Sweden, has indicated performance variations with different colour temperatures of lights with the same lux during work in dark environments (Poom *et al.*, 2007). Operator line of view may be restricted by the crane, cabin walls or protective grills, etc. (Gellerstedt, 1998; Nåbo, 1990), which may result in musculoskeletal injury and accidents if the operator has to alter their position to see properly (Eger *et al.*, 2010; Thomas *et al.*, 1994; Hansson, 1990). Despite lack of research, it seems reasonable to assume that restricted visibility affects performance negatively by either lowering productivity or decreasing the quality of work in terms of product quality or safety. Recent developments have resulted in rotating and levelling cabins, first among harvesters and lately also among forwarders, where the cabin automatically compensates for unevenness and rotates so that the harvester head or grapple is kept directly ahead of the operator. In addition, in many machines, visibility restrictions have also been partly compensated for by introducing a filmed view of the outdoor environment. Due to these solutions, it is possible for the operator to see what is going on in front of machine and behind it without changing position or stretching. Information presentation and visibility are fundamental to the implementation of teleoperated or autonomous vehicles. Viewing angle and abstraction level have been shown to affect operator performance (Westerberg & Shiriaev, 2013).

Several design propositions have been developed to ease the use of bucking related information (Lopez, 2009; Norén *et al.*, 2008; Järrendal & Tinggård Dillekås, 2007; Lundin *et al.*, 2005; Forsberg, 2002). These developments have been driven by the discovery that the majority of interfaces on the market were violating design principles. However, there are no indications that current designs significantly degrade bucking performance (Study IV). Nevertheless, with the addition of advanced automation and further decision support (e.g. route planning in logging sites and teleoperation of machines, Westerberg & Shiriaev, 2013; Mohtashami *et al.*, 2012) there will be a need for new interfaces and interactive techniques (Wickens & Hollands, 1999; Sanders & McCormick, 1993).

4.3 Organization: culture and structures

Work organization (and its human–technology interactions) was acknowledged as a major influence on forestry work during early mechanization (cf. Bostrand, 1984; Kolodny & Kiggundu, 1980; Gardell, 1976) and, following a period of research focus on technological solutions and physical problems, received increased attention again during the 2000s. Work organization is a wide concept dealing with subjects such as work schedules, job design (tasks, skill and effort required, and degree of worker control), relationships with supervisors and co-workers, job security, carrier opportunities, management style, and organizational climate, culture, communications, and payment systems. Research on the effects of shift schedule in forestry has shown somewhat contradictory results, thus it seems that there is no single optimal way of arranging work schedules. In Sweden, from the 1980s to the end of the 90s some schedules were designed to include more variation and pauses in the work, and the results were promising in terms of both health and productivity (see Ager, 2014; Synwoldt & Gellerstedt, 2003). Many, but not all, contractors that tried these so-called “overlapping” shifts but went back to working straight shifts (eight hours straight per operator) after a few years on the basis that the overlapping shift was not economically feasible (Ager, 2014; Persson *et al.*, 2003). In general, daytime work is found to be most productive, but it is difficult to determine whether this is due to natural variation in cardiac rhythm, better visibility during daylight or other benefits of single shift work (Gallis, 2013; Lebel *et al.*, 2010; Mitchell *et al.*, 2008; Nicholls *et al.*, 2004; Persson *et al.*, 2003; Synwoldt & Gellerstedt, 2003; Pontén, 2000). Nevertheless, there might also be benefits to shift work, such as higher redundancy and flexibility of the organization (Hultåker, 2006) and lower fixed machine costs (Mitchell *et al.*, 2008). The general conclusion, though, is that operator performance degrade after 9-10 hours of daily work including regular pauses (Gallis, 2013; Passicot & Murphy, 2013; Murphy & Vanderburg, 2007; Nicholls *et al.*, 2004). Task variation, breaks and control over work tasks are related to beneficial health effects (Hanse & Winkel, 2008), and have been found to be beneficial for productivity and machine uptime in a small South African case study (Steyn *et al.*, 2011). However, past experience has shown that it can be difficult to find additional tasks for machine operators (Persson *et al.*, 2003) and such measures are probably not sufficient to solve neck and shoulder associated problems (Persson *et al.*, 2003). Moreover, frequent changes between, for example, harvester and forwarder operations may degrade performance initially on either machine (Hultåker, 2006). Night shifts may, for example, also induce higher insurance costs (Mitchell *et al.*, 2008).

The importance of human skill has been discussed, and to facilitate continuous learning and training there has to be a well-functioning learning culture within the organization. For learning organizations, it is important that there are systems for knowledge exchange within and between organizations, that new knowledge is accepted and implemented, and that errors are seen as opportunities to learn and not as something to be hidden (Jacobsen & Thorsvik, 2002). One study on Croatian private forestry contractors (Landekić et al., 2013) showed that as little as 50% of employees had received formalized job training. Moreover, few Polish operators had received any training in working techniques despite a willingness to participate (Nowacka, 2012). The problem of lack of training has also been acknowledged by Vik and Veiersted (2005). In Europe in general, contractors performing forestry services see little or no use in providing formalized training for their workers (Lewark *et al.*, 2010), which is viewed with scepticism with regard to training outcome, relevance to work, and return on investment. Some of this scepticism is likely also due to the fact that many forest workers consider education and formalized training merely as a way of gaining theoretical knowledge, while long-term practical experience is considered to be the most important way of gaining competence (Hugosson, 1999). Thus, theoretical knowledge is not fully trusted. Nevertheless, learning does not only happen in formalized settings. A culture that embraces knowledge exchange and transfer within the organization has been put forward as being important for the organization's problem solving skills and knowledge production (Hugosson, 1999). Moreover, knowledge exchange provides opportunities for learning from co-workers' experiences and thus ensuring that important knowledge does not leave the company with exchange of personnel. Internal knowledge exchange typically functions best in smaller organizations (Jacobsen & Thorsvik, 2002), which most forestry contractors in Sweden count as (Study II). Nevertheless, knowledge exchange between organizations is likely to be especially important for enterprises with few employees where the shared body of knowledge is consequently less. Contractor associations, other contractors, machine manufacturers, research institutes, clients, seminars and workshops, forestry fairs and exhibitions, and magazines have been identified as important sources for interorganizational knowledge exchange among European forestry contractors (Lewark *et al.*, 2010; Kutzschenbach, 2006). It was also found that information exchange between those sources was mostly informal.

5 Study II - Labour Organization in Swedish forestry

This chapter elaborates on the organizational context of Swedish contract forestry, and especially the structures of CTL logging contractors. The organizational context (O) is studied in isolation, without acknowledging human (H) or technology (T) interactions. Study II thus in many ways sets the scene for studies of HTO components in Swedish logging operations.

5.1 Materials and Methods

5.1.1 Data collection

Study II was based on the Swedish Forest Agency's annual written questionnaire to Swedish forestry contractors. When possible, comparisons were made with previous results based on the same survey for the years 1993-1998 (Ejermo, 2001) to obtain trends and growth rates.

A stratified random sample of forestry contractors was drawn from Statistics Sweden's Business Register (CFAR) to estimate the numbers of contractors, clients, machines, work hours, working owners, and their employees for the years 2006-2009. The combined group of working owners and employees will henceforth be referred to as workers. Four strata were constructed according to the stated number of employees: one-person enterprise = 0, small-sized enterprise = 1-4, medium-sized enterprise = 5-9, large-sized enterprise = 10 or more. Responses were received from 700 to 770 forestry contractors, corresponding to ca. 20% of the estimated total population of Swedish forestry contractors. The total response rate varied from 53% to 59%.

A survey was also conducted to determine the number of machine operators employed by the four biggest large-scale forestry companies (i.e. companies with at least ten employees in forestry or companies with at least 5,000 hectares of forest land, *Swedish Statistical Yearbook of Forestry 2011*) in 2009.

5.1.2 Data analysis

Answers to the questionnaire were weighted by the actual sampling fraction for each stratum to obtain estimates of the total population. Combined ratio estimates were calculated to estimate ratios of the following variables: work hours, numbers of clients, workers, and machines per company or per worker (See paper II or Cochran (1977) for equations).

