# Exploring the Role of Individual Characteristics in Shaping User Experience during Human–Robot Collaboration in Manufacturing Contexts

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RESEARCH

# Exploring the Role of Individual Characteristics in Shaping User Experience during Human–Robot Collaboration in Manufacturing Contexts

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**Abstract**

As Industry 5.0 emphasizes human-centric manufacturing, understanding how individual characteristics influence user experience in human–robot collaboration (HRC) is increasingly important. This study investigates how individual characteristics (i.e., personality traits and attitudes toward robots) affect user experience during collaborative tasks with a cobot in a manufacturing setting. Individual characteristics were collected through the NEO-FFI-3 (for personality traits) and NARS (for attitude toward robots) questionnaires. Participants completed three assembly tasks of varying product complexity, both with and without the assistance of a cobot. Affective states (measured via SAM) and perceived workload (NASA-TLX) were assessed alongside psychophysiological indicators (electrodermal activity and heart rate variability). Findings highlight the significant influence of individual characteristics in moderating user experience, offering valuable insights for designing adaptive, human-centered cobot systems. Most notably, operators with high levels of extraversion or agreeableness showed greater appreciation when working with a cobot. More caution is needed in implementing HRC with operators who have a high level of neuroticism, openness, and conscientiousness, which may require specific customization in order to fully exploit the benefits of collaborative robotics.

**Keywords** Human–robot collaboration · Industry 5.0 · Manufacturing · Human-centricity · Individual characteristics

**Abbreviations**

| | |
|---|---|
| ANODE | Analysis of Deviance |
| ANOVA | Analysis of Variance |
| EDA | Electrodermal Activity |
| GLMM | Generalized Linear Mixed Model |
| HRC | Human-Robot Collaboration |
| HRV | Heart Rate Variability |
| NARS | Negative Attitude toward Robots Scale |
| PPG | Photopletismogram |
| SAM | Self-Assessment Manikin |
| SCR | Skin Conductance Response |
| MOLR | Mixed-effect Ordinal Logistic Regression |

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## 1 Introduction

The evolution toward Industry 5.0 places the human at the core of technological innovation, advocating for sustainable, resilient, and human-centric manufacturing systems [1]. Within this context, Human–Robot Collaboration (HRC) plays a pivotal role in achieving synergy between human operators and collaborative robots (cobots) [2]. Optimizing such interaction requires an understanding of how individual differences affect the collaboration process [3, 4]. Some works highlighted the importance of aligning robot behavior with individual characteristics. Görür et al. [5] proposed a framework for adaptive cobots that respond to changing user characteristics, demonstrating improvements in perceived collaboration quality and trust. Aly and Tapus [6] showed that matching robot verbal and nonverbal behavior to human personality increases engagement. Yamamoto et al. [7] expanded on this by showing that complementary personalities between users and robots can be preferred in non-task-oriented contexts. These findings underline the need for dynamic, user-adaptive systems in real-world applications [8, 9].

Personality and attitude are essential human attributes for social interaction, even with robotic agents [10]. Several personality models are present in the literature, but the most commonly used and descriptive one is the Big Five, which decomposes personality in the following traits: neuroticism, extraversion, openness, agreeableness, and conscientiousness [10, 11]. A detailed description of each personality trait is provided in Sect. 2.2. Particularly in the field of social Human–Robot Interaction (HRI), several studies have been conducted on the influence of personality and attitude toward robots [12].

Neuroticism is more consistently related to defensive or strained interaction patterns. Takayama and Pantofaru [13] showed that neuroticism increased personal space when robots approached people. Similarly, high neuroticism is often linked to lower engagement and greater distance from robots [12].

Extraversion is one the most robustly supported personality trait in the literature. Kabacińska et al. [12] synthesized evidence linking user extraversion to preferred interaction distance, preference for similar robot personality, more positive impressions of robots, greater enjoyment, and more active engagement. Kaplan et al. [14] further showed, in a sample of 486 participants, that higher extraversion predicted stronger anthropomorphism of robots, which often feeds likeability, trust, and acceptance.

Openness is generally associated with receptivity to robots, novelty, and exploratory engagement. Kabacińska et al. [12] linked openness with higher perceived positivity and realism of robots and with better performance in some robot-mediated tasks. The current evidence therefore points to openness as a potentially important facilitator of adaptation to new robotic partners, but the number of physical HRI studies is rather small [12].

Agreeableness generally appears to facilitate smoother, lower-friction interaction. For instance, Takayama and Pantofaru [13] found that agreeableness predicted smaller personal space when people approached. Kabacińska et al. [12] associated agreeableness with greater enjoyment of interaction, more positive attitudes, and, in several studies, higher comfort and engagement.

Conscientiousness may tend to show the most ambivalent profile [12]. On the one hand, conscientious participants sometimes judged robots more positively and could be more comfortable or engaged in interaction. On the other hand, some studies highlighted that higher conscientiousness was associated with perceiving a robot as more stressful and with less appreciation for a robot that behaved in a highly social manner [12].

Some previous studies have explored the influence of personality traits on trust, acceptance, and performance in industrial HRC scenarios. For example, Sarkar et al. [15] demonstrated that traits like openness and previous experience with robots impact trust development in industrial cobots. Similarly, Porubčinová and Fidlerová [16] emphasized the relevance of emotional attitude and personality in technology adoption models for Industry 4.0, suggesting a need for personalized design in cobotic systems. In a related context, Arora et al. [17] found that personality traits such as extraversion and agreeableness positively influence robot likeability and interaction fluency, particularly when robots exhibit anthropomorphic features. Westhoven and Tegtmeier [18] provided evidence that openness can predict helping behavior toward robots, a finding that may translate into smoother collaboration in industrial contexts.

Naneva et al. (2020) showed that attitudes, anxiety, trust, and acceptance are all relevant to the use and quality of robot interaction, but also highlighted that their effects remain context-dependent and sometimes inconsistent across domains. Therefore, despite the growing interest in personalized and human-centered HRC in manufacturing, two main gaps emerge. First, research on individual differences has mainly been conducted in social or non-industrial HRI settings, whereas evidence from industrial assembly processes remains limited. Second, the literature provides very limited evidence on whether stable individual characteristics moderate the effect of HRC, relative to manual assembly, across tasks with products of different complexity.

The aim of this paper is to explore how individual characteristics (i.e., personality traits and attitudes toward robots) moderate the effects of product complexity and cobot support in an assembly process on user experience. This exploration is necessary to understand the implicit needs and preferences of operators with different individual characteristics, enabling the design of human-centered HRC systems that can ensure the operator's well-being at the individual level. Human-centricity can be operationalized through measurable operator-centered outcomes, such as evaluation of workload, affective state, and psychophysiological response. A study was implemented consisting in assembling three products with different level of product complexity, both manually and with the support of a cobot, and collecting information on user experience in terms of perceived workload, affective state, and psychophysiological response. Personality traits (i.e., neuroticism, extraversion, openness, agreeableness, and conscientiousness) and attitude toward robots were also evaluated through dedicated tools. The main addressed research question is: "*How do individual characteristics influence and moderate user experience in industrial HRC?*". Based on the literature, the following research hypotheses guided the exploratory study:

- H1: Neuroticism is associated with a less positive response to HRC.

- H2: Extraversion is associated with a more positive response to HRC.
- H3: Openness is associated with a more positive response to HRC.
- H4: Agreeableness is associated with a more positive response to HRC.
- H5: Negative attitude toward robots is associated with a less positive response to HRC.

The role of conscientiousness was examined exploratorily, since prior evidence is less consistent especially in industrial HRC settings.

Compared with prior HRC studies, this paper offers novel insights by contributing in three ways. First, it examines the role of stable individual characteristics in a task-oriented industrial assembly setting rather than in a purely social or simulated interaction context. Second, it evaluates whether such characteristics moderate the effect of cobot support relative to manual assembly across products with different levels of complexity. Third, it combines subjective measures with psychophysiological indicators to provide a broader characterization of user experience in industrial HRC. In this sense, the study identifies potential moderators that can guide the design of human-centered HRC systems.

The paper is structured as follows. Section 2 presents the methodology used to explore the research question and hypotheses, describing the experimental setup, collected data, and data processing. Section 3 illustrates the results obtained by analyzing the data collected though the experiment. In Sect. 4, a discussion of the moderating effect of individual characteristics on user experience related to the research hypotheses in HRC is presented. Finally, conclusions and future work are presented in Sect. 5.

## 2 Methodology

This section presents the methodology used to explore the effect of individual characteristics (i.e., personality and attitude toward robots) on user experience concerning HRC by analyzing both self-reported and physiological responses.

### 2.1 Experimental Setup

Three different products of different complexity (i.e., a mechanical equipment, a tile cutter, and a diaphragm pump) were used in order to recreate realistic assembly processes (Fig. 1). Three different products were used to introduce different assembly scenarios and limit possible bias in operator evaluations and opinions due to the assembled product. For more details on the assessment of the assembly complexity, see Appendix A. These assembly processes were implemented both in manual setting, in which the operator performs all operations alone, and in collaborative setting, in which the operator works together with a UR3e collaborative robot (Fig. 2). For more details on the list and allocation of operations, see Appendix A. By comparing the two types of settings, possible differences in assembly mode based on the personal characteristics of the operator can be brought out. In total, by combining the three products with the two settings, six different configurations were implemented and carried out in the "Mind 4 Lab" (Manufacturing Industry 4.0 Laboratory) at the "Politecnico di Torino".

### 2.2 Equipment

Two introductory questionnaires were used to collect personal characteristics: the Negative Attitude toward Robots Scale (NARS) [19] and the NEO Five-Factor Inventory-3 (NEO-FFI-3) Form S-Adult [20].

The NARS [19] measures humans' attitudes toward robots, i.e., feelings or ways of thinking that affects a person's behavior toward robots. It is composed by 14 items divided in three 5-point Likert-scales (from "strongly disagree" to "strongly agree"): (i) *Negative Attitudes toward Situations and Interactions with Robots* (S1) (scoring from 6 to 30), (ii) *Negative Attitudes toward Social Influence of Robots* (S2) (scoring from 5 to 25), and (iii) *Negative Attitudes toward Emotions in Interaction with Robots* (S3) (scoring from 3 to 15). See Appendix B for additional details.

The NEO-FFI-3 [20] is a 60-item instrument that assesses the Big Five (i.e., the most widely accepted theory in personality psychology) personality traits [11]:

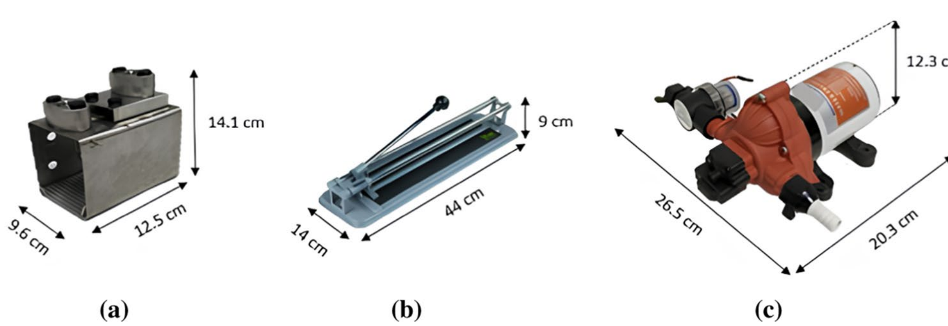


**Fig. 1** Products involved in the manual and HRC assemblies: (**a**) mechanical equipment, (**b**) tile cutter, (**c**) diaphragm pump


**Fig. 2** The UR3e cobot during the collaborative assembly of the tile cutter

- *Neuroticism* describes a person's tendency to respond to stressors with negative emotions, including fear, sadness, anxiety, guilt, and shame. This trait can be thought of as an alarm system. People experience negative emotions as a sign that something is wrong in the world. Fear is a response to danger, guilt a response to having done something wrong. However, not everyone has the same reaction to a given situation. High *Neuroticism* scorers are more likely to react to a situation with strong negative emotions. Low *Neuroticism* scorers are more likely to brush off their misfortune and move on.
- *Extraversion* describes a person's inclination to seek stimulation from the outside world, especially in the form of attention from other people. Extraverts engage actively with others to earn friendship, admiration, power, status, excitement and romance. Introverts, on the other hand, conserve their energy and do not work as hard to earn these social rewards.
- *Openness* describes a person's tendency to think abstractly. Those who are high in *Openness* tend to be creative, adventurous and intellectual. They enjoy playing with ideas and discovering novel experiences. Those who are low in *Openness* tend to be practical, traditional and focused on the concrete. They tend to avoid the unknown and follow traditional ways.
- *Agreeableness* describes the extent to which a person prioritizes the needs of others over their own needs. People who are high in *Agreeableness* experience a great deal of empathy and tend to get pleasure out of serving and taking care of others. People who are low in *Agreeableness* tend to experience less empathy and put their own concerns ahead of others.
- *Conscientiousness* describes a person's level of goal orientation and persistence. Those who are high in *Conscientiousness* are organized and determined, and are able to forgo immediate gratification for the sake of long-term achievement. Those who are low in this trait are impulsive and easily sidetracked.

Each personality trait is evaluated through a 5-point Likert scale (from “strongly disagree” to “strongly agree”), with a scoring ranging between 0 and 48. see Appendix B for some example items of the NEO-FFI-3.

To collect information on user experience, post-trial self-reporting tools included the NASA Task Workload Index (NASA-TLX) [21] and the Self-Assessment Manikin (SAM) [22].

The NASA-TLX [21] is a common tool to measure perceived workload. It involves the assessment of six dimensions (i.e., *Mental demand*, *Physical demand*, *Temporal demand*, *Performance*, *Effort* and *Frustration*) on a 100-point scale (5-point steps). Through a pairwise comparison procedure, importance weights for each dimension are obtained. For each of the 15 pairs of dimensions, participants are asked to choose the dimension that most influences their perceived workload. Counting the number of times a certain dimension was chosen yields its importance weight. The final perceived *Workload* score (ranging from 0 to 100) is given by the weighted average of the six dimensions. See Appendix B for additional details.

The Self-Assessment Manikin (SAM) [22] is a widely used image-based assessment tool to measure the affective reaction to a certain situation or event. It is based on the Pleasure-Arousal-Dominance (PAD) model, which represents affective states on three dimensions: valence, arousal, and dominance. Valence (or pleasure) describes the positivity or negativity of an elicited emotion (e.g., fear, anger, or boredom tend to be negative emotions, whereas relaxation or joy tend to be positive emotions). Arousal refers to how excited a person is, regardless of whether the excitement derives from a positive or negative emotion (e.g., boredom and relaxation are characterized by low arousal, whereas euphoria, fear, or anger tend to have a high arousal). Finally, dominance describes how much one feels in control of a situation, i.e., a feeling of control and influence over one’s surroundings and others (e.g., fear or anxiety are usually characterized by low dominance, while relaxation or anger by a high dominance). The original 9-point scale SAM was used in the study to collect affective state of the participants during the different assembly configurations. See Appendix B for additional details.

