

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Motivation and Research Gap	1
1.2	Aim of the Research, Research Questions and Procedure	5
1.3	Thesis Outline	9
1.4	The Thesis in the Context of the Philosophy of Science	11
<b>2</b>	<b>Theoretical Background: The use of Virtual Reality Head-Mounted Devices for Planning and Training in the Context of Manual Order Picking</b>	<b>13</b>
2.1	Virtual Reality Head-Mounted Devices as a Tool for Planning and Training	13
2.1.1	Fundamentals of Virtual Reality Technology	13
2.1.2	Limitations of Contemporary Virtual Reality Head-Mounted Devices	17
2.1.3	State of Research on using Virtual Reality in a Planning Context	19
2.1.4	State of Research on Learning and Training in Virtual Realities	20
2.2	Human-Centred Planning and Training in the Context of Manual Order Picking	23
2.2.1	Fundamentals of Order Picking and Order Picking Technology	23
2.2.2	Fundamentals of the Planning and Design of Order Picking Systems	25
2.2.3	State of Research on the Planning of Order Picking Systems	27

2.2.4	State of Research on Learning and Training in Manual Order Picking .....	29
2.3	State of Research on the use of Virtual Reality in Manual Order Picking and Specification of the Research Gap .....	30
<b>3</b>	<b>Systematic Literature Review of Previous Studies that use Virtual Reality Head-Mounted Devices for Simulating Manual Activities .....</b>	<b>33</b>
3.1	Tertiary Analysis of Previously Published Literature Reviews .....	34
3.2	Framework for the Content Analysis of the Literature Sample .....	36
3.2.1	Defining Manual Activities in Order Picking .....	36
3.2.2	Development of a Framework for the Content Analysis .....	38
3.3	Methodological Approach: Searching and Sampling the Literature .....	40
3.3.1	Keywords and Database Search .....	40
3.3.2	Inclusion and Exclusion Criteria and Sample Generation .....	41
3.3.3	Discussion of the Sample Generation Process .....	44
3.4	Analysis of the Literature Samples .....	44
3.4.1	Quantitative Analyses .....	45
3.4.2	Application of the Content Analysis Framework .....	49
3.5	Conclusion of the Literature Review .....	56
<b>4</b>	<b>Experimental Design for Evaluating the Usability of Virtual Reality for Planning and Training in the Context of Manual Order Picking and Execution of the Study .....</b>	<b>57</b>
4.1	Specification of the Research Design .....	57
4.1.1	Criteria for Quality in Research Designs .....	57
4.1.2	Laboratory Experiments as the Research Design to Investigate Manual Order Picking in Virtual Realities .....	59
4.2	Implementation of the Research Design .....	64
4.2.1	Overview of the Design Process Together with Logistics Managers and Engineers .....	65
4.2.2	Experimental Groups and Randomization .....	67
4.2.3	Experimental Procedure and Treatments .....	67
4.2.4	Laboratory Setup and Apparatus .....	70

---

4.3	Operationalisation of the Research Questions .....	80
4.3.1	Selection of the Dependent Variables .....	80
4.3.2	Measurement of the Dependent Variables .....	82
4.3.3	Questionnaire Design .....	84
4.4	Execution of the Research Study .....	86
4.4.1	Sampling Process, Time of the Experiments and Sample Description .....	86
4.4.2	Validation and Verification of the Experimental Setup Using the Questionnaire Results .....	92
4.4.3	Data Preparation .....	97
<b>5</b>	<b>Results of the Comparison Between Virtual and Real Order Picking .....</b>	101
5.1	Research Hypotheses .....	101
5.2	Procedure and Methods for the Inferential Statistics Analyses .....	105
5.3	Results of the Hypotheses Testing using Inferential Statistics ..	108
5.3.1	Perceived Workload .....	108
5.3.2	Set Completion Times .....	112
5.3.3	Picking Times .....	116
5.3.4	Searching Times .....	118
5.3.5	Number of Erroneous Orders .....	120
5.3.6	Number of Orders with Dropped Items .....	123
5.3.7	Summary of Results .....	126
5.4	Discussion of the Results .....	127
5.4.1	Validation and Discussion of the Experimental Setup ..	127
5.4.2	Comparison of Human Performance in Virtual and Real Order Picking .....	128
<b>6</b>	<b>Analysis of Learning Curves in Virtual and Real Order Picking ..</b>	133
6.1	Occurrence of Learning Effects in General and Selection of Dependent Variables for the Analysis of Learning Curves ..	133
6.2	Curve Fitting .....	138
6.2.1	Learning Curve Models .....	138
6.2.2	Results of the Fitted Learning Curve Models .....	145
6.2.3	Discussion of the Fitted Learning Curves for Picking Times per Item .....	158
6.2.4	Discussion of the Fitted Learning Curves for Searching Times .....	160
6.3	Evaluating the Quality of Fit of the Learning Curve Models ..	162

6.3.1	Quality Measures for the Comparison of the Learning Curve Models .....	163
6.3.2	Results for Picking Times per Item .....	164
6.3.3	Results for Searching Times .....	165
6.3.4	Discussion .....	167
6.4	Comparing Learning Curves between Virtual and Real Order Picking .....	171
6.4.1	Research Hypotheses .....	171
6.4.2	Results for Picking Times per Item .....	174
6.4.3	Results for Searching Times .....	176
6.4.4	Discussion .....	179
6.5	Using Learning Curves for Predicting Human Performance in the Real Environment .....	182
6.6	Using Learning Curves to Estimate the Number of Orders Necessary for Familiarization in Virtual Reality .....	184
7	<b>Conclusion</b> .....	187
7.1	Summary of Results and Answer to the Research Questions .....	187
7.2	Implications for Research and Practice .....	189
7.3	Limitations and Outlook on Future Research .....	191
	<b>Bibliography</b> .....	195