The data analysis was conducted for the entire population of logging and silviculture contractors, but also for logging contractors separately. To be categorized as a predominantly logging contractor, the enterprise had to spend at least 30% less time on tasks typical to silviculture contractors. Typical logging tasks were: mechanized harvesting, mechanized forwarding, operation of a chipper, motor-manual thinning, and motor-manual final felling. Typical silvicultural tasks were: mechanized soil scarification, planting, and pre-commercial thinning. About 10% of all contractors, corresponding to 10% of total forestry work hours, did not fit into either group according to the above definitions.

Using a benchmark of 25% of one person's yearly working time in Sweden, we defined occasional contractors as enterprises with less than 455 hours per year in forestry work and typical contractors as enterprises working more than 455 hours per year. Thus, forestry work was not necessarily the main occupation of occasional contractors.

5.2 Results

5.2.1 Forestry contractors' development and structure

From 1993 to 2009, the estimated number of contractors in Swedish forestry increased by 80% (*Figure 2*). In 2009, there were 2,488 typical contractors primarily focused on forestry work in Sweden and 1,074 occasional contractors. Logging remained the main task of Swedish contractors in 2009; 27% of all work was allocated to mechanized harvesting and 25% to forwarding. Taken together, motor-manual thinning and final felling comprised no more than 3% of all work. However, the amount of time spent on silvicultural activities had increased since 1998 (*Figure 2*), and it became clear from the data that most contractors focused on either silvicultural services or logging services.

In 2009, most contractors (2,358 companies, 65%) were machine owners. The number of purpose-built forestry machines remained relatively constant between 1993 and 1998 but increased by almost 50% by 2009, at 5,960 machines in total. Machines for silvicultural work (mainly soil scarifiers) increased the most (ca. 120%), although there were only 466 machines in total by 2009. The vast majority of machines were harvesters (2,201) and forwarders (2,501), machine which had increased by 51% and 39%, respectively. In addition, there was a large growth (323%, 724 pieces by 2009) in the number of other than purpose-built forestry machines.

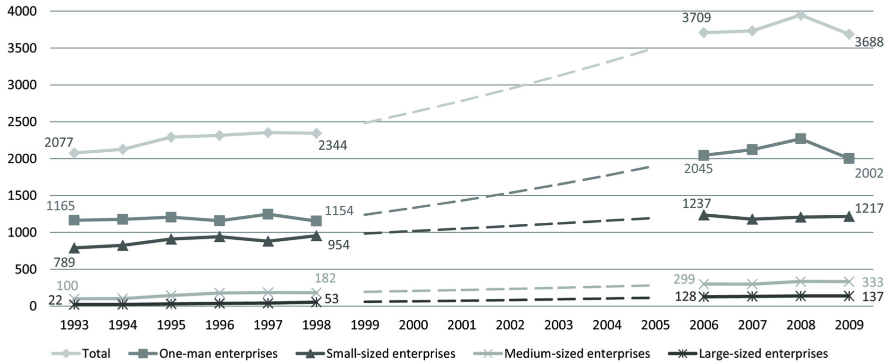

Figure 2. Number of forestry contractors in Sweden 1993-2009. Data for 1993-1998 adapted from Ejermo (2001); dotted lines represent changes between estimates for 1998 and 2006. The estimates for 2006-2009 have a relative standard error of less than 25%.

5.2.2 Logging contractors 2009

In 2009, there were 2,219 logging contractors in Sweden and they employed 6,337 workers. Less than 2% of workers were women (*Table 1*). Logging contractors carried out almost all work in mechanized harvesting and mechanized forwarding but less than half (47% in 2009) of motor-manual felling. In accordance with the high degree of mechanized work, only 13% of logging contractors were purely manual or motor-manual (did not own any machines, *Table 1*). Twenty-two percent of logging contractors worked less than 455 hours per year (occasional contractors) and 78% were typical contractors with more work hours (*Table 1*). Ninety-nine percent of logging contractor work was carried out by typical contractors. Average working time per worker and year was 1,334 hours for workers in typical logging enterprises, in 2009. Average working time increased with increasing company size.

Typical logging contractors were mainly contracted by large-scale forestry companies (51% of the work), but other, mainly private, forest owners were the most important clients for occasional logging contractors (79% of the work). On average, logging contractors worked for five clients, but 38% were contracted by only one client.

Large-scale forestry companies themselves employed 541 machine operators, which accounted for 8.5% of all logging workers in Sweden in 2009.

Overall, most work (42% of total work hours) was performed by workers in small-sized enterprises, i.e. enterprises with an average of three workers, while one-person logging enterprises with an average of 1.3 workers accounted for only 14% of total logging contractor work. Large-sized logging enterprises, with on average 11 workers per enterprise, accounted for 15% of logging contractors' total work in 2009.

Table 1. *Estimated properties of logging contractors in 2009.*

Variable	Value
Contractors	2219
One-person	1020
Small-sized	850
Medium-sized	276
Large-sized	73
Typical (> 455h a year)	1740
Occasional (< 455h a year)	478
Workers	6337
Women	108
Men	6229
Machines	4808
Special Machines	4398
Worker per Special Machine	1.5
No machine	295

Note. Special Machine = machine purpose-built for forestry work; No machine = number of contractors who do not own any machine.

6 Study III - Technology and human reactions

This chapter addresses technological aspects and human reactions. Specifically, the aim is to assess the contribution of crane work to overall vibration exposure in small forwarders, and the possible effects of three grapple and brake-link combinations on whole body vibration exposure and performance. Study III thus addresses the T and H-T aspects of the HTO framework.

6.1 Materials and methods

6.1.1 Data collection

Repeated field measurements of cabin WBV in a Vimek 608.2 BioCombi forwarder (Vimek AB, Vindeln, Sweden) were acquired while a single operator was forwarding standardized wood piles on a standardized track using three types of crane equipment. Each monitored work cycle (observation) corresponded to one round on the standardized track, beginning with loading the empty bunk and ending when the last log was unloaded. Through time studies, each work cycle was split into work elements (WEs) and WBVs were analysed within and over WEs. Thus, the design consisted of two fixed factors (crane equipment and WE) within five sets of repetitions (blocks). Collisions between the grapple or lifted logs, and trees or the base machine were also counted, as were the alignments of end surfaces of the logs. Fuel consumption was measured for each work cycle, and forwarding productivity (seconds per work cycle) was calculated from time study data. The three types of crane equipment were randomly assigned within blocks to minimize possibilities of order and carry-over effects confounding the results.

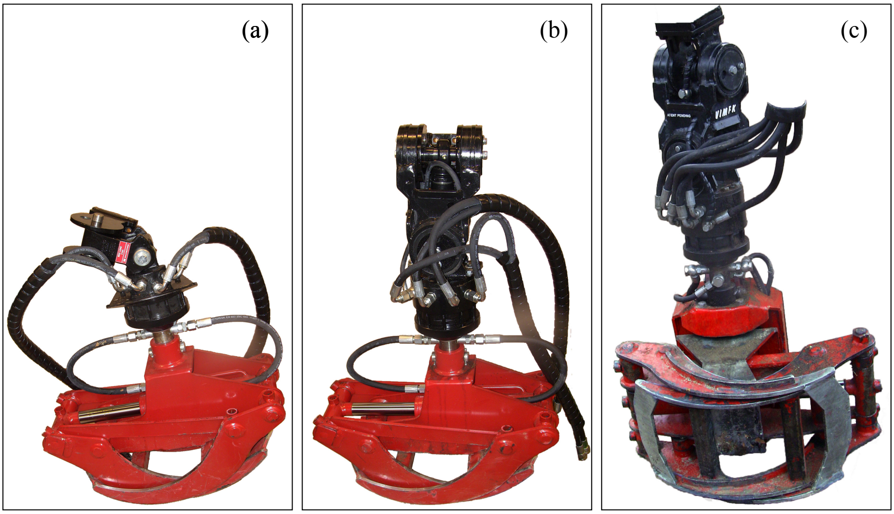

Figure 3. The three studied grapples from left to right: a Vimek standard grapple with no brake-link (standard grapple); a Vimek standard grapple with Vimek dynamic brake-link (brake-link grapple); and a Vimek tilt grapple with a Vimek dynamic brake-link (braked tilt grapple).