The Empatica E4 biosensor wristband was also implemented to collect Electrodermal Activity (EDA) data at 4 Hz, heart data through Photopletismogram (PPG) at 64 Hz, and 3-axis accelerometer data at 32 Hz. The device also provided the heart rate NN-intervals. PPG and EDA data were used as arousal and mental strain indicators, evaluating Heart Rate Variability (HRV) and average Skin Conductance Response (SCR) in each configuration.

## 2.3 Experimental Procedure

Eighteen participants (ten males and eight females aged between 20 and 25 years old) with no prior experience with cobots were involved in the study. Figure 3 outlines the experimental study procedure. Initially, the objectives of the study and its procedure were explained to the participant, their demographics were collected, and the initial questionnaires (i.e., the NEO-FFI-3 and NARS) were administered. The experimental supervisor subsequently seated the participant in the experiment location and explained the various steps of the assembly task, also illustrating the different configurations. After any questions were discussed, the Empatica E4 biosensor was firmly placed on the participant's left wrist and 15 min were waited for the electrodes to adhere well to the skin and to obtain reliable EDA data. Next, the participant was invited to relax and remain still to record 2 min of physiological signals at rest (i.e., the baseline of the physiological signals). After this phase was completed, the participant started the assembly phase. For each setting, the participant performed a training trial to learn the assembly process, avoiding first-exposure confusion, and then, if everything was clear, performed the assembly without any external support. Each participant performed the assembly of each product in both modalities in random order, for a total of 6 trials per participant. At the end of each trial, the post-trial questionnaires (i.e., NASA-TLX and SAM) were administered, and the participant was involved in a quick debriefing. Within-subject trial order randomization was implemented, randomly assigning the sequence of assembly settings for each individual participant, to ensure that the order of exposure did not introduce systematic bias (e.g., fatigue, learning) [23]. Furthermore, since the entire experimental session lasted approximately 90 min and participants were exposed to only one trial for each of the different assembly settings, the order effects were further mitigated.

## 2.4 Data Analysis Methodology

The list of all dependent and independent variables collected in the study is summarized in Table 1.

From physiological signals, potential artifacts (e.g., unusual peaks, extreme values) were identified and

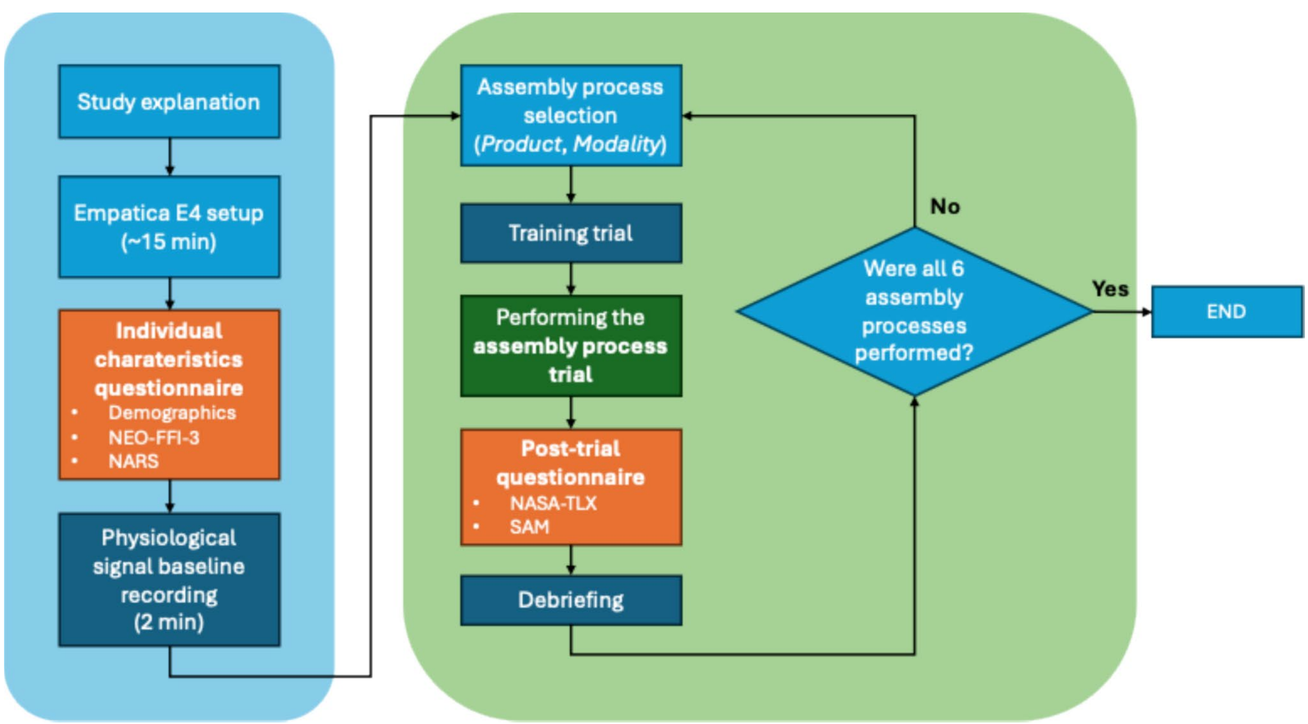


**Fig. 3** Experimental study procedure flow-chart

removed. By using the MATLAB-software "Ledalab", EDA signal was decomposed in tonic component and phasic component though Continuous Decomposition Analysis (CDA) [24]. The tonic component is characterized by the Skin Conductance Level (SCL), which represents the long-term fluctuations in EDA that are not directly derived by external stimuli. Short-term EDA fluctuations elicited by an external stimulus represents phasic component. From the phasic component, Skin Conductance Responses (SCRs), which are amplitude differences between the SCL and response peaks, are detected. In the present study, the average SCR (*Average SCR*) was calculated for each configuration, representing a stress response and phasic activity indicator [25]. Regarding heart data, NN-intervals (i.e., time intervals between systolic peaks) were obtained from PPG. As HRV measure for parasympathetic activity, the Root Mean Square of Successive Differences of NN-intervals (RMSSD) was included due to its common usage [26, 27].

A series of Mixed-effect Ordinal Logistic Regression (MOLR) models were implemented in order to investigate the relationship of the individual characteristics with the subjective responses the SAM dimensions. The "ordinal" package from the software R was used to fit MOLR models [28]. The MOLR model was chosen for its suitability in (i) modelling dependent variables defined on an ordinal scale (such as the SAM dimensions), and (ii) handling the participant effect as a random block effect [4]. MOLR models are based on Cumulative Link Mixed Models (CLMMs) and can be specified in terms of cumulative logits as follows (supposing to have $K$ levels of the ordinal response variable, $n$ observations and $J$ participants):

$$logit\left(\mathbb{P}\left(Y_{ij} \leq k\right)\right) = \log\left(\frac{\mathbb{P}\left(Y_{ij} \leq k\right)}{1 - \mathbb{P}\left(Y_{ij} \leq k\right)}\right) = \theta_k - \boldsymbol{x}_{ij}^{\mathrm{T}}\boldsymbol{\beta} - u_j \text{ for } k = 1, \ldots, K-1 \tag{1}$$

with $i = 1, \ldots, n$ and $j = 1, \ldots, J$. The term $\mathbb{P}\left(Y_{ij} \leq k\right)$ is the probability that the observation $i$ of the participant $j$ is associated with a rating below or equal to $k$. Note that the logit is not defined for $k = K$, since $\mathbb{P}\left(Y_{ik} \leq K\right) = 1$. The coefficients $\theta_k$ are called threshold parameters and act as model intercepts. Data of the independent variables of observation

**Table 1** Summary of independent and dependent variables

| Type of variable | Variable | Description |
|---|---|---|
| *Independent variables* | *Product* | Product to be assembled (*Mechanical equipment, Tile-cutter, Pump*) |
| | *Modality* | Modality of the assembly (*Manual, HRC*) |
| | *Pers_N* | Neuroticism score |
| | *Pers_E* | Extraversion score |
| | *Pers_O* | Openness score |
| | *Pers_A* | Agreeableness score |
| | *Pers_C* | Conscientiousness score |
| | *NARS_S1* | "Negative Attitudes toward Situations and Interactions with Robots" score from NARS |
| | *NARS_S2* | "Negative Attitudes toward Social Influence of Robots" score from NARS |
| | *NARS_S3* | "Negative Attitudes toward Emotions in Interaction with Robots" score from NARS |
| | *Participant* | Participant ID |
| *Dependent variables* | *Mental demand* | NASA-TLX dimension representing how mentally demanding is a task |
| | *Physical demand* | NASA-TLX dimension representing how physically demanding is a task |
| | *Temporal demand* | NASA-TLX dimension representing how temporally demanding is a task |
| | *Performance* | NASA-TLX dimension representing how well a task is perceived to be performed |
| | *Effort* | NASA-TLX dimension representing how much effort is perceived during the task |
| | *Frustration* | NASA-TLX dimension representing how many negative feelings are perceived in a task |
| | *Workload* | NASA-TLX dimension representing the overall perceived workload score |
| | *Valence* | SAM dimension assessing how positive is the emotion (9-point scale) |
| | *Arousal* | SAM dimension assessing how much agitated a person feels (9-point scale) |
| | *Dominance* | SAM dimension assessing how strong is the dominance feeling (9-point scale) |
| | *Average SCR* | Average skin conductance response |
| | *RMSSD* | Root mean square of successive differences of NN-intervals |

$i$ of participant $j$ are contained in the vector $\boldsymbol{x}_{ij}^{\mathrm{T}}$, while the model parameters are in vector $\boldsymbol{\beta}$. The term $u_j$ represents the random effect for participant $j$, where $u_j \sim N(0, \sigma^2)$. Note that the negative sign in front of $\boldsymbol{x}_{ij}^{\mathrm{T}}\boldsymbol{\beta}$ ensures that positive parameters are associated with increased probability for higher levels as the independent variables increase.

Since the NASA-TLX dimension scores and psychophysiological responses can be treated as continuous variables, Generalized Linear Mixed Models (GLMMs) were implemented to explore the relationship with the individual characteristics and to handle the participant effect as a random block effect. In particular, the logarithm was used as link function, leading to log-linear mixed models, as the response variables can be only positive. Models were fitted using the "lmerTest" package from the software R. The models can be represented as follows:

$$log(Y_{ij}) = \boldsymbol{x}_{ij}^{\mathrm{T}}\boldsymbol{\beta} + u_j \text{ with } i = 1, \dots, n \text{ and } j = 1, \dots, J \tag{2}$$

where $\boldsymbol{x}_{ij}^{\mathrm{T}}$ is the vector containing data of the independent variables for observation $i$ of participant $j$, $\boldsymbol{\beta}$ the vector for the model parameters, and $u_j$ the random effect for participant $j$ with $u_j \sim N(0, \sigma^2)$.

The fitted models aimed to explore the influence of individual characteristics (i.e., personality traits and attitude towards robots) on the user experience response variables, also in relation to product complexity and cobot support. From a theoretical perspective, the effect of an individual characteristic on user experience can vary depending on the product complexity or the presence of a cobot. Therefore, the introduction of the interaction terms enabled to model and explore the contextual and person-specific nature of the HRC user experience, in line with a human-centered perspective. The formula used for the models is reported below using the Wilkinson notation [29], where "1" indicates the intercept inclusion, "∗" the inclusion of all combinations of terms and their interactions, and "(1|)" the inclusion of a random intercept for mixed models:

$$\begin{aligned} Y \sim\ & 1 + Product * Modality + Product * Pers\_N + Product * Pers\_E + Product * Pers\_O + Product \\ & * Pers\_A + Product * Pers\_C + Product * NARS\_S1 + Product * NARS\_S2 + Product * NARS\_S3 \\ & + Modality * Pers\_N + Modality * Pers\_E + Modality * Pers\_O + Modality * Pers\_A + Modality * Pers\_C \\ & + Modality * NARS\_S1 + Modality * NARS\_S2 + Modality * NARS\_S3 + (1|Participant) \end{aligned} \tag{3}$$

Significance of the model terms will be analyzed and discussed in the following section for each dependent variable.

## 3 Results

In this section, the analysis results for each response variable are reported.

### 3.1 Perceived Workload (NASA-TLX)

Table 2 reports the results of the Analysis of Variance (ANOVA) for the GLMMs of each NASA-TLX dimension, showing the significance of each model term. Appendix C contains the coefficient estimates for each model term.

#### 3.1.1 Workload

Focusing on the overall perceived workload (*Workload*) (Table 3), in general there was a positive effect of the complexity of the product to be assembled (*Product*) ($\beta_{ProductTilecutter} = 0.430$, $\beta_{ProductPump} = 1.360$). In addition, HRC modality increased the perceived workload when assembling the simplest product (i.e., the mechanical equipment) ($\beta_{ModalityHRC} = 0.769$), but the effect decreased when assembling more complex products ($\beta_{ProductTilecutter \bullet ModalityHRC} = -0.266$, $\beta_{ProductPump \bullet ModalityHRC} = -0.246$). Concerning the significant influences (i.e., model terms with a p-value < 0.05) of personal characteristics:

- Operators with greater neuroticism (*Pers_N*) showed a slight significant increase in *Workload* when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_N} = 0.010$, $\beta_{ProductPump \bullet Pers\_N} = 0.023$).
- Operators with greater extraversion (*Pers_E*) experienced an increase in *Workload* during the assembly of more complex products ($\beta_{ProductTilecutter \bullet Pers\_E} = 0.029$, $\beta_{ProductPump \bullet Pers\_E} = 0.026$).
- Operators with greater openness (*Pers_O*) showed a slight increase in *Workload* during HRC ($\beta_{ModalityHRC \bullet Pers\_O} = 0.014$).
- Operators with greater agreeableness (*Pers_A*) reported an increased *Workload* in general ($\beta_{Pers\_A} = 0.089$), however, it was counterbalanced in the HRC modality ($\beta_{ModalityHRC \bullet Pers\_A} = -0.034$).
- More conscientious operators (*Pers_C*) experienced an increase in *Workload* when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_C} = 0.023$, $\beta_{ProductPump \bullet Pers\_C} = 0.018$).

**Table 2** ANOVA table for NASA-TLX with resulting p-values for each model term

| Model term | Workload | Mental demand | Physical demand | Temporal demand | Performance | Effort | Frustration |
|---|---|---|---|---|---|---|---|
| *Product* | < 0.001 *** | 0.217 | 0.016 * | < 0.001 *** | 0.064 | 0.409 | 0.051 |
| *Modality* | 0.024 * | 0.353 | 0.547 | 0.014 | 0.021 * | < 0.001 *** | 0.131 |
| *Pers_N* | 0.238 | 0.865 | 0.272 | 0.242 | 0.610 | 0.580 | 0.353 |
| *Pers_E* | 0.574 | 0.888 | 0.892 | 0.499 | 0.039 * | 0.390 | 0.571 |
| *Pers_O* | 0.157 | 0.149 | 0.102 | 0.295 | 0.499 | 0.107 | 0.041 * |
| *Pers_A* | 0.012 * | 0.027 * | 0.032 * | 0.022 * | 0.132 | 0.099 | 0.586 |
| *Pers_C* | 0.169 | 0.126 | 0.468 | 0.227 | 0.827 | 0.261 | 0.373 |
| *NARS_S1* | 0.216 | 0.888 | 0.148 | 0.301 | 0.581 | 0.261 | 0.817 |
| *NARS_S2* | 0.084 | 0.100 | 0.890 | 0.107 | 0.270 | 0.605 | 0.782 |
| *NARS_S3* | 0.081 | 0.262 | 0.208 | 0.241 | 0.052 | 0.142 | 0.352 |
| *Product · Modality* | < 0.001 *** | < 0.001 *** | 0.039 * | < 0.001 *** | 0.940 | 0.003 ** | 0.001 * |
| *Product · Pers_N* | < 0.001 *** | < 0.001 *** | 0.182 | < 0.001 *** | 0.462 | 0.986 | 0.111 |
| *Product · Pers_E* | < 0.001 *** | 0.109 | < 0.001 *** | 0.351 | < 0.001 *** | < 0.001 *** | 0.570 |
| *Product · Pers_O* | 0.078 | < 0.001 *** | 0.064 | 0.046 * | 0.777 | 0.085 | < 0.001 *** |
| *Product · Pers_A* | 0.261 | < 0.001 *** | 0.386 | < 0.001 *** | < 0.001 *** | < 0.001 *** | < 0.001 *** |
| *Product · Pers_C* | < 0.001 *** | < 0.001 *** | 0.168 | < 0.001 *** | < 0.001 *** | < 0.001 *** | 0.001 ** |
| *Product · NARS_S1* | < 0.001 *** | 0.002 ** | < 0.001 *** | < 0.001 *** | < 0.001 *** | < 0.001 *** | 0.027 * |
| *Product · NARS_S2* | 0.002 ** | < 0.001 *** | 0.913 | 0.285 | 0.003 ** | 0.175 | < 0.001 *** |
| *Product · NARS_S3* | < 0.001 *** | 0.368 | < 0.001 *** | < 0.001 *** | 0.028 * | < 0.001 *** | 0.809 |
| *Modality · Pers_N* | 0.016 * | 0.162 | 0.007 ** | 0.438 | 0.748 | 0.245 | < 0.001 *** |
| *Modality · Pers_E* | 0.122 | 0.970 | 0.032 * | < 0.001 *** | 0.001 ** | 0.061 | 0.506 |
| *Modality · Pers_O* | 0.020 * | < 0.001 *** | < 0.001 *** | 0.175 | 0.920 | 0.367 | < 0.001 *** |
| *Modality · Pers_A* | < 0.001 *** | < 0.001 *** | < 0.001 *** | 0.812 | 0.013 * | < 0.001 *** | 0.342 |
| *Modality · Pers_C* | 0.092 | < 0.001 *** | 0.005 ** | 0.294 | 0.058 | 0.007 ** | 0.915 |
| *Modality · NARS_S1* | 0.172 | 0.011 * | 0.544 | 0.020 * | 0.023 * | 0.289 | 0.015 * |
| *Modality · NARS_S2* | < 0.001 *** | < 0.001 *** | < 0.001 *** | < 0.001 *** | 0.002 ** | < 0.001 *** | 0.204 |
| *Modality · NARS_S3* | 0.109 | 0.307 | 0.156 | 0.165 | 0.004 ** | 0.948 | 0.580 |

(*) $0.05 > p \geq 0.01$, (**) $0.01 > p \geq 0.001$, (***) $p < 0.001$

- Operators with a negative attitude toward interaction with robots (*NARS_S1*), with a negative attitude toward robots' social influence (*NARS_S2*), or greater concern for emotion in robot interaction (*NARS_S3*) showed in general a decrease in *Workload* when assembling more complex products ($\beta_{ProductTilecutter \bullet NARS\_S1} = -0.063$, $\beta_{ProductPump \bullet NARS\_S1} = -0.080$, $\beta_{ProductTilecutter \bullet NARS\_S2} = -0.040$, $\beta_{ProductPump \bullet NARS\_S2} = -0.050$, $\beta_{ProductTilecutter \bullet NARS\_S3} = -0.064$, $\beta_{ProductPump \bullet NARS\_S3} = -0.127$). In addition, operators with a higher *NARS_S2* score obtained a slightly lower *Workload* score during HRC modality ($\beta_{ModalityHRC \bullet NARS\_S2} = -0.060$).

#### 3.1.2 Mental Demand

By examining the dimensions that constitute *Workload* in detail, more information can be gained about its characterization. Looking at *Mental demand* (Table 4), in general, the presence of the cobot (*Modality*) during more complex product assemblies (*Product*) significantly decreased *Mental demand* ($\beta_{ProductTilecutter \bullet ModalityHRC} = -0.583$, $\beta_{ProductPump \bullet ModalityHRC} = -0.660$), indicating a general cognitive support of the cobot. Regarding the effect of individual characteristics:

- Operators with greater neuroticism (*Pers_N*) showed a decrease in *Mental demand* when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_N} = -0.056$, $\beta_{ProductPump \bullet Pers\_N} = -0.049$).
- Operators with greater openness (*Pers_O*) or conscientiousness (*Pers_C*) showed a slight increase in *Mental demand* during the assembly of more complex products ($\beta_{ProductTilecutter \bullet Pers\_O} = 0.090$, $\beta_{ProductPump \bullet Pers\_O} = 0.121$, $\beta_{ProductTilecutter \bullet Pers\_C} = 0.068$, $\beta_{ProductPump \bullet Pers\_C} = 0.059$)

**Table 3** Summary of the GLMM fixed-terms for workload

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 1.108 | - |
| *Product* | *Tilecutter* | 0.430 | *Workload* increased in general when assembling more complex products |
| | *Pump* | 1.360 | |
| *Modality* | *HRC* | 0.769 | HRC modality increased *Workload* |
| *Pers_N* | - | −0.032 | - |
| *Pers_E* | - | −0.023 | - |
| *Pers_O* | - | −0.025 | - |
| *Pers_A* | - | 0.089 | Operators with greater agreeableness showed increased *Workload* in general |
| *Pers_C* | - | −0.039 | - |
| *NARS_S1* | - | 0.092 | - |
| *NARS_S2* | - | 0.128 | - |
| *NARS_S3* | - | 0.174 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.266 | *Modality* effect was mitigated when assembling more complex products |
| | *Pump · HRC* | −0.246 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.010 | Greater neuroticism implied a light increase in *Workload* when assembling more complex products |
| | *Pump· Pers_N* | 0.023 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.029 | Greater extraversion implied a slight increase in *Workload* during the assembly of more complex products |
| | *Pump· Pers_E* | 0.026 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.007 | - |
| | *Pump· Pers_O* | −0.016 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.014 | - |
| | *Pump· Pers_A* | −0.009 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.023 | Greater conscientiousness implied a slight increase in *Workload* when assembling more complex products |
| | *Pump· Pers_C* | 0.018 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.063 | Operators with a negative attitude toward interaction with robots showed a decrease in *Workload* when assembling more complex products |
| | *Pump· NARS_S1* | −0.080 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.040 | Operators with a negative attitude toward robots' social influence showed a decrease in *Workload* when assembling more complex products |
| | *Pump· NARS_S2* | −0.050 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.064 | Operators with concerns for emotion in robot interaction showed a decrease in *Workload* when assembling more complex products |
| | *Pump· NARS_S3* | −0.127 | |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.011 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.008 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.014 | Greater openness implied a slight increase in *Workload* during HRC |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.034 | The HRC modality counterbalanced the general increasing effect in operators with greater agreeableness |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.008 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.020 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.060 | A decrease of *Workload* emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.037 | - |

or HRC modality ($\beta_{ModalityHRC \bullet Pers\_O} = 0.090$, $\beta_{ModalityHRC \bullet Pers\_C} = 0.050$).

- Operators with greater agreeableness (*Pers_A*) showed higher *Mental demand* in general ($\beta_{Pers\_A} = 0.209$), however the assembly of more complex products and the HRC modality offset this effect ($\beta_{ProductTilecutter \bullet Pers\_A} = -0.068$, $\beta_{ProductPump \bullet Pers\_A} = -0.098, \beta_{ModalityHRC \bullet Pers\_A} = -0.092$).
- Operators with a negative attitude toward interaction with robots (*NARS_S1*) reported a slight increase in *Mental demand* when assembling more complex products or working in HRC modality ($\beta_{ProductTilecutter \bullet NARS\_S1} = 0.120$, $\beta_{ProductPump \bullet NARS\_S1} = 0.125, \beta_{ModalityHRC \bullet NARS\_S1} = 0.083$).

**Table 4** Summary of the GLMM fixed-terms for mental demand

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 1.056 | - |
| *Product* | *Tilecutter* | 0.292 | - |
| | *Pump* | 1.451 | |
| *Modality* | *HRC* | −0.146 | - |
| *Pers_N* | - | 0.047 | - |
| *Pers_E* | - | −0.011 | - |
| *Pers_O* | - | −0.168 | - |
| *Pers_A* | - | 0.209 | Operators with greater agreeableness showed increased *Mental demand* in general |
| *Pers_C* | - | −0.114 | - |
| *NARS_S1* | - | −0.135 | - |
| *NARS_S2* | - | 0.349 | - |
| *NARS_S3* | - | 0.175 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.583 | In general, the HRC modality during the assembly of more complex product decreased *Mental demand* |
| | *Pump · HRC* | −0.660 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | −0.056 | Greater neuroticism implied slightly less *Mental demand* when assembling more complex products |
| | *Pump· Pers_N* | −0.049 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.025 | - |
| | *Pump· Pers_E* | −0.003 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | 0.090 | Greater openness implied more *Mental demand* when assembling more complex products |
| | *Pump· Pers_O* | 0.121 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.068 | Greater agreeableness implied a mitigation in *Mental demand* when assembling more complex products |
| | *Pump· Pers_A* | −0.098 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.068 | Greater conscientiousness implied slightly more *Mental demand* when assembling more complex products |
| | *Pump· Pers_C* | 0.059 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | 0.120 | Operators with a negative attitude toward interaction with robots showed an increase in *Mental demand* when assembling more complex products |
| | *Pump· NARS_S1* | 0.125 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.209 | Operators with a negative attitude toward robots' social influence showed a decrease in *Mental demand* when assembling more complex products |
| | *Pump· NARS_S2* | −0.222 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.090 | - |
| | *Pump· NARS_S3* | −0.054 | |
| *Modality · Pers_N* | *HRC · Pers_N* | −0.014 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | 0.000 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.090 | Greater openness implied an increase in *Mental demand* during HRC modality |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.092 | The HRC modality counterbalanced the general increasing effect in operators with greater agreeableness |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.050 | Greater conscientiousness implied a slight increase in *Mental demand* during HRC modality |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.083 | Operators with a negative attitude toward interaction with robots showed an increase in *Mental demand* during HRC modality |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.157 | A decrease of *Mental demand* emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.053 | - |

- Operators with a negative attitude toward the social influence of robots (*NARS_S2*) were found to have a decrease in *Mental demand* during the assembly of more complex products or HRC modality ($\beta_{ProductTilecutter\bullet NARS\_S2} = -0.209$, $\beta_{ProductPump\bullet NARS\_S2} = -0.222$, $\beta_{ModalityHRC\bullet NARS\_S2} = -0.060$).

#### 3.1.3 Physical Demand

Observing *Physical demand* (Table 5), it was in general positively influenced by the complexity of the

**Table 5** Summary of the GLMM fixed-terms for physical demand

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 0.904 | - |
| *Product* | *Tilecutter* | 0.909 | *Physical demand* increased in general when assembling more complex products |
| | *Pump* | 1.249 | |
| *Modality* | *HRC* | 0.307 | - |
| *Pers_N* | - | −0.039 | - |
| *Pers_E* | - | −0.016 | - |
| *Pers_O* | - | −0.063 | - |
| *Pers_A* | - | 0.119 | Operators with greater agreeableness reported increased *Physical demand* in general |
| *Pers_C* | - | −0.032 | - |
| *NARS_S1* | - | 0.155 | - |
| *NARS_S2* | - | 0.059 | - |
| *NARS_S3* | - | 0.236 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.140 | In general, the HRC modality during the assembly of more complex product offset *Physical demand* |
| | *Pump · HRC* | −0.164 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.006 | - |
| | *Pump· Pers_N* | 0.013 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.048 | Greater extraversion implied slightly more *Physical demand* when assembling more complex products |
| | *Pump· Pers_E* | 0.032 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.019 | - |
| | *Pump· Pers_O* | −0.019 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.012 | - |
| | *Pump· Pers_A* | 0.002 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.001 | - |
| | *Pump· Pers_C* | 0.013 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.058 | Operators with a negative attitude toward interaction with robots showed a decrease in *Physical demand* when assembling more complex products |
| | *Pump· NARS_S1* | −0.092 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.008 | - |
| | *Pump· NARS_S2* | −0.003 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.139 | Operators with concerns for emotion in robot interaction showed a decrease in *Physical demand* when assembling more complex products |
| | *Pump· NARS_S3* | −0.176 | |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.015 | Greater neuroticism implied slightly more *Physical demand* in HRC modality |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.015 | Greater extraversion implied slightly less *Physical demand* in HRC modality |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.046 | Greater openness implied a slight increase in *Physical demand* during HRC modality |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.052 | The HRC modality counterbalanced the general increasing effect in operators with greater agreeableness |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.018 | Greater conscientiousness implied a slight increase in *Physical demand* during HRC modality |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.011 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.092 | A decrease of *Physical demand* emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.042 | - |

product to be assembled (*Product*) ($\beta_{ProductTilecutter} = 0.909$, $\beta_{ProductPump} = 1.249$). However, the presence of the cobot (*Modality*) during more complex product assemblies decreased *Physical demand*, indicating a general physical support of the cobot ($\beta_{ProductTilecutter \bullet ModalityHRC} = -0.140$, $\beta_{ProductPump \bullet ModalityHRC} = -0.164$). Concerning the individual characteristics:

- Operators with greater neuroticism (*Pers_N*), openness (*Pers_O*) or conscientiousness (*Pers_C*) perceived