The three studied types of crane equipment were (*Figure 3*): (a) a Vimek standard grapple (standard grapple); (b) a Vimek standard grapple with Vimek dynamic brake-link (brake-link grapple); and (c) a Vimek tilt grapple with a Vimek dynamic brake-link (braked tilt grapple). The gripping area was the same for all grapples (0.16 m^2) and the mass of a single pile was not a limiting factor for the crane or any of the studied grapples.

Vibrations were measured in three orthogonal axes according to ISO 2631-1 (ISO, 1997) using a MTi-G triaxial accelerometer (Xsens, Enschede, Netherlands) placed on the floor close to the centre of the cabin, in front of the chair. The placement ensured that the operator's weight, height and the chair's dampening would not affect the measurement. Samples were taken at a frequency of 100 Hz during each approximately 40-minute work cycle using a XKF Scenario "2.7 Automotive unit" (Xsens, Enschede, Netherlands).

The field study was conducted during October 7-22, 2013, with one trial (work cycle) per day for the first block, and subsequently two trials per day. One designated researcher filmed all the trials and made all the measurements.

6.1.2 Data processing and analysis

All data processing was performed off-line using a commercial software package (MATLAB R2014a 8.3, MathWorks Inc., Natick, USA) with the Continuous Sound and Vibration Analysis program (Zechmann, 2013). The acceleration data were converted from the recorded time domain to frequency domain with a frequency range up to 50 Hz. In the analyses, 1/3 octave band values were calculated from 0.1 to 50 Hz. The resulting data were then used to calculate frequency-weighted root mean square (r.m.s.) acceleration and fourth power vibration dose value (VDV) values with respect to health effects on a seated driver in accordance with ISO 2631-1 (ISO, 1997). VDV and r.m.s. values were calculated with respect to the three orthogonal axes (x, y and z), and the sum vector (v). The crest factor and the 8-hour equivalent, A(8), were calculated for all orthogonal axes over each measurement period.

Data were analysed using Minitab 16 (Minitab Ltd, State College, PA, USA). Analysis of variance (ANOVA) was used to analyse the fixed effects of WE and crane equipment type, and the fixed interaction between them, on the vibration measurement. The ANOVA models also included the random block effect. A general linear model (GLM) was applied when analysing the ANOVA models and Tukey's Honest Significant Difference (HSD) test of means was used for pairwise comparisons. Moreover, the fixed effects of crane equipment type on the number of collisions, and alignments, were analysed with a GLM including block as a random factor. In all analyses the significance level was set to 5%.

6.2 Results

The frequency distributions were similar for all crane equipment types; i.e. low-frequency vibrations were more intense during driving than during crane work, with no visible differences in frequency spectra over the vertical (z) direction between driving and crane work, but accelerations in the horizontal directions (x and y) were highest in the frequency range 1.25-4 Hz during crane work and 0.25-5 Hz during driving.

Driving had higher vibration magnitudes than crane work (*Table 2*). However, on average, more than four times as much time was spent on crane work than on driving. Thus, for the time weighted r.m.s. value, A(8), the relationship was reversed (*Table 2*). A high crest factor in the x-direction (mean 12, max 15) indicated occurrences of shocks during crane work. Nevertheless, other indicators of shock occurrences (VDV_x, and VDV_y) were higher during driving than during crane work. In contrast, VDV_z was higher during crane work than during driving. Consequently, the overall vector (VDV_v) was not affected by WE.

Crane activities significantly affected all vibration measures, but the interaction between crane activities and crane equipment was non-significant. *Crane in* and *release & reorganize* were the most time consuming crane activities and the WEs with the highest average vector vibrations. However, they differed in that crane in had high values in the y-direction while release &

reorganize had high values in the x-direction (*Table 2*). Since no effect of crane equipment type on any vibration measurements was found during crane work (*Table 2*) it can be concluded that the studied crane working techniques and crane equipment types were found to have little or no effect on daily WBV exposure with respect to seated health.

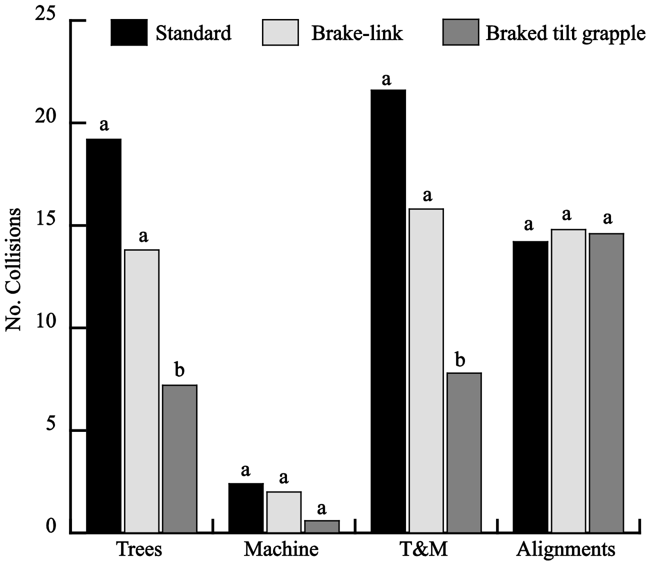

Figure 4. Average numbers of collisions – with residual trees (Trees), the Machine, or both (T&M) – and alignments of end surfaces of the logs per work cycle with each type of crane equipment. Means within categories with different letters are significantly different (Turkey's HSD, $p < 0.05$).

Significant differences were found between crane equipment types in the frequency of collision with residual trees. Fewest trees were hit when using the braked tilt grapple and most trees were hit when using the standard grapple (*Figure 4*). However, applying collisions and alignments as covariates in the ANOVA did not reveal any significant relationship between collisions or alignments and vibration levels in any direction, nor for the sum vector for any of the vibration measurements.

Preliminary data indicate that work with the braked tilt grapple resulted in about 15% higher fuel consumption than the other grapples, while productivity was 3-5% higher. However, the differences were not significant according to the preliminary analyses (Öhman & Häggström, unpublished manuscript).

Table 2. *Frequency-weighted acceleration in the three orthogonal axes (x, y and z), the sum vector (v) and the A(8) value for indicated work elements according to "health" in ISO 2631-1. Measurements were taken at the feet.*

Type of work	WE	N	Duration (s)	a_{wx} (m/s^2)		a_{wy} (m/s^2)		a_{wz} (m/s^2)		a_v (m/s^2)		A(8) (m/s^2)		VDV_v (m/s$^{1.75}$)	
				Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Work cycle	Crane Work[1]	15	1537-1887	0.15^B	0.01	0.21^B	0.01	0.32^B	0.08	0.41^B	0.06	0.079^A	0.019	4.24^A	0.37
	Driving	15	335-502	0.31^A	0.03	0.33^A	0.03	0.35^A	0.04	0.57^A	0.05	0.042^B	0.003	4.42^A	0.37
Crane activity	Crane In	15	380-638	0.14^b	0.01	0.23^a	0.02	0.32^{bc}	0.08	0.42^{bc}	0.06	0.042^a	0.010	3.06^a	0.37
	Crane Out	15	262-309	0.11^c	0.01	0.16^c	0.02	0.28^d	0.07	0.34^d	0.05	0.028^c	0.007	2.20^b	0.35
	Grip	15	157-313	0.11^c	0.01	0.22^a	0.02	0.30^{cd}	0.07	0.39^c	0.06	0.026^c	0.005	2.21^b	0.29
	Release & Reorganize	15	343-628	0.17^a	0.02	0.19^b	0.01	0.34^{ab}	0.07	0.43^{ab}	0.05	0.043^a	0.010	3.01^a	0.28
	Unloading	15	256-345	0.16^a	0.02	0.23^a	0.03	0.34^a	0.09	0.45^a	0.08	0.035^b	0.009	3.02^a	0.44

Note: Mean values within columns and type of work with different superscript letters (A-B for the full work cycle and a-d for crane activities) are significantly different ($p < 0.05$, Turkey's HSD). WE = Work Element; SD = Standard Deviation.