**Table 6** Summary of the GLMM fixed-terms for temporal demand

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | −0.495 | - |
| *Product* | *Tilecutter* | 1.944 | *Temporal demand* increased in general when assembling more complex products |
| | *Pump* | 3.242 | |
| *Modality* | *HRC* | 1.035 | - |
| *Pers_N* | - | −0.054 | - |
| *Pers_E* | - | −0.001 | - |
| *Pers_O* | - | −0.021 | - |
| *Pers_A* | - | 0.131 | Operators with greater agreeableness reported increased *Temporal demand* in general |
| *Pers_C* | - | −0.052 | - |
| *NARS_S1* | - | 0.124 | - |
| *NARS_S2* | - | 0.163 | - |
| *NARS_S3* | - | 0.131 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.191 | In general, the HRC modality during the assembly of more complex product offset *Temporal demand* |
| | *Pump · HRC* | −0.327 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.040 | Greater neuroticism implied slightly more *Temporal demand* when assembling more complex products |
| | *Pump· Pers_N* | 0.057 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | −0.009 | - |
| | *Pump· Pers_E* | 0.003 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.021 | Greater openness implied slightly less *Temporal demand* when assembling more complex products |
| | *Pump· Pers_O* | −0.020 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.075 | Greater agreeableness implied a mitigation in *Temporal demand* when assembling more complex products |
| | *Pump· Pers_A* | −0.056 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.032 | Greater conscientiousness implied slightly more *Temporal demand* when assembling more complex products |
| | *Pump· Pers_C* | 0.030 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.049 | Operators with a negative attitude toward interaction with robots showed a decrease in *Temporal demand* when assembling more complex products |
| | *Pump· NARS_S1* | −0.181 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.030 | - |
| | *Pump· NARS_S2* | −0.024 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | 0.097 | Operators with concerns for emotion in robot interaction showed a slight increase in *Temporal demand* when assembling the tile cutter, but a decrease when assembling the diaphragm pump |
| | *Pump· NARS_S3* | −0.173 | |
| *Modality · Pers_N* | *HRC · Pers_N* | −0.005 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.028 | Greater extraversion implied slightly less *Temporal demand* in HRC modality |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.011 | - |
| *Modality · Pers_A* | *HRC · Pers_A* | 0.002 | - |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.007 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.044 | A slight increase in *Temporal demand* emerged during HRC modality in operators with a negative attitude toward interaction with robots |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.096 | A decrease of *Temporal demand* emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.042 | - |

slightly higher physical demand during HRC modality ($\beta_{ModalityHRC\bullet Pers\_N} = 0.015$, $\beta_{ModalityHRC\bullet Pers\_O} = 0.046$, $\beta_{ModalityHRC\bullet Pers\_C} = 0.018$).

- Operators with greater extraversion (*Pers_E*) reported an additional increase in *Physical demand* when assembling more complex products ($\beta_{ProductTilecutter\bullet Pers\_E} = 0.048$, $\beta_{ProductPump\bullet Pers\_E} = 0.032$), however the HRC modality compensated this effect ($\beta_{ModalityHRC\bullet Pers\_E} = -0.015$).
- Operators with greater agreeableness (*Pers_A*) perceived higher physical demand in general ($\beta_{Pers\_A} = 0.119$), but

**Table 7** Summary of the GLMM fixed-terms for performance (i.e., a reverse item)

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 4.343 | - |
| *Product* | *Tilecutter* | 0.705 | - |
| | *Pump* | −0.507 | |
| *Modality* | *HRC* | 0.954 | Operators generally perceived a slight deterioration in performance during HRC modality |
| *Pers_N* | - | 0.000 | - |
| *Pers_E* | - | −0.066 | - |
| *Pers_O* | - | −0.012 | - |
| *Pers_A* | - | 0.001 | - |
| *Pers_C* | - | −0.003 | - |
| *NARS_S1* | - | −0.102 | - |
| *NARS_S2* | - | 0.121 | - |
| *NARS_S3* | - | 0.102 | - |
| *Product · Modality* | *Tilecutter· HRC* | 0.020 | - |
| | *Pump · HRC* | 0.029 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.008 | - |
| | *Pump· Pers_N* | 0.010 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.061 | Operators with greater extraversion perceived a slight deterioration in their performance when assembling more complex products |
| | *Pump· Pers_E* | 0.061 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.004 | - |
| | *Pump· Pers_O* | 0.004 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.055 | Operators with greater agreeableness reported slightly better performance when assembling more complex products |
| | *Pump· Pers_A* | −0.014 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.013 | Operators with greater conscientiousness reported a slight deterioration in performance when assembling the tile cutter, but a slight improvement when assembling the diaphragm pump |
| | *Pump· Pers_C* | −0.038 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | 0.025 | Operators with a negative attitude toward interaction with robots showed a slight decrease in performance when assembling more complex products |
| | *Pump· NARS_S1* | 0.130 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.079 | Operators with a negative attitude toward robots' social influence perceived a slight improvement in performance when assembling more complex products |
| | *Pump· NARS_S2* | −0.061 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.054 | Operators with concerns for emotion in robot interaction perceived a slight improvement in performance when assembling the tile cutter, but a slight worsening when assembling the diaphragm pump |
| | *Pump· NARS_S3* | 0.067 | |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.002 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.028 | A slight improvement in performance during HRC was perceived by operator with greater extraversion |
| *Modality · Pers_O* | *HRC · Pers_O* | −0.001 | - |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.029 | A slight improvement in performance during HRC was perceived by operator with greater agreeableness |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.015 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.052 | Operators with a negative attitude toward interaction with robots reported slightly worse performance during HRC |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.061 | A slight improvement in perceived performance emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.106 | Operators with concerns for emotion in robot interaction perceived worse performance during HRC |

in HRC modality the perceived physical demand was lower ($\beta_{ModalityHRC \bullet Pers\_A} = -0.052$).

- Operators with a negative attitude toward interaction with robots (*NARS_S1*) or greater concern for emotion in robot interaction (*NARS_S3*) showed a decrease in *Physical demand* when assembling more complex products ($\beta_{ProductTilecutter \bullet NARS\_S1} = -0.058$, $\beta_{ProductPump \bullet NARS\_S1} = -0.092$ ,

**Table 8** Summary of the GLMM fixed-terms for effort

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 1.302 | - |
| *Product* | *Tilecutter* | −0.362 | - |
| | *Pump* | −0.396 | |
| *Modality* | *HRC* | 1.656 | Operators generally perceived an increase in *Effort* during HRC modality |
| *Pers_N* | - | −0.015 | - |
| *Pers_E* | - | 0.011 | - |
| *Pers_O* | - | −0.037 | - |
| *Pers_A* | - | 0.051 | - |
| *Pers_C* | - | −0.055 | - |
| *NARS_S1* | - | 0.150 | - |
| *NARS_S2* | - | 0.046 | - |
| *NARS_S3* | - | 0.344 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.209 | In general, the HRC modality during the assembly of more complex product offset *Effort* |
| | *Pump · HRC* | −0.195 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.000 | - |
| | *Pump· Pers_N* | −0.001 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.028 | Greater extraversion implied slightly more *Effort* when assembling more complex products |
| | *Pump· Pers_E* | 0.029 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.015 | - |
| | *Pump· Pers_O* | −0.020 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | 0.030 | Greater agreeableness implied slightly more *Effort* when assembling more complex products |
| | *Pump· Pers_A* | 0.058 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.032 | Greater conscientiousness implied slightly more *Effort* when assembling more complex products |
| | *Pump· Pers_C* | 0.022 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.101 | Operators with a negative attitude toward interaction with robots showed a decrease in *Effort* when assembling more complex products |
| | *Pump· NARS_S1* | −0.069 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | 0.029 | - |
| | *Pump· NARS_S2* | 0.033 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.218 | Operators with concerns for emotion in robot interaction showed a decrease in *Effort* when assembling more complex products |
| | *Pump· NARS_S3* | −0.279 | |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.007 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.013 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | −0.007 | - |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.031 | Greater agreeableness implied a slight decrease in *Effort* during HRC modality |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.017 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | −0.019 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.068 | A slight decrease of *Effort* emerged during HRC modality in operators with a negative attitude toward robots' social influence |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.002 | - |

$\beta_{ProductTilecutter \bullet NARS\_S3} = -0.139$, $\beta_{ProductPump \bullet NARS\_S3} = -0.176$).

- Operators with a negative attitude toward the social influence of robots (*NARS_S2*) reported slightly less perceived physical demand during HRC modality ($\beta_{ModalityHRC \bullet NARS\_S2} = -0.092$).

### 3.1.4 Temporal Demand

Concerning *Temporal demand* (Table 6), in general operators felt more time pressure as the product complexity increased ($\beta_{ProductTilecutter} = 1.944$, $\beta_{ProductPump} = 3.242$). In addition, increased time pressure was felt in HRC modality

($\beta_{ModalityHRC} = 1.035$), but this effect decreased as the product complexity increased ($\beta_{ProductTilecutter \bullet ModalityHRC} = -0.191$, $\beta_{ProductPump \bullet ModalityHRC} = -0.327$). Focusing on individual characteristics:

- Operators with greater neuroticism (*Pers_N*) perceived higher time pressure when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_N} = 0.040$, $\beta_{ProductPump \bullet Pers\_N} = 0.057$).
- Operators with greater extraversion (*Pers_E*) or with a negative attitude toward the social influence of robots (*NARS_S2*) reported slightly less perceived time pressure during HRC modality ($\beta_{ModalityHRC \bullet Pers\_E} = -0.028$, $\beta_{ModalityHRC \bullet NARS\_S2} = -0.096$).
- Operators with greater openness (*Pers_O*) perceived slightly less time pressure during the assembly of more complex products ($\beta_{ProductTilecutter \bullet Pers\_O} = -0.021$, $\beta_{ProductPump \bullet Pers\_O} = 0.020$).

**Table 9** Summary of the GLMM fixed-terms for frustration

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 5.961 | - |
| *Product* | *Tilecutter* | −2.815 | - |
| | *Pump* | −0.939 | |
| *Modality* | *HRC* | −1.390 | - |
| *Pers_N* | - | 0.100 | - |
| *Pers_E* | - | 0.018 | - |
| *Pers_O* | - | −0.136 | Operators with greater openness reported decreased *Frustration* in general |
| *Pers_A* | - | −0.082 | - |
| *Pers_C* | - | −0.021 | - |
| *NARS_S1* | - | 0.065 | - |
| *NARS_S2* | - | −0.078 | - |
| *NARS_S3* | - | 0.259 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.702 | In general, the HRC modality during the assembly of more complex product decreased *Frustration* |
| | *Pump · HRC* | −0.002 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | −0.041 | - |
| | *Pump· Pers_N* | −0.004 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.022 | - |
| | *Pump· Pers_E* | 0.026 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.009 | Greater openness implied less *Frustration* when assembling more complex products |
| | *Pump· Pers_O* | −0.119 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | 0.119 | Greater agreeableness implied more *Frustration* when assembling more complex products |
| | *Pump· Pers_A* | 0.192 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.013 | Greater conscientiousness implied slightly more *Effort* when assembling the tile cutter, but less when assembling the diaphragm pump |
| | *Pump· Pers_C* | −0.071 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.136 | Operators with a negative attitude toward interaction with robots showed a decrease in *Frustration* when assembling more complex products |
| | *Pump· NARS_S1* | −0.183 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | 0.140 | Operators with a negative attitude toward robots' social influence showed an increase in *Frustration* when assembling more complex products |
| | *Pump· NARS_S2* | 0.280 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.049 | - |
| | *Pump· NARS_S3* | −0.071 | |
| *Modality · Pers_N* | *HRC · Pers_N* | −0.097 | Greater neuroticism implied slightly less *Frustration* in HRC modality |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.014 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.114 | Greater openness implied more *Frustration* in HRC modality |
| *Modality · Pers_A* | *HRC · Pers_A* | 0.028 | - |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.002 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.142 | An increase in *Frustration* during HRC modality in operators with a negative attitude toward interaction with robots |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.063 | - |
| *Modality · NARS_S3* | *HRC · NARS_S3* | −0.051 | - |

- Operators with greater agreeableness (*Pers_A*) tended to feel slightly higher time pressure in general ($\beta_{Pers\_A} = 0.131$). However, it was mitigated when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_A} = -0.075$, $\beta_{ProductPump \bullet Pers\_A} = -0.056$).
- More conscientious operators (*Pers_C*) experienced an increase in *Temporal demand* when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_C} = 0.032$, $\beta_{ProductPump \bullet Pers\_C} = 0.030$).
- Operators with a negative attitude toward interaction with robots (*NARS_S1*) showed a slight decrease in *Temporal demand* when assembling more complex products ($\beta_{ProductTilecutter \bullet NARS\_S1} = -0.049$, $\beta_{ProductPump \bullet NARS\_S1} = -0.181$). However, they perceived higher time pressure during HRC modality ($\beta_{ModalityHRC \bullet NARS\_S1} = 0.044$).
- Operators with greater concern for emotion in robot interaction (*NARS_S3*) reported a slight increase in *Temporal demand* when assembling the tile cutter ($\beta_{ProductTilecutter \bullet NARS\_S3} = 0.097$), while a decrease when assembling the water pump ($\beta_{ProductPump \bullet NARS\_S3} = -0.173$).

### 3.1.5 Performance

Focusing on *Performance* (i.e., a reverse dimension) (Table 7), operators generally perceived a slight decrease in perceived performance during HRC modality ($\beta_{ModalityHRC} = 0.954$). Regarding the significant effects of individual characteristics:

- Operators with greater extraversion (*Pers_E*) reported generally better perceived performance ($\beta_{Pers\_E} = -0.066$), even more during HRC modality ($\beta_{ModalityHRC \bullet Pers\_E} = -0.028$). However, they felt a slight worsening when assembling the more complex products ($\beta_{ProductTilecutter \bullet Pers\_E} = 0.061$, $\beta_{ProductPump \bullet Pers\_E} = 0.061$).
- Operators with greater agreeableness (*Pers_A*) or with a negative attitude toward the social influence of robots (*NARS_S2*) reported slightly better performance when assembling more complex products ($\beta_{ProductTilecutter \bullet Pers\_A} = -0.055$, $\beta_{ProductPump \bullet Pers\_A} = -0.014$, $\beta_{ProductTilecutter \bullet NARS\_S2} = -0.079$, $\beta_{ProductPump \bullet NARS\_S2} = -0.061$). In addition, they perceived better performance when working in HRC modality ($\beta_{ModalityHRC \bullet Pers\_A} = -0.029 \beta_{ModalityHRC \bullet NARS\_S2} = -0.061$).
- Operators with greater conscientiousness (*Pers_C*) reported a performance worsening when assembling the tile cutter ($\beta_{ProductTilecutter \bullet Pers\_C} = 0.013$), while an improvement when assembling the water pump ($\beta_{ProductPump \bullet Pers\_C} = -0.038$).
- Operators with a negative attitude toward interaction with robots (*NARS_S1*) or greater concern for emotion in robot interaction (*NARS_S3*) perceived a deterioration in their performance in HRC modality ($\beta_{ModalityHRC \bullet NARS\_S1} = 0.052$, $\beta_{ModalityHRC \bullet NARS\_S3} = 0.106$). Operators with high *NARS_S1* scores felt also an additional decrease when assembling more complex products ($\beta_{ProductTilecutter \bullet NARS\_S1} = 0.025$, $\beta_{ProductPump \bullet NARS\_S1} = 0.130$). On the other hand, operators with high *NARS_S3* scores reported better performance with the tile cutter assembly ($\beta_{ProductTilecutter \bullet NARS\_S3} = -0.054$) and worse with the water pump ($\beta_{ProductPump \bullet NARS\_S3} = 0.067$).

**Table 10** ANODE table for SAM with resulting *p*-values for each model term

| Model term | Valence | Arousal | Dominance |
|---|---|---|---|
| *Product* | < 0.001 *** | < 0.001 *** | < 0.001 *** |
| *Modality* | 0.001 ** | 0.014 * | < 0.001 *** |
| *Pers_N* | 0.268 | 0.127 | 0.730 |
| *Pers_E* | 0.035 * | 0.873 | 1.000 |
| *Pers_O* | 0.337 | 0.120 | 0.240 |
| *Pers_A* | 0.379 | 0.190 | 0.054 |
| *Pers_C* | 0.058 | 0.518 | 0.104 |
| *NARS_S1* | 0.053 | 0.687 | 0.191 |
| *NARS_S2* | 0.308 | 1.000 | 0.287 |
| *NARS_S3* | 1.000 | 0.837 | 0.352 |
| *Product · Modality* | 0.074 | 0.001 ** | < 0.001 *** |
| *Product · Pers_N* | < 0.001 *** | < 0.001 *** | < 0.001 *** |
| *Product · Pers_E* | < 0.001 *** | < 0.001 *** | < 0.001 *** |
| *Product · Pers_O* | < 0.001 *** | 0.002 ** | < 0.001 *** |
| *Product · Pers_A* | < 0.001 *** | 0.005 ** | < 0.001 *** |
| *Product · Pers_C* | < 0.001 *** | 0.026 * | < 0.001 *** |
| *Product · NARS_S1* | 0.793 | < 0.001 *** | 0.409 |
| *Product · NARS_S2* | 0.120 | 0.005 ** | < 0.001 *** |
| *Product · NARS_S3* | 0.960 | 0.225 | < 0.001 *** |
| *Modality · Pers_N* | < 0.001 *** | 0.128 | 1.000 |
| *Modality · Pers_E* | 0.002 ** | < 0.001 *** | 0.119 |
| *Modality · Pers_O* | < 0.001 *** | 0.121 | < 0.001 *** |
| *Modality · Pers_A* | < 0.001 *** | < 0.001 *** | < 0.001 *** |
| *Modality · Pers_C* | 0.838 | < 0.001 *** | 0.169 |
| *Modality · NARS_S1* | 0.377 | 0.086 | 0.052 |
| *Modality · NARS_S2* | 0.063 | 0.264 | 1.000 |
| *Modality · NARS_S3* | < 0.001 *** | < 0.001 *** | 0.434 |

(*)$0.05 > p \geq 0.01$, (**)$0.01 > p \geq 0.001$, (***)$p < 0.001$

**Table 11** Summary of the MOLR model fixed-terms for the SAM dimensions

| Model term | Model parameter | Coefficient ($\beta$) | | | *Comment on significant effects* |
|---|---|---|---|---|---|
| | | *Valence* | *Arousal* | *Dominance* | |
| *Thresholds (Intercepts)* | $\theta_1$ | - | −7.184 | - | - |
| | $\theta_2$ | - | −2.567 | - | |
| | $\theta_3$ | 3.354 | −0.409 | −9.633 | |
| | $\theta_4$ | 5.026 | 2.146 | −7.841 | |
| | $\theta_5$ | 6.776 | 4.111 | −7.427 | |
| | $\theta_6$ | 9.234 | 5.758 | −5.169 | |
| | $\theta_7$ | 11.03 | - | −2.969 | |
| | $\theta_8$ | 12.824 | - | −0.481 | |
| *Product* | *Tilecutter* | 6.784 | −7.916 | 0.474 | In general, an increase in *Valence* and *Dominance* with a decrease in *Arousal* were observed when assembling the tile cutter. The effects are the opposite when assembling the diaphragm pump |
| | *Pump* | −0.403 | 4.848 | −2.854 | |
| *Modality* | *HRC* | 3.685 | −5.227 | −6.653 | In general, in HRC modality higher scores in *Valence* and lower in *Arousal* were observed, at the cost of a reduction in *Dominance* |
| *Pers_N* | - | 0.102 | 0.516 | −0.040 | - |
| *Pers_E* | - | 0.317 | −0.316 | 0.245 | Operators with greater extraversion reported higher *Valence* in general |
| *Pers_O* | - | 0.034 | −0.566 | 0.025 | |
| *Pers_A* | - | −0.204 | 0.568 | −0.216 | |
| *Pers_C* | - | 0.008 | −0.125 | 0.069 | |
| *NARS_S1* | - | 0.308 | −0.728 | −0.004 | |
| *NARS_S2* | - | 0.240 | 0.068 | 0.406 | |
| *NARS_S3* | - | −0.329 | 0.654 | −1.499 | |
| *Product · Modality* | *Tilecutter· HRC* | 0.899 | 0.160 | 1.501 | In general, the HRC modality during the assembly of more complex product offset the decrease in *Dominance*. For the tile cutter assembly, a slight offset in *Arousal* emerged, while for the diaphragm pump an additional reduction was observed |
| | *Pump · HRC* | 0.361 | −1.236 | 1.577 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | −0.112 | −0.278 | 0.166 | When assembling more complex products, operators with greater neuroticism reported slightly lower *Valence* and *Arousal*, but slightly higher *Dominance* |
| | *Pump· Pers_N* | −0.141 | −0.267 | 0.122 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | −0.213 | 0.423 | −0.378 | When assembling more complex products, operators with greater extraversion reported slightly lower *Valence* and *Dominance* and slightly higher *Arousal* |
| | *Pump· Pers_E* | −0.202 | 0.230 | −0.448 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | 0.134 | 0.188 | 0.428 | When assembling more complex products, operators with greater openness reported higher *Valence, Arousal,* and *Dominance* |
| | *Pump· Pers_O* | 0.260 | 0.240 | 0.438 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | 0.256 | −0.086 | −0.348 | When assembling more complex products, operators with greater agreeableness reported slightly higher *Valence* and lower *Arousal*, but also lower *Dominance* |
| | *Pump· Pers_A* | 0.147 | −0.237 | −0.321 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | −0.246 | −0.056 | 0.041 | When assembling more complex products, operators with greater conscientiousness reported slightly lower *Valence* and *Arousal*, but slightly higher *Dominance* |
| | *Pump· Pers_C* | −0.119 | −0.141 | 0.206 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | −0.026 | 0.334 | 0.185 | Operators with a negative attitude toward interaction reported higher *Arousal* when assembling more complex product |
| | *Pump· NARS_S1* | −0.091 | 0.670 | 0.081 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.216 | −0.017 | −0.379 | Operators with a negative attitude toward robots' social influence reported slightly lower *Arousal* and *Dominance* when assembling more complex product |
| | *Pump· NARS_S2* | −0.020 | −0.346 | −0.370 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | −0.119 | −0.275 | 0.865 | Operators with concerns for emotion in robot interaction reported higher *Dominance* when assembling more complex product |
| | *Pump· NARS_S3* | −0.055 | 0.102 | 0.854 | |

**Table 11** (continued)

| Model term | Model parameter | Coefficient *(β)* | | | *Comment on significant effects* |
|---|---|---|---|---|---|
| | | *Valence* | *Arousal* | *Dominance* | |
| *Modality · Pers_N* | *HRC · Pers_N* | −0.141 | −0.060 | −0.022 | During HRC modality, greater neuroticism implied a slight decrease in *Valence* |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.110 | 0.251 | 0.091 | During HRC modality, *Valence* of operators with greater extraversion was slightly offset, with a slight increase in *Arousal* |
| *Modality · Pers_O* | *HRC · Pers_O* | −0.223 | 0.093 | −0.175 | During HRC modality, greater openness implied a slight decrease in *Valence* and *Dominance* |
| *Modality · Pers_A* | *HRC · Pers_A* | 0.275 | −0.222 | 0.269 | During HRC modality, greater agreeableness implied an increase in *Valence* and *Dominance* and a decrease in *Arousal* |
| *Modality · Pers_C* | *HRC · Pers_C* | −0.007 | 0.124 | 0.059 | During HRC modality, greater conscientiousness implied a slight increase in *Arousal* |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.100 | 0.207 | −0.242 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.159 | 0.137 | 0.023 | - |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.598 | −0.666 | −0.277 | During HRC modality, operators with concerns for emotion in robot interaction reported higher *Valence* and less *Arousal* |

#### 3.1.6 Effort

Regarding the dimension *Effort* (Table 8), in HRC modality the perceived effort increased in general ($\beta_{ModalityHRC} = 1.656$), but this effect was mitigated as the product complexity increased ($\beta_{ProductTilecutter•ModalityHRC} = -0.209$, $\beta_{ProductPump•ModalityHRC} = -0.195$). This suggests the cobot better supported in more complex assembly processes. Concerning the significant influence of individual characteristics:

- Operators with greater extraversion (*Pers_E*) reported higher *Effort* when assembling products with higher complexity ($\beta_{ProductTilecutter•Pers\_E} = 0.028$, $\beta_{ProductPump•Pers\_E} = 0.029$).
- Operators with greater agreeableness (*Pers_A*) felt higher *Effort* when assembling products with higher complexity ($\beta_{ProductTilecutter•Pers\_A} = 0.030$, $\beta_{ProductPump•Pers\_A} = 0.058$). However, they reported lower perceived effort during HRC modality ($\beta_{ModalityHRC•Pers\_A} = -0.031$).
- More conscientious operators (*Pers_C*) perceived slightly more effort when assembling products with higher complexity ($\beta_{ProductTilecutter•Pers\_C} = 0.032$, $\beta_{ProductPump•Pers\_C} = 0.022$) or working in HRC modality ($\beta_{ModalityHRC•Pers\_C} = 0.017$).
- Operators with a negative attitude toward interaction with robots (*NARS_S1*) or greater concern for emotion in robot interaction (*NARS_S3*) perceived less *Effort* when assembling products with higher complexity ($\beta_{ProductTilecutter•NARS\_S1} = -0.101$, $\beta_{ProductPump•NARS\_S1} = -0.069$, $\beta_{ProductTilecutter•NARS\_S3} = -0.218$, $\beta_{ProductPump•NARS\_S3} = -0.279$).
- Operators with a negative attitude toward the social influence of robots (*NARS_S2*) reported slightly lower perceived effort during HRC modality ($\beta_{ModalityHRC•NARS\_S2} = -0.068$).

#### 3.1.7 Frustration

Focusing on the dimension *Frustration* (Table 9), in general, during the assembly of more complex products (*Product*), the cobot presence (*Modality*) helped to reduce the perceived frustration ($\beta_{ProductTilecutter•ModalityHRC} = -0.702$, $\beta_{ProductPump•ModalityHRC} = -0.002$). Regarding the effect of individual characteristics:

- Operators with greater neuroticism (*Pers_N*) reported slightly less perceived frustration during HRC modality ($\beta_{ModalityHRC•Pers\_N} = -0.097$).
- Operators with greater openness (*Pers_O*) reported slightly less *Frustration* in general ($\beta_{Pers\_O} = -0.136$), and even less when assembling more complex products ($\beta_{ProductTilecutter•Pers\_O} = -0.009$, $\beta_{ProductPump•Pers\_O} = -0.119$). However, they reported an increase in *Frustration* when working in HRC modality ($\beta_{ModalityHRC•Pers\_O} = 0.114$).
- Operators with greater agreeableness (*Pers_A*) or with a negative attitude toward the social influence of robots (*NARS_S2*) showed higher *Frustration* when assembling

more complex products ($\beta_{ProductTilecutter \bullet Pers\_A} = 0.119$, $\beta_{ProductPump \bullet Pers\_A} = 0.192$, $\beta_{ProductTilecutter \bullet NARS\_S2} = 0.140$, $\beta_{ProductPump \bullet NARS\_S2} = 0.280$).

- Operators with greater conscientiousness (*Pers_C*) felt slightly higher *Frustration* when assembling the tile cutter ($\beta_{ProductTilecutter \bullet Pers\_C} = 0.013$) and less *Frustration* when assembling the water pump ($\beta_{ProductPump \bullet Pers\_C} = -0.071$).
- Operators with a negative attitude toward interaction with robots (*NARS_S1*) showed less *Frustration* when assembling more complex products ($\beta_{ProductTilecutter \bullet NARS\_S1} = -0.136$, $\beta_{ProductPump \bullet NARS\_S1} = -0.183$). However, they reported an increase in *Frustration* when working in HRC modality ($\beta_{ModalityHRC \bullet NARS\_S1} = 0.142$).

## 3.2 Affective State (SAM)

Table 10 reports the results of the Analysis of Deviance (ANODE) for each MOLR model of the SAM dimensions, showing the significance of each model term. Appendix C contains the coefficient estimates for each model term.