[1] Crane Work includes all crane activities pooled

7 Study IV - Human behaviour and human–technology interaction

This chapter addresses aspects of human (visual) behaviour and human–technology interaction, i.e. the H and H-T aspects of the HTO framework. Specifically, the visual behaviour of CTL harvester operators during real-life harvesting operations is examined. The study had two main objectives: firstly, to obtain and categorize information on harvester operators' visual behaviour; secondly, to evaluate an eye-tracking system as a diagnostic tool in real-world harvesting work in terms of the quality, precision and accuracy of data it can provide, and the process of data analysis, in terms of ease of analysis

7.1 Materials and methods

7.1.1 Data collection

The eye movements of six harvester operators were tracked during separate CTL harvesting sessions in which two operators were engaged in first thinning, two in second thinning and two in final felling operations in central Sweden during autumn 2012. Four of the operators had sight impairment, including astigmatism in one case, although none had strabismus (eye misalignment).

Eye movement data were recorded with Tobii Glasses (Tobii Technology AB, Sweden), which utilize a monocular right eye pupil-centre and corneal reflection technique to record eye movements and scene video as seen by the wearer at 30 Hz with overlaid gaze cursor. The glasses are light head-mounted eye-trackers that allowed the operators to move freely during the study (*Figure 5*). The harvesting operations were simultaneously recorded with an ultra-wide angle lens GoPro camera (GoPro, Inc., California, USA) positioned at the side window and directed towards the front windshield to capture both the forest scene and the machine work.

To capture the harvester operators' natural work behaviour, they were instructed to work as normal in the stand they were scheduled to work in that day using the machine they usually operated. In each session eye-tracking and GoPro video data were collected for about 10 to 15 minutes of work, during which a researcher was riding in the cabin with the operator. Each of these naturalistic observational sessions was followed by a retrospective think-aloud (RTA) interview during which the operators viewed the eye-tracking-video with gaze cursor overlay and were asked to explain their actions, what they had looked at, or describe their reasoning in a review of the work and decision process.

Figure 5. Eye-tracking equipment (Tobii Glasses) in use during the study.

7.1.2 Data analysis

Machine work was coded manually using the ELAN video transcription software (Max Planck Institute for Psycholinguistics, Netherlands). Both the GoPro recordings and eye-tracking videos were imported to ELAN and synced to more precisely determine the time that the operators allocated to five standard harvester WEs: crane work, positioning-to-cut and felling, processing, release of the top, and driving; and also miscellaneous work. Cues to define exact start times for cutting each tree and log (when the saw symbol appeared on the harvester's computer screen, or when the saw or

Table 3. *Areas of interest (AOIs) analysed in the study.*

AOI element	Definition
Harvester head	The harvester head. When possible also categorized by the specific sections: saw unit, upper delimbing knives, multi-tree handling equipment, and rotator and backside.
Saw unit	The part of the harvester head where the saw is located.
Upper delimbing knives	The parts of the harvester head where the upper delimbing knives are located.
Multi-tree handling equipment	The part of the harvester head where the multi-tree handling equipment, or the rotator, is located during all elements but processing.
Rotator and backside	The backside of the harvester head and the centre part of the feeding rolls while upright. The backside and the part of the harvester head where the rotator is located while tilted down and during processing.
Bucking monitor	The bucking monitor. Dwell times on this AOI include the saccade from the previously dwelled AOI and the saccade to the next dwelled AOI.
Forest	The forest, individual trees and ground. When possible also categorized by the specific sections: canopy, standing tree, falling tree, upcoming processing site, pile, between pile and delimbed stem (*Figure 1*).
Canopy	The canopy, as seen in upward gazes, including head movements towards the canopy without any hits.
Standing tree	Individual standing trees gazed at close to the machine.
Falling tree	The top and stem of the falling tree, including gazes in its felling direction.
Upcoming processing site	An area where the harvester head and tree are to be positioned to process the tree. Fixations on this area are by definition look-ahead fixations.
Pile	The ground or pile where the processed logs will be put.
Between pile and delimbed stem	Area between the piles and delimbed stem.
Gripped tree	A tree gripped with the harvester head, either a delimbed or unprocessed part of the stem. When possible also categorized by the specific sections: delimbed stem and unprocessed tree.
Delimbed stem	A part of a tree that has been fed through the harvester head but not yet cut and put in a pile
Unprocessed tree	A part of a fell-cut tree that has not yet been delimbed or released from the harvester head.
Unclassified (N/A)	Gaze that cannot be classified in any of the above categories.

saw sound became perceptible in the videos) were identified in a separate time study. The gaze recordings from the Tobii Glasses were examined frame by frame using the video player functionality in Tobii Studio (Tobii Technology AB, Sweden).

The number, duration and order of dwells in each operator's recording were coded for each area of interest (AOI) in all WEs. A dwell was defined as a gaze in an AOI lasting at least 100 ms from entry to exit. An exit was defined as a hit outside that AOI. The 16 AOIs were constructed based on RTA data, interviews with six exceptionally skilled operators in 2011 and on results presented by Gellerstedt (2002). Different sets of AOIs were analysed for the entire work cycle, positioning-to-cut and felling, and for processing. Dwell time, dwell frequency (dwells/s), and one-way transitions between AOIs (transition matrices) were then calculated. RTA data were analysed and the purpose of the dwell, or the attribute of interest during the dwell, was categorized by AOI.

7.2 Results

The operators conducted the work by continuously manoeuvring the joysticks without visual supervision. Their eyes dwelled on the harvester head and various aspects of the forest most of the time (82%, *Figure 6f*). Dwells on the forest (in its broadest sense) often served a general purpose of getting an overview and organizing the work, whereas dwells on the harvester head were of a more specific monitoring and guiding character (Table 7).

During crane work, the harvester head was in focus most of the time (45% of total dwell time, presented in circles in *Figure 6a*) and the canopy was the third most attended area (8% of total dwell time, presented in circles in *Figure 6a*). Most transitions in dwells went from the harvester head towards the forest (29.5% of total transitions, represented by arrows in the direction of transition in *Figure 6a*), and the operators very rarely looked at the canopy directly after looking at the harvester head (1.4% of total transitions, represented by arrows in the direction of transition in *Figure 6a*). Thus, a high proportion of gazes at the canopy must have come from the harvester head via the forest (see *Figure 6a*).

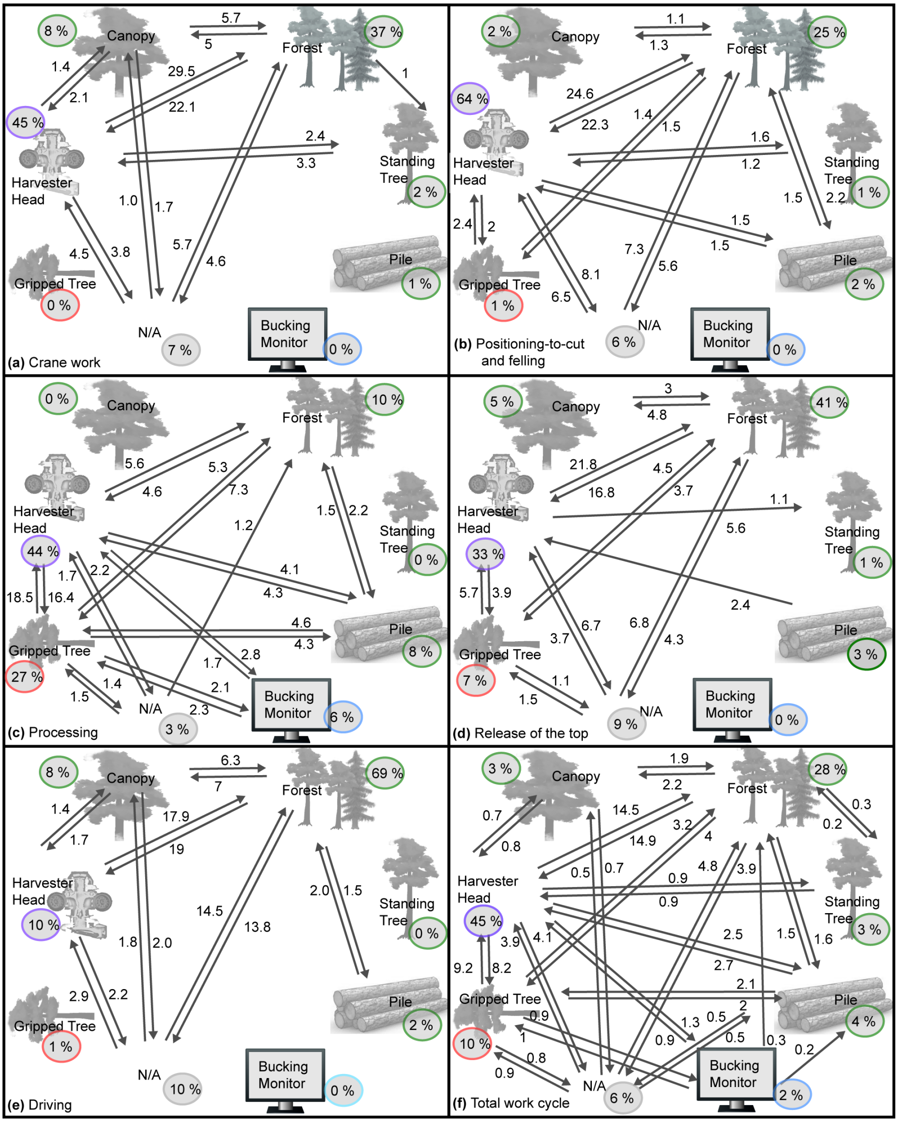

Figure 6. Percentages of transitions from one area of interest (AOI) to another. Transitions with frequencies ≥ 1% of the total number of transitions are shown for all WEs (in panels a-e) except for the total work cycle (in panel f), which shows all shifts between AOIs with frequencies ≥ 0.2% of the total number. Numbers in circles indicate percentages of the total dwell time allocated to the designated AOIs. N/A = dwells not defined.

Table 4. *Attributes of information searched for and purposes of gaze towards areas of interest (AOIs) according to the retrospective think aloud (RTA) interviews with the operators. Detailed information carried by features, or objects, within the AOIs are also listed.*

AOI	Information carrier	Purpose
Forest	Damaged trees or trees otherwise not fit for future growth. Landmarks and terrain features that signal good bearing capacity.	Getting a general overview. Identifying where the trees are. Identifying which trees should be felled. Deciding how to organize work, e.g. where to drive and where to put piles. Deciding which directions to fell trees and where they will land. Deciding which tree to handle next. Deciding whether thinning can be finished from the current machine position: do more trees need to be thinned and how far can the machinery reach? Ensuring the crane and harvester head is not touching any trees in the stand.
Tree	Straight or curved stem.	
Canopy	Small or dry crowns. If trees are straight or curved. Suppressed crowns. Double stems.	Identifying trees to remove. Looking for tree damage. Ensuring the crane does not touch the trees. Planning felling directions.
Pile		Deciding or identifying where to place logs. Determining if piles are present for placing the logs. Shifting between delimbed stems and piles to check that logs are put in the right piles (involving gaze shifts between piles, stems and sometimes the bucking monitor).
Upcoming processing site		Finding a suitable place to process a tree. Estimating where to feed trees. Ensuring that nothing is hit while processing (e.g. other trees). Deciding whether to put a log in an old pile or make a new one (involves gaze shifts between the upcoming processing site and the pile).
Falling tree	The side of remaining trees that the canopy/crown ended up in. The felling direction.	Avoiding trees getting stuck in another tree. Checking if a tree got stuck. Searching for an opening in which to fell. Checking that the felling direction is the same as intended.

AOI	Information carrier	Purpose
Delimbed stem	Crookedness.	Deciding where the stem is fed and checking that nothing gets hit (e.g. trees and the machine). Identifying species
Unprocessed tree	Damage, e.g. broken tops or crookedness. (Remaining) length and diameter.	Checking if the stem is large enough for log processing. Checking if it is possible to make another log.
Harvester head	Positions of hoses.	
Saw unit		Searching for the exact point to fell-cut. Ensuring that there are no rocks or other things that may damage the saw during felling. Monitoring when the cut is complete. Monitoring to ensure that the saw does not cut too little or too deep. Considering increasing or decreasing the length of a log.
Bucking monitor	Species. Length. Diameter.	Checking that the right species is entered. Changing assortment. Ensuring that the machine-measures are correct. Checking whether the length has to be adjusted. Obtaining support for sorting logs into piles. Ensuring that no error messages have come up before working at maximum crane reach.

NOTE: The table presents a collection of all comments made about the AOIs during the unstructured RTA that could be categorized within the given categories. Thus, this is not a complete list of purposes or information-carrying areas that are attended during forest harvesting. Neither is there any intention to produce a complete overlap between the detailed information-carrying areas described within each AOI and the presented purposes for dwelling on them.

7.2.1 Viewing the canopy

Dwells on the canopy were associated with activities including planning the felling and making decisions about which trees to remove (Table 4). The canopy was mainly dwelled on during driving, crane work and release of the top (*Figure 6*). The operators' gaze dwelled on the canopy once or twice per felled tree. The longest and most frequent dwells occurred during second thinning.

7.2.2 Guiding positioning-to-cut and felling

When positioning-to-cut and felling the tree, the operators made long dwells on the harvester head. The long dwell times were composed of several dwells on different parts of the harvester head, especially the saw unit. Accordingly, they looked at the harvester head to find exact felling-cut points and to ensure that the saw was not damaged during operation (Table 4). During no other WE was the proportion of dwell time on the harvester head as high (*Figure 6*).

7.2.3 Felling the tree

During felling, operators looked most often at, or beneath, the tree being felled. A marked exception, however, was during first thinning, where the operators' looked at only about 70% of the trees being felled. The main reason for watching the falling trees was to ensure that nothing went wrong (Table 4). However, instead of following the falling trees all the way until they hit the ground, the operators' eyes moved on to other objects.

7.2.4 Preparing processing

Often, while the tree was still falling, the operators' eyes made look-ahead fixations towards where the log was to be fed, i.e. the upcoming processing site and sometimes towards the processed wood pile, forest, and standing trees around this site. Many dwells on this site followed a dwell on a tree being felled or the saw unit of the harvester head. During felling, most dwells on the upcoming processing site were followed by a transition to the pile or saw unit of the harvester head, whereas during processing most dwells on this AOI were followed by transitions to the delimbed stem. Almost one third of the dwell time during processing that was spent looking at the forest (see *Figure 6*) could be classified as look-ahead dwells towards the upcoming processing site.

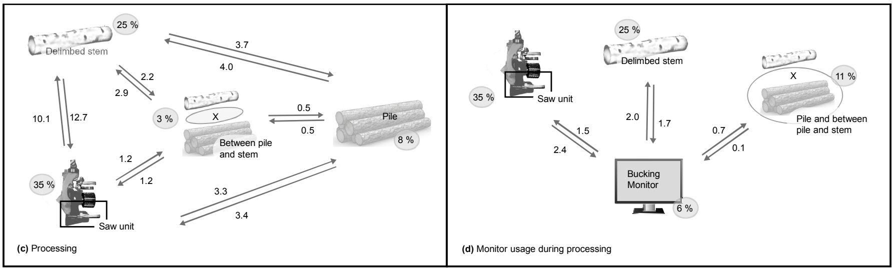

Figure 7. Typical dwell sequences during the processing WE, showing transition frequencies and dwell time proportions. Percentages of total transitions are marked along the arrows in the direction of the transition. Numbers in circles show percentages of the total dwell time during processing that were allocated to the designated AOIs.

7.2.5 Focus on feeding, cutting and sorting

While processing, the operators maintained a strong visual focus on feeding, cutting and sorting the logs (*Figure 7a*). During processing, the operators had the highest proportions of gazes (in terms of dwell frequencies and total time) directed towards the gripped tree, pile and bucking monitor (*Figure 6*). Many dwells on the harvester head were for the purpose of acquiring information about the saw and cutting process (Table 4). Consequently, most hits (58%) just before (0-233 ms prior to) cutting were focused on the saw unit of the harvester head. This was 23 percentage points more than the processing WE average.