Referring to Table 11, in general, concerning *Product*, for the tile cutter an increase in valence ($\beta_{ProductTilecutter} = 6.784$) and dominance ($\beta_{ProductTilecutter} = 0.474$) and a decrease in arousal ($\beta_{ProductTilecutter} = -7.916$) were observed, while for the water pump the opposite (i.e., a decrease in valence ($\beta_{ProductPump} = -0.403$) and dominance ($\beta_{ProductPump} = -2.854$) and an increase in arousal ($\beta_{ProductPump} = 4.848$)). In the HRC setting (*Modality*), positive effects were observed in general, with an increase in valence ($\beta_{ModalityHRC} = 3.685$) and a decrease in arousal ($\beta_{ModalityHRC} = -5.227$), however, accompanied by a decrease in dominance ($\beta_{ModalityHRC} = -6.653$). However, the presence of the cobot in the more complex product assembly offset the decrease in dominance ($\beta_{ProductTilecutter \bullet ModalityHRC} = 1.501$, $\beta_{ProductPump \bullet ModalityHRC} = 1.577$), and decreased arousal in the case of the diaphragm pump assembly ($\beta_{ProductPump \bullet ModalityHRC} = -1.236$), suggesting greater positive impact in these situations. Regarding the significant influences of personal characteristics:

- Operators with greater neuroticism (*Pers_N*) derived less increase in pleasure (*Valence*) in the HRC modality ($\beta_{ModalityHRC \bullet Pers\_N} = -0.141$) or during the assembly of more complex products ($\beta_{ProductTilecutter \bullet Pers\_N} = -0.112$, $\beta_{ProductPump \bullet Pers\_N} = -0.141$). However, during the assembly of more complex products, they reported slightly less *Arousal* ($\beta_{ProductTilecutter \bullet Pers\_N} = -0.278$, $\beta_{ProductPump \bullet Pers\_N} = -0.267$) and higher *Dominance* ($\beta_{ProductTilecutter \bullet Pers\_N} = 0.166$, $\beta_{ProductPump \bullet Pers\_N} = 0.122$).
- More extraverted operators (*Pers_E*) showed higher baseline *Valence* ($\beta_{Pers\_E} = 0.317$) and saw a slightly attenuated *Valence* boost in the HRC modality ($\beta_{ModalityHRC \bullet Pers\_E} = -0.110$). They also showed a slight increase in *Arousal* in the HRC modality ($\beta_{ModalityHRC \bullet Pers\_E} = 0.251$), indicative of greater involvement. However, when assembling more complex products, a decrease in *Valence* ($\beta_{ProductTilecutter \bullet Pers\_E} = -0.213$, $\beta_{ProductPump \bullet Pers\_E} = -0.202$) and *Dominance* ($\beta_{ProductTilecutter \bullet Pers\_E} = -0.378$, $\beta_{ProductPump \bullet Pers\_E} = -0.448$) and an increase in *Arousal* ($\beta_{ProductTilecutter \bullet Pers\_E} = 0.423$, $\beta_{ProductPump \bullet Pers\_E} = 0.230$) were observed.
- Operators with greater openness (*Pers_O*), when assembling more complex products, showed an

**Table 12** ANOVA table for psychophysiological responses with resulting p-values for each model term

| Model term | Average_SCR | RMSSD |
|---|---|---|
| *Product* | 0.067 | 0.237 |
| *Modality* | 0.224 | 0.026 * |
| *Pers_N* | 0.637 | 0.211 |
| *Pers_E* | 0.560 | 0.216 |
| *Pers_O* | 0.022 * | 0.752 |
| *Pers_A* | 0.239 | 0.290 |
| *Pers_C* | 0.196 | 0.498 |
| *NARS_S1* | 0.132 | 0.194 |
| *NARS_S2* | 0.009 ** | 0.679 |
| *NARS_S3* | 0.011 * | 0.673 |
| *Product · Modality* | 0.034 * | 0.005 ** |
| *Product · Pers_N* | 0.052 | 0.130 |
| *Product · Pers_E* | 0.012 * | 0.088 |
| *Product · Pers_O* | 0.887 | 0.137 |
| *Product · Pers_A* | 0.217 | < 0.001 *** |
| *Product · Pers_C* | 0.017 * | 0.170 |
| *Product · NARS_S1* | 0.859 | 0.051 |
| *Product · NARS_S2* | 0.121 | 0.992 |
| *Product · NARS_S3* | 0.451 | 0.240 |
| *Modality · Pers_N* | < 0.001 *** | 0.620 |
| *Modality · Pers_E* | 0.215 | 0.885 |
| *Modality · Pers_O* | < 0.001 *** | 0.002 ** |
| *Modality · Pers_A* | < 0.001 *** | 0.149 |
| *Modality · Pers_C* | 0.797 | 0.813 |
| *Modality · NARS_S1* | 0.255 | 0.616 |
| *Modality · NARS_S2* | 0.817 | 0.044 * |
| *Modality · NARS_S3* | 0.748 | 0.701 |

(*)$0.05 > p \geq 0.01$, (**)$0.01 > p \geq 0.001$, (***)$p < 0.001$

**Table 13** Summary of the GLMM fixed-terms for average SCR

| Model term | Model parameter | *Coefficient ($\beta$)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 2.104 | - |
| *Product* | *Tilecutter* | −2.152 | - |
| | *Pump* | −0.302 | |
| *Modality* | *HRC* | −0.784 | - |
| *Pers_N* | - | −0.029 | - |
| *Pers_E* | - | 0.001 | - |
| *Pers_O* | - | −0.183 | Operators with greater openness showed lower phasic activity in general |
| *Pers_A* | - | 0.146 | - |
| *Pers_C* | - | −0.042 | - |
| *NARS_S1* | - | −0.172 | - |
| *NARS_S2* | - | 0.266 | Operators with a negative attitude toward robots' social influence showed higher phasic activity in general |
| *NARS_S3* | - | −0.596 | Operators with concerns for emotion in robot interaction showed lower phasic activity in general |
| *Product · Modality* | *Tilecutter· HRC* | −0.320 | In general, the HRC modality during the assembly of more complex product reduced the phasic activity |
| | *Pump · HRC* | −0.430 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.036 | - |
| | *Pump· Pers_N* | −0.001 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.048 | Greater extraversion implied a slight increase in phasic activity when assembling more complex product |
| | *Pump· Pers_E* | 0.058 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | 0.001 | - |
| | *Pump· Pers_O* | −0.009 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | −0.049 | - |
| | *Pump· Pers_A* | −0.015 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.012 | Greater conscientiousness implied slightly higher phasic activity when assembling the tile cutter, but less when assembling the diaphragm pump |
| | *Pump· Pers_C* | −0.041 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | 0.029 | - |
| | *Pump· NARS_S1* | 0.006 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | 0.054 | - |
| | *Pump· NARS_S2* | 0.098 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | 0.097 | - |
| | *Pump· NARS_S3* | −0.005 | |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.068 | Greater neuroticism implied slightly higher phasic activity in HRC modality |
| *Modality · Pers_E* | *HRC · Pers_E* | −0.021 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.116 | Greater openness implied higher phasic activity in HRC modality |
| *Modality · Pers_A* | *HRC · Pers_A* | −0.106 | Greater agreeableness implied lower phasic activity in HRC modality |
| *Modality · Pers_C* | *HRC · Pers_C* | −0.004 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | −0.052 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | 0.009 | - |
| *Modality · NARS_S3* | *HRC · NARS_S3* | −0.024 | - |

increase in *Valence* ($\beta_{ProductTilecutter\bullet Pers\_O} = 0.134$, $\beta_{ProductPump\bullet Pers\_O} = 0.260$), *Arousal* ($\beta_{ProductTilecutter\bullet Pers\_O} = 0.188$, $\beta_{ProductPump\bullet Pers\_O} = 0.240$), and *Dominance* ($\beta_{ProductTilecutter\bullet Pers\_O} = 0.428$, $\beta_{ProductPump\bullet Pers\_O} = 0.438$), suggesting a higher engagement. However, they in reported in the HRC modality an attenuation of the increase in *Valence* ($\beta_{ModalityHRC\bullet Pers\_O} = -0.223$) and slightly amplified the loss of sense of control (*Dominance*) ($\beta_{ModalityHRC\bullet Pers\_O} = -0.175$).

- Operators with greater agreeableness (*Pers_A*) appreciated the presence of the cobot more, showing further increase in *Valence* ($\beta_{ModalityHRC\bullet Pers\_A} = 0.275$) and relaxation (i.e., reduced *Arousal*)

**Table 14** Summary of the GLMM fixed-terms for RMSSD

| Model term | Model parameter | *Coefficient (β)* | *Comment on significant effects* |
|---|---|---|---|
| *Intercept* | - | 4.081 | - |
| *Product* | *Tilecutter* | −0.738 | - |
| | *Pump* | 0.261 | |
| *Modality* | *HRC* | 1.310 | In general, greater HRV was observed during HRC modality |
| *Pers_N* | - | −0.014 | - |
| *Pers_E* | - | 0.010 | - |
| *Pers_O* | - | 0.046 | - |
| *Pers_A* | - | −0.054 | - |
| *Pers_C* | - | −0.009 | - |
| *NARS_S1* | - | 0.035 | - |
| *NARS_S2* | - | 0.006 | - |
| *NARS_S3* | - | 0.020 | - |
| *Product · Modality* | *Tilecutter· HRC* | −0.207 | In general, the assembly of more complex products slightly offset the effect of HRC modality |
| | *Pump · HRC* | −0.339 | |
| *Product· Pers_N* | *Tilecutter· Pers_N* | −0.017 | - |
| | *Pump· Pers_N* | 0.001 | |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.020 | - |
| | *Pump· Pers_E* | 0.027 | |
| *Product· Pers_O* | *Tilecutter· Pers_O* | −0.032 | - |
| | *Pump· Pers_O* | −0.020 | |
| *Product· Pers_A* | *Tilecutter· Pers_A* | 0.051 | Greater agreeableness implied greater HRV when assembling the tile cutter, but a slight decrease when assembling the diaphragm pump |
| | *Pump· Pers_A* | −0.007 | |
| *Product· Pers_C* | *Tilecutter· Pers_C* | −0.019 | - |
| | *Pump· Pers_C* | 0.003 | |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | 0.090 | - |
| | *Pump· NARS_S1* | 0.003 | |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | −0.003 | - |
| | *Pump· NARS_S2* | 0.001 | |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | 0.056 | - |
| | *Pump· NARS_S3* | −0.035 | |
| *Modality · Pers_N* | *HRC · Pers_N* | −0.004 | - |
| *Modality · Pers_E* | *HRC · Pers_E* | 0.001 | - |
| *Modality · Pers_O* | *HRC · Pers_O* | −0.043 | Greater openness implied less HRV in HRC modality |
| *Modality · Pers_A* | *HRC · Pers_A* | 0.020 | - |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.003 | - |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.016 | - |
| *Modality · NARS_S2* | *HRC · NARS_S2* | −0.047 | Operators with a negative attitude toward robots' social influence showed slightly lower HRV in HRC modality |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.017 | - |

($\beta_{ModalityHRC \bullet Pers\_A} = -0.222$) and less loss of sense of control (*Dominance*) ($\beta_{ModalityHRC \bullet Pers\_A} = 0.269$) in HRC modality. When assembling more complex products, they also showed a slight increase in *Valence* ($\beta_{ProductTilecutter \bullet Pers\_A} = 0.256$, $\beta_{ProductPump \bullet Pers\_A} = 0.147$) and relaxation ($\beta_{ProductTilecutter \bullet Pers\_A} = -0.086$, $\beta_{ProductPump \bullet Pers\_A} = -0.237$), but also a decrease in *Dominance* ($\beta_{ProductTilecutter \bullet Pers\_A} = -0.348$, $\beta_{ProductPump \bullet Pers\_A} = -0.321$).

- More conscientious operators (*Pers_C*) reported lower values of pleasure (*Valence*) when assembling more complex product ($\beta_{ProductTilecutter \bullet Pers\_C} = -0.246$, $\beta_{ProductPump \bullet Pers\_C} = -0.119$), but also an increase in relaxation (i.e., reduced

**Table 15** Summary of the main moderating pattern of individual characteristics and potential practical interpretation for HRC design

| Individual characteristic | Main pattern in HRC | Outcome domains where the pattern is most visible | Practical interpretation |
|---|---|---|---|
| *Neuroticism* | Less positive response to HRC | *Workload*, *Physical demand*, *Frustration*, *Valence*, and *Average_SCR* | Predictability, reassurance, and gradual familiarization may be important |
| *Extraversion* | More positive response to HRC | *Physical demand*, *Temporal demand*, *Performance*, *Valence*, and *Arousal* | These operators may benefit earlier from cobot support, especially in complex tasks |
| *Openness* | Less positive response to HRC | *Workload*, *Mental demand*, *Physical demand*, *Frustration*, *Valence*, *Dominance*, *Average_SCR*, and *RMSSD* | Greater autonomy in managing the cobot's support may be beneficial to reduce the feeling of constraint |
| *Agreeableness* | More positive response to HRC | *Workload*, *Mental demand*, *Physical demand*, *Performance*, *Effort*, *Valence*, *Arousal*, *Dominance*, and *Average_SCR* | Cobot support may be particularly well received |
| *Conscientiousness* | Less positive response to HRC | *Mental demand*, *Physical demand*, *Effort*, and *Arousal* | Efficiency-oriented design of the HRC that better involves these operators may be beneficial |
| *Negative attitude toward interaction with robots* | Less positive response to HRC | *Mental demand, Temporal demand, Performance,* and *Frustration* | Reassurance and gradual familiarization may be beneficial |
| *Negative attitude toward the social influence of robots* | More positive response to HRC | *Workload*, *Mental demand*, *Physical demand*, *Temporal demand*, *Performance*, *Effort*, and *RMSSD* | Onboarding should address expectations about social influence of the cobot |
| *Negative attitude toward emotions in robot interaction* | More positive response to HRC | *Performance*, *Valence*, and *Arousal* | Onboarding should address expectations about emotional interaction with the cobot |

*Arousal* ($\beta_{ProductTilecutter•Pers\_C} = -0.056$, $\beta_{ProductPump•Pers\_C} = -0.141$) and *Dominance* ($\beta_{ProductTilecutter•Pers\_C} = 0.041, \beta_{ProductPump•Pers\_C} = 0.206$), suggesting a slight decrease in engagement. However, a slightly increase of *Arousal* during HRC modality ($\beta_{ModalityHRC•Pers\_C} = 0.124$) was observed.

- Operators with a negative attitude toward interaction with robots (*NARS_S1*) reported a slight increase in *Arousal* during the assembly of more complex products ($\beta_{ProductTilecutter•NARS\_S1} = 0.334$, $\beta_{ProductPump•NARS\_S1} = 0.670$).
- Operators with a negative attitude toward the social influence of robots (*NARS_S2*) showed a decrease in *Arousal* ($\beta_{ProductTilecutter•NARS\_S2} = -0.017$, $\beta_{ProductPump•NARS\_S2} = -0.346$) and *Dominance* ($\beta_{ProductTilecutter•NARS\_S2} = -0.379, \beta_{ProductPump•NARS\_S2} = 0.370$) as product complexity increased.
- Operators with greater concern for emotion in robot interaction (*NARS_S3*) felt slightly higher *Dominance* in more complex products ($\beta_{ProductTilecutter•NARS\_S3} = 0.865$, $\beta_{ProductPump•NARS\_S1} = 0.854$). In HRC modality, they experienced greater increases in pleasure (*Valence*) ($\beta_{ModalityHRC•NARS\_S3} = 0.598$) and decreases in *Arousal* ($\beta_{ModalityHRC•NARS\_S3} = -0.666$), as the implemented cobot had no emotions.

### 3.3 Psychophysiological Response

Table 12 shows the results of the ANOVA table for the GLMMs of the average SCR (*Average_SCR*) and HRV (*RMSSD*) with the significance for each model term. Appendix C contains the coefficient estimates for each model term.