7.2.6 Utilization of digital bucking information

The bucking monitor was looked at very rarely and almost only during processing. Even then, the monitor was observed for just 6% of the WE time, often just before the log was cut or the suggested cutting position was manually changed. Most (95%) transitions to and from the monitor were to or from the area of the pile, delimbed stem or saw unit of the harvester head (*Figure 7b*). Nevertheless, there were large between-operator differences in dwells on the bucking monitor. Moreover, 64% of all dwells on the bucking monitor were attributable to one operator and only 6% of the total number of dwells on the bucking monitor occurred during first thinning. One operator in first thinning and one in second thinning dwelled on the bucking monitor only once during the recorded sessions. Besides that single dwell, the monitor was not even visible in the eye-tracking video of the operator in first thinning; however, the tracking was interrupted during seven downward nods of the head that brought the bucking monitor back to clear visibility in the video. However, operators' gaze generally dwelt on the bucking monitor longer and more frequently during second thinning and final felling than during first thinning.

7.2.7 Finding and choosing the next tree or position for the machine

The tasks of identifying, locating and/or choosing the next tree to cut (or save) or a new position for the machine can only be done while looking at aspects of the forest. This visual behaviour often occurred already before the top of the prior log was released from the harvester head, i.e. there were sharp increases in both the frequency and time of dwell on the forest and canopy, accompanied by sharp falls in frequency and time of dwell on the pile and the gripped tree, relative to those in the prior WE, processing (*Figure 6c-d*). However, the operators also sometimes planned ahead, thus reducing the need to search for the next tree after each tree is processed. For example, one operator first showed a high level of situational awareness when shifting focus to a car passing on the nearby road exactly when the last cut in processing was initiated, the operator then showed foresightedness when the next saccade went directly to the next tree to cut with no sign of visual searching in the forest. Moreover, to resume the work process the operator apparently had no need to refocus on the harvester head or the unprocessed top that had been released without visual supervision. The harvester head was not dwelt upon again until it approached the next tree to be cut.

In general, it can be assumed that information specific to driving, strip road preparation and tree selection were gathered during driving (Table 4). This was done while the operators made long and frequent dwells on the forest and canopy (*Figure 6e*), the average dwell duration on the forest was, for example, higher during driving than during any other WE.

8 Discussion and conclusions

The overall aim of this thesis was to contribute new knowledge on working conditions in mechanized logging operations and their relationship to system performance by examining aspects of the operator, the machine, and the work organization. An HTO framework was used in Study I to scrutinize the problems existing in the interactions between the human operator, the technology and the work organization, while at the same time taking into consideration the context in which the work is performed. Studies II, III and IV were used to extend the body of knowledge on aspects of the concepts H, T and O. In each of these studies, different methods and measuring techniques were used.

In Study II we found that more than 90% of logging workers were employed by contractors. The previous established understanding that Swedish logging contractors are mainly small enterprises, i.e. three employees on average, was also confirmed. Furthermore, despite the fact that the share of larger enterprises has increased in recent years, only a few employ more than 10 persons including the working owner. When working in a small enterprise with few colleagues, information exchange tends to be informal but rather effective (Jacobsen & Thorsvik, 2002). However, the body of knowledge and experience within the company may not be sufficient for ensuring safe practices and improving knowledge of new technologies, work methods or practices. Consequently, the “network” of inter-organizational knowledge exchange, as discussed in Study I, is important for company development. However, for this sharing to be efficient it is important to have national, and perhaps international, organizations that the contractors can draw on. Trust between actors is important for the shared information to be trusted. Trust is also important when there is an interest in having contractors share their knowledge and experiences with others.

In Study II, it was also emphasized that most logging contractors were working purely with machine operations. Thus, efforts to improve health and performance through increased task rotation, as discussed in Study I, have limited possibilities to be implemented within most companies, apart from rotating between harvester and forwarder work.

In Study III, crane work was basically ruled out as a major source of WBV at levels harmful to the human body. However, it should be emphasized that this was a small study with only one operator and one machine. More important results of this study were the positive effects on residual trees in the stand through the use of an active brake-link with the possibility of precise tilting of the grapple and the gripped logs. Avoiding damage to the residual stand is a high priority in terms of both environmental concerns and avoiding costly growth losses for the landowner (e.g. Sirén *et al.*, 2013). The differences in collision frequency between crane equipment types observed in this study would therefore be of interest when selecting thinning equipment to minimize damage to residual trees. Moreover, the results of Study III suggest smoother operation of the grapple, and thus a more relaxed and comfortable work environment for the operator. Cranes with automated or semi-automated controls have also achieved smoother trajectories of the crane and less unwanted movements of the grapple (Hansson & Servin, 2010). Such systems may therefore prove especially valuable for novices in crane operations, both by helping them reach higher performance faster and by reducing equipment damage through improved controllability, as indicated in Study III. Possible hindrances to implementation of the technology studied in Study III include increased fuel consumption during usage (Öhman & Häggström, unpublished manuscript) and purchase price.

The results from Study III are in accordance with the results of several other studies on vibration exposure during driving versus crane work (e.g. Rehn *et al.*, 2005a; Hansson, 1990). Efforts to reduce WBV exposure should thus aim at minimizing exposure to WBVs during driving. This can be achieved organizationally by reducing the number of machine hours and by refusing to work in the most severe terrains conditions. WBV reduction can also be achieved technologically by adding stability and better dampening systems, but also by reducing the maximum driving speed. However, the latter suggestion may induce other risks related to machine manoeuvrability, and thus a negative knock-on effect on productivity.

Nevertheless, if attempting to reduce operators' exposure to crane work induced WBVs, i.e. for comfort or fatigue reasons, the results from Study III imply that technological modifications that increase the stability of the base machine should be considered as a first option. This is based on the plausible assumption that the predominant vibrations in the z-direction in Study III, i.e. up and down (*Table 2*), reflect the tilting of the machine while handling logs. The recommendation is also supported by findings that WBVs are negatively correlated with machine weight (Rehn *et al.*, 2005a). However, for environmental reasons, improved stability of the base machine should not be achieved by adding weight to the machine. Lightweight machines minimize damage to forest soils, which ideally should remain unaffected by forest operations. This trade-off exemplifies the challenges involved in designing efficient work conditions adapted to the worker under tight constraints on how the work environment can be modified or influenced by the work. Other measures to reduce crane work induced vibrations include improved hydraulics and crane control systems, which offer the potential to make operations smoother and more comfortable for the operator (Hansson & Servin, 2010).

From the performance perspective, a highly interesting finding relates to the utilization of bucking data from the onboard monitor, as revealed by the gaze behaviour investigation in Study IV. It was shown that bucking information is utilized and important, as the information was used by all operators at some point. There were also indications of task dependency in gaze allocation, i.e. the information on the bucking monitor and information from areas surrounding the falling tree were less frequently attended to, i.e. less interesting, during first thinning than during second thinning and final felling. Thus, the gaze analysis indicates an information search pattern that is felling type and/or stand dependent, i.e. the number of assortments and/or tree sizes determines the perceived information need. The presentation and design of bucking information may, at best, have a very slight impact on operator performance due to the sparse amount of time spent observing it. However, there will be a need for new interactive techniques (see Westerberg & Shiriaev, 2013) when, for example, adding advanced automation and decision support (e.g. route planning in logging sites, Mohtashami *et al.*, 2012). By providing an understanding of monitor usage, Study IV may have an impact on the design process of adaptive displays or other future interactive systems.

8.1 Strengths and limitations

The HTO framework stresses the need to scrutinize problems that exist in the interactions between H, T and O, while also taking into consideration the context in which the work is performed. Individual studies II, III and IV each had a narrow focus on either human, technology or organization aspects. However, in line with a hermeneutic research paradigm (see e.g. Johansson, 2000), this is typical when applying a systems perspective; one must shift between the narrow view and the wider scope in order to understand all aspects and draw the pieces of the puzzle together.

The main strength of this thesis is the use of several different methods and techniques to examine the research questions. Large samples and more general analysis, as in Study II, as well as small samples and more detailed analysis, as in studies III and IV, were used. In Study I the data was mainly qualitative, in studies II and III it was purely quantitative, and Study IV combined the two approaches. The information obtained from the qualitative material in Study IV was essential for interpreting the findings from the quantitative material.

The combination of structured literature search and snowballing approach in Study I enabled identification of papers highly relevant to the situation of workers in mechanized forestry but published under other topics and in non-forestry journals. Those papers would have been missed if solely applying a structured search.

One limitation of Study I is that many (potentially) interesting studies and research reports from, for instance, the organizations SCION (New Zeeland) and FERIC (Canada) are missing due to their online unavailability. Apart from the apparent problem of missing data, this may have affected the view of the system. It has been noted that European researchers have different research traditions to their American colleagues; they have, for example, treated the harvester and forwarder as separate research subjects, whereas American researchers have mainly investigated the harvester and forwarder as a complete harvesting system (Nurminen *et al.*, 2006). Thus, the European research tradition may have had a greater influence on the results, in which the harvester and the forwarder are described as separate, but interrelated, subsystems. Moreover, due to the focus on mechanized CTL operations with a harvester-forwarder system, Nordic literature is overrepresented in the literature list.

A strength of Study II is the large sample on which it was based, i.e. an estimated 20% of the total population replied. This has an positive effect on the findings' accuracy and external validity. Moreover, the large sample size allowed segmentation, thus conclusions could be confidently drawn about the logging contractors subgroup, which was the main interest when initiating the study.

When interpreting Study II, it should be taken into consideration that the results based on the strata (one-man, small-sized, medium-sized, and large-sized enterprises) are not exactly the same as results for enterprises with 0, 1-4, 5-8, or 9 or more employees. However, the chosen method was used to enable population total estimates and comparisons with the 1993-1998 data sets. The average number of workers for each stratum was also consistent with the categorization. It should also be noted that the register from which the population was drawn has some inconsistencies, but consistencies between repeated measures indicate the reliability of our results, even in instances with high relative standard error. Moreover, the study covered about 20% of the estimated population of Swedish contractors, which must be regarded as a substantial part of the population.

Study III was conducted as a field experiment on small samples in a standardized but natural environment, from which generalizations should be made with care. During the experiment, standardization of the track and efforts to eliminate unwanted sources of vibration, i.e. ground roughness, helped isolate the effects of the studied factors. However, the recorded vibration values in Study III are only valid under the prevailing conditions during the study. Nevertheless, there are no (obvious) indications that the obtained relationship between grapple type and vibration should be falsified under other conditions or in other machines. Moreover, the vibration exposure during driving would become higher in a more uneven terrain, thus reducing the impact of crane induced vibrations.

It should also be noted that the upper frequency limit in this study was 50 Hz compared to the standard 100 Hz, thus the results should be interpreted cautiously. Nevertheless, inspection of the frequency spectra reviled that the highest vibration magnitudes were below 50 Hz. Thus, the limitations in measuring technology should not have had a major impact on the calculated exposure and the relative levels are fully comparable.

Study IV was conducted as a naturalistic observational study to gain insight into harvester operators' gaze behaviour and perceived information need. The approach was chosen due to the immaturity of gaze tracking as a research method and the, to date, scare knowledge on eye movements in forestry operations. To the best of our knowledge, a portable eye-tracker has never before been used to study eye movements during work in a forestry machine. Thus, the approach provided possibilities to explore and evaluate gaze behaviour, the AOIs, and the eye-tracking technology. This revealed aspects of the work that could be interesting to test experimentally in forthcoming studies, e.g. if there are differences on a population level in dwell patterns during different operation types when felling, and if those differences are due to the bucking prescriptions or the size of the tree.

In study IV, it was difficult to obtain usable high quality data. Six recordings were used in Study IV, but four more recordings were conducted in relation to this research; two of those were tracked during special forest conditions and were therefore not included in this study, the other two had too low proportions of gaze samples (59-71%) in combination with severe problems with exposure in the video and were therefore excluded from analysis. Parts of the analysed data of the two operators with the lowest proportions of gaze samples seemed to contain some systematic errors. Firstly, a systematic displacement in the estimated point of gaze, i.e. a minor offset in the scan path, was visible in parts of two recordings. A more thorough procedure for calibration testing may have spotted and corrected this problem already in the field. Nevertheless, in general, the operators themselves did not observe any displacement while watching the eye-tracking video and only one of them expressed a vague statement about possibilities of a minor misplacement. Moreover, the given displacement was negligible with respect to the AOI-analysis since the offset could be compensated for.

Secondly, we also encountered difficulties in tracking the gaze when driving, which may be due to vibration as well as rapid head movements and changes in illumination due to these head movements. The usability of eye-tracking equipment in natural settings are well known to be limited by, for example, pupil position in the eye outline, head movement, vibration, illumination, monocular vs. binocular tracking, physical properties of the tracked eye and the number of cameras in the (fixed) eye-tracking system (Holmqvist *et al.*, 2011; Morimoto & Mimica, 2005). Moreover, variation in illumination, causing the pupil to constrict and dilate, is also likely to have a negative effect on the accuracy of the eye-tracker (Wyatt, 2010). Thus, it is likely that the gaze allocation on the forest is somewhat overestimated compared to the gaze on, for example, specific trees or the harvester head. In general, when interpreting Study IV, it should taken into consideration that the quality of the scene video reduced the number of dwells that could be assigned to the more detailed AOIs. Additionally, the measure of dwell time on the AOI bucking monitor reflects the time that the eyes were directed away from the ongoing tree processing. Thus, it included saccades or fixations shorter than 100 ms to and from the monitor which, in turn, may have contributed to minor underestimation of dwell time on the forest.

We assumed natural vision to be a mainly top-down and goal-directed and less influenced by bottom-up saliency (see Orquin & Mueller Loose, 2013; Tatler *et al.*, 2011; Ballard & Hayhoe, 2009; Land, 2009), and used the measures as approximations of overt attention and of the nature of information acquisition during harvesting. However, we did not study attention and information acquisition per se, but eye movements and introspective reports on information acquisition. We cannot rule out that some objects were attended to in the periphery; partly because the study was conducted with experienced operators in a well acquainted task (see Strasburger *et al.*, 2011). Moreover, it is possible that operators were not processing information from the focused AOI, but instead thinking about something else. However, during the short and intensely active time that the operators were studied (ca. 15 min) it is unlikely that they would have lost focus on the task.

8.2 Experiences of using eye tracking

This section discusses and provides recommendations for eye tracking research based on experiences of using eye tracking in a naturalistic observational field study. The discussion covers both data gathering experiences from the field and experiences of data processing and analysis.

8.2.1 Experiences and recommendations in the field

When planning the field study, it is important to acknowledge that not all humans are suitable subjects for eye-tracking, since features of the participant, like eye colour, eyelid droop, astigmatism etc., and artefacts such as glasses and mascara affect the tracking quality (Holmqvist *et al.*, 2011). The studies with the two operators wearing glasses under the eye-tracking glasses resulted in the poorest data quality, while the operator wearing contact lenses underneath the eye-tracking glasses achieved data in line with the three operators without sight impairment. Glasses with correction for astigmatism did not provide worse data than glasses without. Thus, it is important to determine whether participants have sight impairment, use contact lenses, glasses or mascara, or have a distinctly dominant eye. However, confirmed sight impairment does not necessarily mean that the person must be excluded from the study.

When conducting the study, one should always try to keep the illumination fixed (Holmqvist *et al.*, 2011). However, as shown in Study IV, this is impossible in outdoor environments. Changes in illumination, between, for example, the harvester head and the canopy, were of such a magnitude that tracking was often lost completely for some time. Nevertheless, good planning based on the sun's position with regard to the operator's line of sight, i.e. the intended AOIs, can reduce illumination variation.

Reliable calibration is essential for the validity and generalization of the results. Therefore, it is important not to rely solely on built-in calibration. For example, the Tobii eye-tracker calibrates at focal points of one metre from the eye; this is therefore where precision is highest, and deviations will occur when the focus shifts from this point. In thinning, work is often performed at a boom length of 10 m. Thus, asking the participant to look at various objects in the environment (preferably intended AOIs) provides important validation of the calibration and makes it possible to adjust the gaze position after recordings. Moreover, vibrations and head and body movement decrease the data precision and increase the likelihood that the eye tracker moves out of position (Holmqvist *et al.*, 2011). Since harvester operators move their head in a vibrating environment, recalibration with the AOIs should be done at least twice during recordings; before and after the study. In addition, to help ensure usable data it is also recommendable to check the calibration against objects in the natural environment at half time as a safeguard against the glasses moving out of position during recording. In studies with a high demand on precision and accuracy, calibration should be done in both bright and dim conditions to enable correction for pupil size (Drewes *et al.*, 2012).