Focusing on the *Average_SCR* (Table 13), a decrease in phasic activity in the HRC modality during assembly of more complex products was observed in general ($\beta_{ProductTilecutter•ModalityHRC} = -0.320$, $\beta_{ProductPump•ModalityHRC} = -0.430$), indicating support of the cobot in handling stress response. Regarding personal characteristics:

- Operators with greater neuroticism (*Pers_N*) showed a slight increase in stress response during HRC ($\beta_{ModalityHRC•Pers\_N} = 0.068$).
- More extraverted operators (*Pers_E*) showed increased phasic activity when assembling more complex products ($\beta_{ProductTilecutter•Pers\_E} = 0.048$, $\beta_{ProductPump•Pers\_E} = 0.058$).
- Operators with greater openness (*Pers_O*) recorded lower phasic activity in general ($\beta_{Pers\_O} = -0.183$), however,

during HRC modality this decrease was partially offset ($\beta_{ModalityHRC \bullet Pers\_O} = 0.116$).

- Operators with greater agreeableness (*Pers_A*) showed greater relaxation during HRC modality ($\beta_{ModalityHRC \bullet Pers\_A} = -0.106$).
- More conscientious operators (*Pers_C*) showed a slight increase in stress response when assembling the tile cutter ($\beta_{ProductTilecutter \bullet Pers\_C} = 0.012$), while lower stress response during the water pump assembly ($\beta_{ProductPump \bullet Pers\_C} = -0.041$).
- Operators with a negative attitude toward the social influence of robots (*NARS_S2*) were found to have a greater stress response in general ($\beta_{NARS\_S2} = 0.266$).
- Operators with a negative attitude toward emotions in robot interaction (*NARS_S3*) showed lower phasic activity in general ($\beta_{NARS\_S3} = -0.596$).

Concerning *RMSSD* (Table 14), greater HRV was observed in general during HRC modality ($\beta_{ModalityHRC} = -1.310$), indicative of greater parasympathetic involvement (i.e., greater relaxation). However, during the assembly of more complex products (*Product*) in HRC modality, this positive effect was slightly compensated ($\beta_{ProductTilecutter \bullet ModalityHRC} = -0.207$, $\beta_{ProductPump \bullet ModalityHRC} = -0.339$). Concerning the significant influences of personal characteristics:

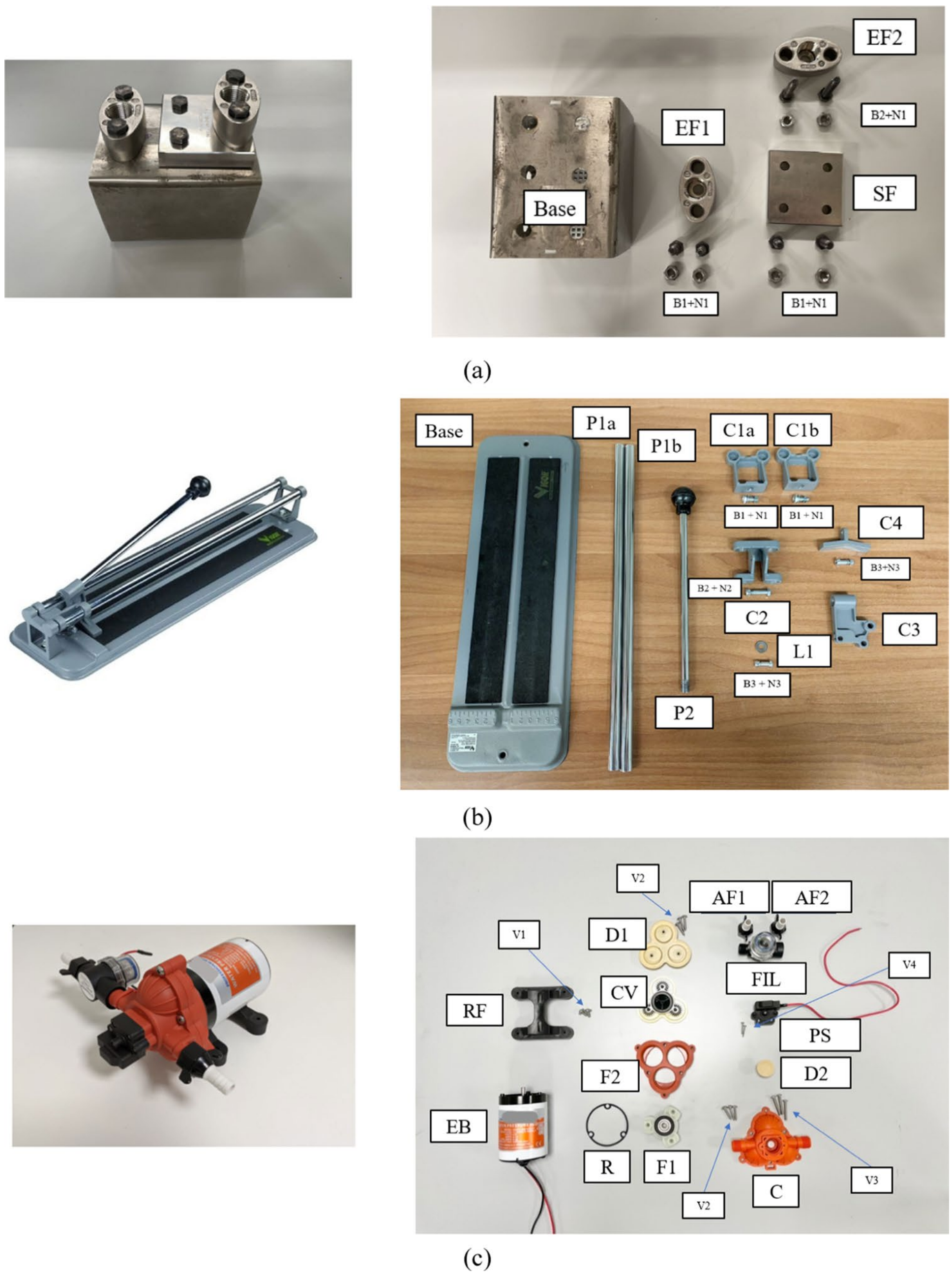


**Fig. 4** Elements of the three assemblies: (**a**) mechanical equipment, (**b**) tile cutter, and (**c**) diaphragm water pump

**Table 16** List of elementary task and task allocation for each assembly product

| Product | Elementary task | HRC modality | | Manual modality |
|---|---|---|---|---|
| | | Human | Cobot | Human |
| Mechanical equipment | 1. Pick and place BASE | | X | X |
| | 2. Pick and place EF1 | | X | X |
| | 3. Screwing EF1 with Base | X | | X |
| | 4. Pick and place SF | | X | X |
| | 5. Screwing SF with Base | X | | X |
| | 6. Pick and place EF2 | | X | X |
| | 7. Screwing EF2 with Base | X | | X |
| | 8. Pick the final product and place out of the assembly area | | X | X |
| Tile cutter | 1. Pick and place Base | | X | X |
| | 2. Pick and place C1a and C1b on Base | X | | X |
| | 3. Preliminary screwing C1a and C1b on Base | X | | X |
| | 4. Placing the subassembly (Base + C1a + C1b) out of the assembly area | | X | X |
| | 5. Pick and place C2 | | X | X |
| | 6. Pick and place C3 in C2 | X | | X |
| | 7. Screwing C3 and C2 | X | | X |
| | 8. Pick and place L1 | X | | X |
| | 9. Screwing L1 and C3 | X | | X |
| | 10. Pick and place C4 in C3 | X | | X |
| | 11. Screwing C4 and C3 | X | | X |
| | 12. Placing the subassembly (C2 + C3 + C4 + L1) out of the assembly area | | X | X |
| | 13. Pick and place subassembly (Base + C1a + C1b) back in the assembly area | | X | X |
| | 14. Insert sub-assembly (C2 + C3 + C4 + L1) in both P1a/P1b | X | | X |
| | 15. Insert P1a/P1b in C1a/C1b | X | | X |
| | 16. Final screwing C1a/C1b on Base | X | | X |
| | 17. Pick and place P2 | X | | X |
| | 18. Screwing P2 | X | | X |
| | 19. Pick the final product and place out of the assembly area | | X | X |
| Diaphragm water pump | 1. Pick and place RF | X | | X |
| | 2. Pick and place EB | | X | X |
| | 3. Screwing EB with RF | X | | X |
| | 4. Pick and place F1 | | X | X |
| | 5. Pick and place F2 | | X | X |
| | 6. Insert F1 in F2 | X | | X |
| | 7. Pick and place D1 on sub-assembly F1 + F2 | X | | X |
| | 8. Screwing D1, F1 and insert CV on D1 | X | | X |
| | 9. Pick and place C | | X | X |
| | 10. Screwing C and F2 | X | | X |
| | 11. Insert R on EB | X | | X |
| | 12. Insert and screwing sub-assembly pump head on EB (joining F1-EB) | X | | X |
| | 13. Pick and place D2 and PS on C | X | | X |
| | 14. Screwing PS and C | X | | X |
| | 15. Pick and place FIL | X | | X |
| | 16. Screwing FIL | X | | X |
| | 17. Pick and place AF1 and AF2 | X | | X |
| | 18. Screwing AF1 and AF2 | X | | X |
| | 19. Pick the final product and place out of the assembly area | | X | X |

**Table 17** Assembly complexity assessment for the three products

| Product | Assembly complexity assessment | | | | | |
|---|---|---|---|---|---|---|
| | $C_{product}$ | $N_p$ | $n_p$ | $N_s$ | $n_s$ | $CI_{product}$ |
| *Mechanical equipment* | **4.22** | 4 | 3 | 6 | 2 | 0.668 |
| *Tile cutter* | **6.67** | 10 | 8 | 5 | 3 | 0.682 |
| *Diaphragm water pump* | **7.33** | 13 | 12 | 13 | 4 | 0.693 |

**Table 18** Example of NEO-FFI-3 items for each scale [20]. Reverse items are indicated with "*"

| Scale | Example of item |
|---|---|
| *Neuroticism* | I am not a worrier. * |
| | At times I have felt bitter and resentful |
| | When I'm under a great deal of stress, sometimes I feel like I'm going to pieces |
| *Extraversion* | I like to have a lot of people around me |
| | I laugh easily |
| | I prefer jobs that let me work alone without being bothered by other people. * |
| *Openness* | I enjoy concentrating on a fantasy or daydream and exploring all its possibilities, letting it grow and develop |
| | I believe letting students hear controversial speakers can only confuse and mislead them. * |
| | I am intrigued by the patterns I find in art and nature |
| *Agreeableness* | I try to be courteous to everyone I meet |
| | At times I bully or flatter people into doing what I want them to |
| | Some people think I'm selfish and egotistical. * |
| *Conscientiousness* | I keep my belongings neat and clean |
| | I'm pretty good about pacing myself so as to get things done on time |
| | I often come into situations without being fully prepared. * |

**Table 19** The NARS questionnaire [19]. Reverse items are indicated with "*"

| Scale | Item |
|---|---|
| *S1: Negative Attitudes toward Situations and Interactions with Robots* | I would feel uneasy if I was given a job where I had to use robots |
| | The word "robot" means nothing to me |
| | I would feel nervous operating a robot in front of other people |
| | I would hate the idea that robots or artificial intelligence were making judgements about things |
| | I would feel very nervous just standing in front of a robot |
| | I would feel paranoid talking with a robot |
| *S2: Negative Attitudes toward Social Influence of Robots* | I would feel uneasy if robots really had emotions |
| | Something bad might happen if robots developed into living beings |
| | I feel that if I depend on robots too much, something bad might happen |
| | I am concerned that robots would be a bad influence on children |
| | I feel that in the future society will be dominated by robots |
| *S3: Negative Attitudes toward Emotions in Interaction with Robots* | I would feel relaxed talking with robots.* |
| | If robots had emotions, I would be able to make friends with them.* |
| | I feel comforted being with robots that have emotions.* |

- Operators with greater agreeableness (*Pers_A*) showed greater relaxation when assembling the tile cutter ($\beta_{ProductTilecutter \bullet Pers\_A} = 0.051$), while a slight decrease during the assembly of the water pump ($\beta_{ProductPump \bullet Pers\_A} = -0.007$).

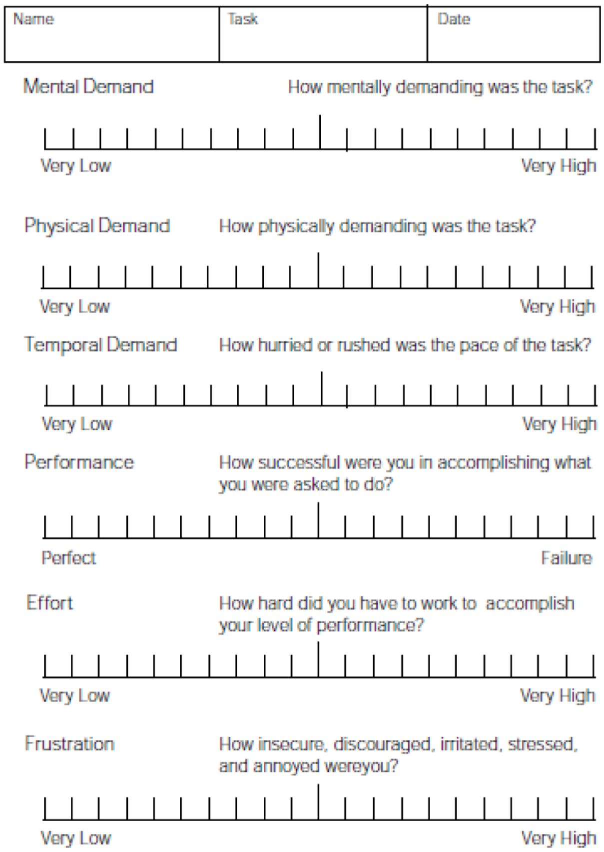


**Fig. 5** The NASA-TLX questionnaire [21]

- Operators with greater openness (*Pers_O*) experienced a slightly attenuated increase in relaxation during HRC modality ($\beta_{ModalityHRC \bullet Pers\_O} = -0.043$).
- Operators with a negative attitude toward robots' social influence (*NARS_S2*) were found to slightly compensate for the increase in parasympathetic activity during HRC modality ($\beta_{ModalityHRC \bullet NARS\_S2} = -0.047$).

## 4 Discussion

The analysis results revealed the influence of the individual characteristics, in particular personality traits and attitude toward robots, on the various response variables related to user experience during HRC, highlighting some interesting relationships. Table 15 reports a summary of the main results which will be discussed in the next subsections.