In Study IV, a monocular tracker was used. However, for future studies use of a binocular tracker for "eye tracking in the wild" is recommended so that both eyes are tracked. Binocular recordings should give better data and problems in tracking should be more easily detected than with monocular recordings. This recommendation is based partly on the observation that the operators' gaze naturally shifted right-left as well as up-down between the corners of the eyes during the work. This could happen, for example, when logs were processed close to the ground below the cabin on the right- or left-hand side of the machine. Since only the right eye was tracked, tracking was sometimes lost and, when processing took place on the left-hand side, the estimated focus was sometimes on an object with no obvious information value.

Reflective interviews with video recordings have previously been successfully utilized in the study of safety critical logging work (Parker, 2010). The glasses provided a non-obtrusive way of studying real-world operations while adding a dimension of data compared to the study of Parker (2010). Non obtrusive studies of behaviour in natural settings, is essential for ecological validity and robust extrapolation of results to real situations (Dicks et al., 2010; Parker, 2010; Klein, 2008).

As previously stated, the qualitative material from the RTA interviews was essential for interpreting and explaining the tracking data. However, interviewees quite often had difficulty verbalizing what they were doing, and difficulty understanding what information we wanted them to provide. Due to the cyclic nature of the task, the interviewees often felt that there was nothing new to tell after the first few fellings had been described. Thus, it is important to prepare the interviews thoroughly and to continuously motivate the interviewee to give more detailed explanations of their dwell patterns and the task. Since the interviewees are the only ones with introspective access to the intentions and purposes of their dwells, they are a valuable asset in detecting and ruling out irregularities and problems in tracking precision. Thus, it can be beneficial to let them view the full recording during the interview. Based on the experience from Study IV, it is also recommended that critical sequences are identified and "walked through" at a very low playback speed so that the interviewee has time to reflect and formulate a response without feeling time pressured by immediate introduction of the next event.

8.2.2 Experiences and recommendations for analysis

When planning and conducting the analysis of collected eye-tracking material, resource availability should be a key determinant. Frame-by-frame analysis is highly time demanding (Study IV, Holmqvist *et al.*, 2011; Land & McLeod, 2000), and the expected gains should be carefully weighed against effort and resource demands. Thus, if conducting frame-by-frame analysis the focus should be on narrowly defined (spatially and/or temporally) parts of the work (recordings). The results of Study IV give a guide as to how and what AOIs can be constructed in this domain, and during what tasks tracking is likely to provide better or lower data quality and, thus, help determine whether eye-tracking is a viable means to answer the research questions. To give an example: from our experience, detailed objects could not be identified correctly either on the bucking monitor (i.e. the exact information consulted from the monitor) or in the forest (i.e. stumps and piles on previous strip roads). This was due partly to tracking precision and accuracy, and partly to video quality and limitations in obtaining 3D information from 2D representations. Thus, research questions on, for instance, strategies for keeping strip roads parallel and at the right distance from each other are likely to fail to be answered.

Nevertheless, detailed quantitative gaze analysis of the recordings may not always be necessary. If aiming for the "whys", analysis of RTA data may provide sufficient, and better, results. Moreover, eye-tracking data should not only be used for answering research questions. An interesting topic for further research is how the video material (i.e. the visualization of gaze behaviour) can be used for instructional purposes.

In Study IV, dwell measures was used as a proxy for gaze allocation. However, we also considered extracting blink data, which is sometimes used as a proxy for mental demand, but we could neither find a satisfactory algorithm that worked when the pupil changed due to changes in light conditions, nor when the same phenomenon produced a loss in tracking due to reasons other than blinking. Thus, further research and development is needed before eye tracking equipment can be used to study the mental work loads of harvester operators in real operations.

Last, but not least, is the issue of validity. Due to the relatively low precision of the eye movement data, it was important to investigate and validate the data set not only by statistical means but also with complementary interview data and scan path evaluation (evaluation of the path of eye movements). Thus, it is important that the researcher evaluating the data is familiar with the conducted task in order to be able to recognize erroneous data.

8.3 Future research

Future studies to address the design and evaluation of operator learning and education are warranted according to Study I. Study IV presented a method for gathering information on gaze behaviour, which can be used to examine and explain good work practices applied by skilled workers. Indeed, knowledge of expert performance and dwell patterns in forestry work may provide valuable insights and material that could be used in teaching or be refined to recommended practices. Eye-tracking may be used to facilitate learning of challenging harvester work by teaching the visual gaze behaviour of skilled operators and providing explanations for information gathering behaviour that is not instantly apparent to novices. Indeed, many studies have shown that task-dependent gaze behaviour can be taught (Diaz *et al.*, 2013; Hayhoe & Rothkopf, 2011; Kandil *et al.*, 2009). However, controversy remains over whether learned gaze behaviour equates with acquired knowledge and the ability to understand the importance of the objects attended and, thus, whether the new behaviour actually improves task performance and situational awareness. Can operators learn where to look, without knowing why? For the novice, learning the behaviour of an expert without acquiring sufficient knowledge of the reasons behind that behaviour could result in a deterioration in situational awareness and, thus, in performance. Eye-tracking may thus prove a valuable tool to improve education and enhance forestry machine operator learning. It is left to future research to determine whether eye-tracking recordings should be used in educational settings to modify operator behaviour by having them mimic visual gaze patterns derived from eye tracking, or whether the technology should be used for extracting operators' implicit knowledge and then applying that knowledge in the development of operator training. It would also be warranted to investigate whether value could be added by combining these two approaches.

Maintenance, which plays a crucial role in the work and performance of the harvester-forwarder system, was not included within the scope of this thesis. While maintenance improvements are acknowledged for their potential financial benefits (Bohlin & Hultåker, 2006), the work itself is generally considered unsafe (e.g. Väyrynen, 1984). Therefore, there are many work environment aspects related to maintenance that deserve further study. To date, there has been little focus on the possibilities of computer-assisted maintenance and repair work. Considering the hours spent on maintenance, a small improvement in time to complete maintenance would greatly benefit the contractor. Better knowledge and support during maintenance and repair should reduce work methods based on trial and error. This can save time, but also improve safety by reducing unnecessary climbing on the machine and other unsafe work practices involved in locating and repairing faults. On the negative side, the potential for faster and safer maintenance work also brings the potential for longer hours in the machine, and thus increased risk of musculoskeletal problems. On the other hand, reductions in maintenance time provide opportunities to invest more time in preventive measures or other constructive tasks such as harvest planning.

It has been stated that the main health and safety problem of today is not lack of knowledge, but putting existing knowledge into practice (Lewark & Kastenholz, 2007). Based on my experience, this is true in many, but not all, cases. The present thesis has shown that although much work has already been implemented, the problem of musculoskeletal pain is multifaceted, and that some promising solutions, such as introducing mini-levers (Murphy & Oliver, 2008; Attebrant *et al.*, 1997; Hagberg & Lidén, 1991) and better dampening of machines, have not been sufficient. Other solutions have failed in practice due to a failure to comprehensively consider the impacts of the change on the organization and the operator, such as introducing new work schedules with less machine time (see. Persson et al., 2003; Synwoldt & Gellerstedt, 2003; Ager). Moreover, automation and decision support systems are rapidly growing research areas in which new knowledge is being constantly produced. Automation in forestry is likely to have a system change affect comparable to that brought by the introduction of mechanization to the harvesting system (see Ager, 2014). Therefore, in order to be prepared, there is a need for continuous research into methods, interfaces, forms of interaction, safety and health and the automation technology itself. It is difficult to predict the future, but the consequences of not trying may be devastating for performance as well as safety in mechanized forestry (see Sarter *et al.*, 1997; Bainbridge, 1983).

8.4 Concluding remarks

The right abilities, skills, techniques and training of operators are not alone sufficient for ensuring high performance of the logging system. Neither are the most advanced and fastest machines. The operator is affected by and interacts with the machines and technologies, the work organization and the environment surrounding the system. Knowledge of all of these parts and their interactions is crucial for successful development of future logging systems. Future forest operations researchers therefore need to be team players and interact to share specialized knowledge on each of these aspects as well as the tools and methods to study them. Given the challenges and current developments indicated above, such research teams may include practitioners in, for example, forestry, robotics, design (interaction and industrial), psychology, medicine, anthropology and human relations.

9 References

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