### 4.1 Moderating Effect of Personality Traits

Operators with a high *Neuroticism* score tended to report higher perceived workload during assembly in HRC modality ($\beta_{Modality \bullet Pers\_N}$), although with a lower level of *Frustration*. They also showed lower pleasure (*Valence*) and greater stress response (i.e., *Average_SCR*) in working with the cobot, therefore supporting H1. Thus, a potential need for action to improve the user experience emerges, such as integrating more transparent interfaces and reassuring feedback to compensate for the onset of negative emotions. The assembly of more complex products ($\beta_{Product \bullet Pers\_N}$) led to a greater overall increase in workload and a decrease in *Valence* and *Arousa*l (i.e., boredom), indicating the need to improve engagement in such situations.

H2 was also supported: operators with a high *Extraversion* score tented to show appreciation during HRC modality. They perceived less *Physical demand*, *Temporal demand*, and improved *Performance* during HRC modality ($\beta_{Modality \bullet Pers\_E}$). They also reported more positive feelings, and during collaboration with the cobot, although they showed slight pleasure (*Valence*) compensation, they reported more *Arousal* and invariant *Dominance* – a symptom of engagement. When assembling more complex products ($\beta_{Product \bullet Pers\_E}$), they perceived a greater workload, accompanied by a decrease in *Valence* and sense of control (*Dominance*) and an increase in *Arousal*. This result further emphasizes the potential positive impact of introducing support systems such as cobots.

Operators with a high *Openness* score exhibited lower appreciation of HRC modality, therefore not supporting H3. They perceived higher workload during HRC ($\beta_{Modality \bullet Pers\_O}$), mainly due to higher perceived *Mental demand*, *Physical demand* and *Frustration*. In addition, they felt less pleasure (*Valence*) and *Dominance* while working during the robot. This discomfort also emerged from psychophysiological signals (i.e., *Average_SCR* and *RMSSD*), where they felt more stressed during HRC interaction. This may be due to feeling more constrained in the presence of the cobot, not feeling freedom in managing the assembly process but having to submit to the cobot's pre-programmed actions. In fact, when assembling more complex products (i.e., the tile cutter and the water pump) ($\beta_{Product \bullet Pers\_O}$), they reported a more positive affective state, with higher levels of *Valence*, *Arousal*, and *Dominance*. One solution might be to leave more management of the assembly process and let them decide what operations the cobot should perform. These operators might appreciate more a cobot that is able to adapt on-the-fly to their needs, even unstructured ones.

Operators with a high *Agreeableness* score benefited the most from the presence of the cobot during assemblies,

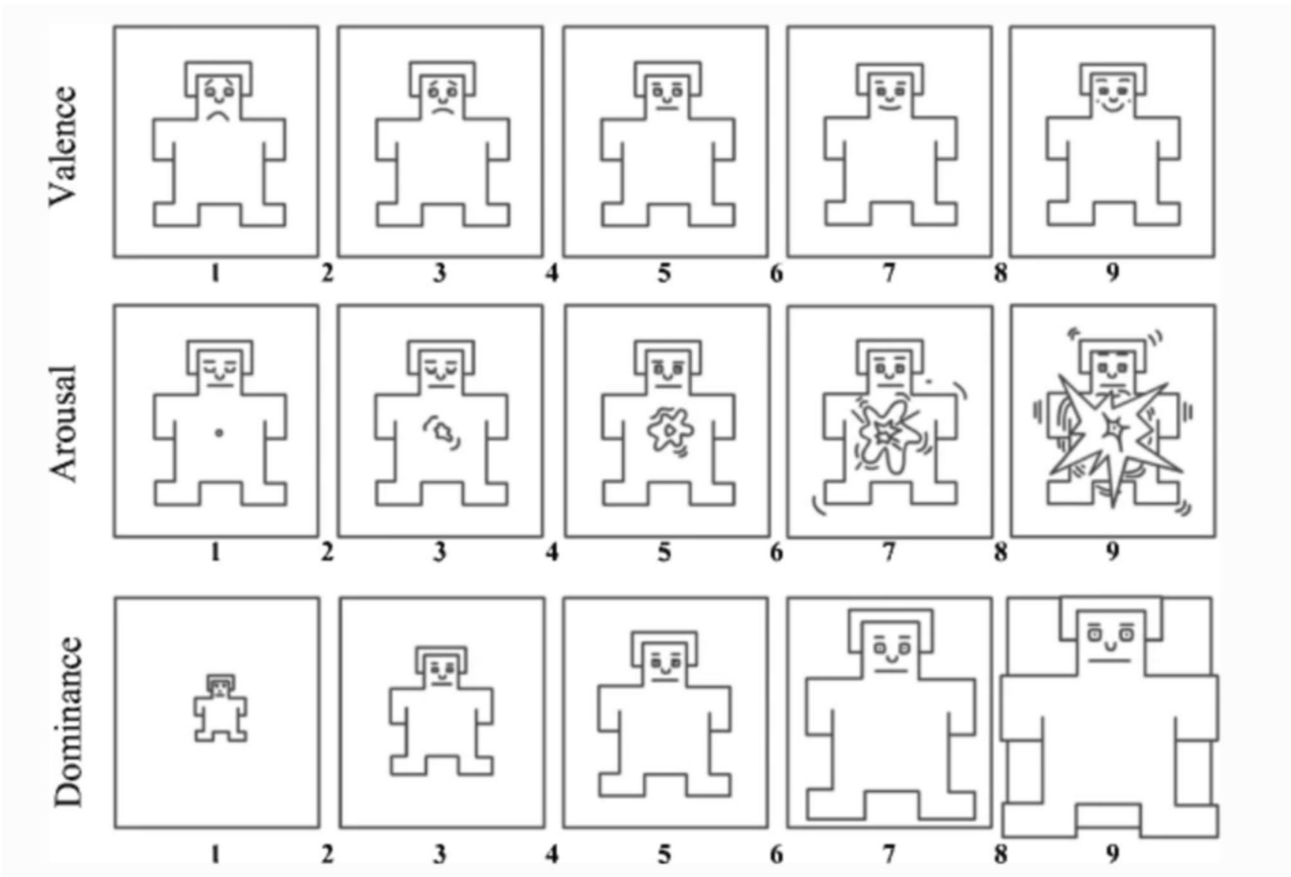


**Fig. 6** The SAM questionnaire [22]

supporting H4. Although they tended to perceive a higher workload due to *Mental demand*, *Physical demand*, and *Temporal demand* ($\beta_{Pers\_A}$), in the HRC modality ($\beta_{Modality \bullet Pers\_A}$) they found an overall improvement, with better perceived *Performance* and lower perceptions of *Mental demand*, *Physical demand*, and *Effort* to achieve their performance level. In addition, in the HRC modality they showed greater *Valence* and *Dominance* and lower *Arousal*, indicative of relaxation and feeling at ease. This phenomenon was also further confirmed by the lowering of *Average_SCR* during HRC modality. During the assembly of more complex products ($\beta_{Product \bullet Pers\_A}$) they perceived less control of the situation (*Dominance*), however the cobot support can help them to mitigate this phenomenon.

Operators with a high *Conscientiousness* score, during the assembly of more complex products ($\beta_{Product \bullet Pers\_C}$), tended to report higher perceived workload, mainly due to the perception of time pressure (*Temporal demand*), and felt less pleasure (*Valence*) and *Arousal* but more *Dominance*. This result highlights the desire of this kind of operator to perform at their best without any particular emotional drive. They tended to report higher perceived *Mental demand*, *Physical demand*, and *Effort* when working with the cobot ($\beta_{Modality \bullet Pers\_C}$). Moreover, they felt slightly more *Arousal* during HRC modality. This may be due to the determination to achieve goals with a certain level of performance, and HRC modality may have been perceived as unnecessary. To remedy this phenomenon, it might be useful to design the HRC interaction by involving the operators to understand how and at what times they would appreciate cobot support.

### 4.2 Moderating effect of the Attitude Towards Robots

Operators with a negative attitude toward interaction with robots (*NARS_S1*) showed a decrease in perceived performance (*Performance*) and an increase in perceived mental demand (*Mental demand*), time pressure (*Temporal demand*), and *Frustration* in HRC modality ($\beta_{Modality \bullet NARS\_S1}$). Therefore, the cobot presence was not perceived as a support. During the assembly of more complex products ($\beta_{Product \bullet NARS\_S1}$), they mitigated the perceived workload and reported a slight increase in *Arousal*.

**Table 20** GLMM parameter estimates for each NASA-TLX dimension

| Model term | Model parameter | Coefficient | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | *Workload* | *Mental demand* | *Physical demand* | *Temporal demand* | *Performance* | *Effort* | *Frustration* |
| *Intercept* | - | 1.108 | 1.056 | 0.904 | -0.495 | 4.343 | 1.302 | 5.961 |
| *Product* | *Tilecutter* | 0.430 | 0.292 | 0.909 | 1.944 | 0.705 | -0.362 | -2.815 |
| | *Pump* | 1.360 | 1.451 | 1.249 | 3.242 | -0.507 | -0.396 | -0.939 |
| *Modality* | *HRC* | 0.769 | -0.146 | 0.307 | 1.035 | 0.954 | 1.656 | -1.390 |
| *Pers_N* | - | -0.032 | 0.047 | -0.039 | -0.054 | 0.000 | -0.015 | 0.100 |
| *Pers_E* | - | -0.023 | -0.011 | -0.016 | -0.001 | -0.066 | 0.011 | 0.018 |
| *Pers_O* | - | -0.025 | -0.168 | -0.063 | -0.021 | -0.012 | -0.037 | -0.136 |
| *Pers_A* | - | 0.089 | 0.209 | 0.119 | 0.131 | 0.001 | 0.051 | -0.082 |
| *Pers_C* | - | -0.039 | -0.114 | -0.032 | -0.052 | -0.003 | -0.055 | -0.021 |
| *NARS_S1* | - | 0.092 | -0.135 | 0.155 | 0.124 | -0.102 | 0.150 | 0.065 |
| *NARS_S2* | - | 0.128 | 0.349 | 0.059 | 0.163 | 0.121 | 0.046 | -0.078 |
| *NARS_S3* | - | 0.174 | 0.175 | 0.236 | 0.131 | 0.102 | 0.344 | 0.259 |
| *Product · Modality* | *Tilecutter· HRC* | -0.266 | -0.583 | -0.140 | -0.191 | 0.020 | -0.209 | -0.702 |
| | *Pump · HRC* | -0.246 | -0.660 | -0.164 | -0.327 | 0.029 | -0.195 | -0.002 |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.010 | -0.056 | 0.006 | 0.040 | 0.008 | 0.000 | -0.041 |
| | *Pump· Pers_N* | 0.023 | -0.049 | 0.013 | 0.057 | 0.010 | -0.001 | -0.004 |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.029 | 0.025 | 0.048 | -0.009 | 0.061 | 0.028 | 0.022 |
| | *Pump· Pers_E* | 0.026 | -0.003 | 0.032 | 0.003 | 0.061 | 0.029 | 0.026 |
| *Product· Pers_O* | *Tilecutter· Pers_O* | -0.007 | 0.090 | -0.019 | -0.021 | -0.004 | -0.015 | -0.009 |
| | *Pump· Pers_O* | -0.016 | 0.121 | -0.019 | -0.020 | 0.004 | -0.020 | -0.119 |
| *Product· Pers_A* | *Tilecutter· Pers_A* | -0.014 | -0.068 | -0.012 | -0.075 | -0.055 | 0.030 | 0.119 |
| | *Pump· Pers_A* | -0.009 | -0.098 | 0.002 | -0.056 | -0.014 | 0.058 | 0.192 |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.023 | 0.068 | 0.001 | 0.032 | 0.013 | 0.032 | 0.013 |
| | *Pump· Pers_C* | 0.018 | 0.059 | 0.013 | 0.030 | -0.038 | 0.022 | -0.071 |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | -0.063 | 0.120 | -0.058 | -0.049 | 0.025 | -0.101 | -0.136 |
| | *Pump· NARS_S1* | -0.080 | 0.125 | -0.092 | -0.181 | 0.130 | -0.069 | -0.183 |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | -0.040 | -0.209 | -0.008 | -0.030 | -0.079 | 0.029 | 0.140 |
| | *Pump· NARS_S2* | -0.050 | -0.222 | -0.003 | -0.024 | -0.061 | 0.033 | 0.280 |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | -0.064 | -0.090 | -0.139 | 0.097 | -0.054 | -0.218 | -0.049 |
| | *Pump· NARS_S3* | -0.127 | -0.054 | -0.176 | -0.173 | 0.067 | -0.279 | -0.071 |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.011 | -0.014 | 0.015 | -0.005 | 0.002 | 0.007 | -0.097 |
| *Modality · Pers_E* | *HRC · Pers_E* | -0.008 | 0.000 | -0.015 | -0.028 | -0.028 | -0.013 | -0.014 |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.014 | 0.090 | 0.046 | 0.011 | -0.001 | -0.007 | 0.114 |
| *Modality · Pers_A* | *HRC · Pers_A* | -0.034 | -0.092 | -0.052 | 0.002 | -0.029 | -0.031 | 0.028 |
| *Modality · Pers_C* | *HRC · Pers_C* | 0.008 | 0.050 | 0.018 | 0.007 | 0.015 | 0.017 | 0.002 |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.020 | 0.083 | 0.011 | 0.044 | 0.052 | -0.019 | 0.142 |
| *Modality · NARS_S2* | *HRC · NARS_S2* | -0.060 | -0.157 | -0.092 | -0.096 | -0.061 | -0.068 | -0.063 |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.037 | 0.053 | 0.042 | 0.042 | 0.106 | 0.002 | -0.051 |
| **Random effect** | - | **St. deviation** | | | | | | |
| | | ***Workload*** | ***Mental demand*** | ***Physical demand*** | ***Temporal demand*** | ***Performance*** | ***Effort*** | ***Frustration*** |
| *Participant* | - | 0.263 | 0.514 | 0.452 | 0.409 | 0.272 | 0.452 | 0.785 |

**Table 21** MOLR model parameter estimates for each SAM dimension

| Model term | Model parameter | Coefficient | | |
|---|---|---|---|---|
| | | *Valence* | *Arousal* | *Dominance* |
| *Thresholds (Intercepts)* | $\theta_1$ | - | -7.184 | - |
| | $\theta_2$ | - | -2.567 | - |
| | $\theta_3$ | 3.354 | -0.409 | -9.633 |
| | $\theta_4$ | 5.026 | 2.146 | -7.841 |
| | $\theta_5$ | 6.776 | 4.111 | -7.427 |
| | $\theta_6$ | 9.234 | 5.758 | -5.169 |
| | $\theta_7$ | 11.03 | - | -2.969 |
| | $\theta_8$ | 12.824 | - | -0.481 |
| *Product* | *Tilecutter* | 6.784 | -7.916 | 0.474 |
| | *Pump* | -0.403 | 4.848 | -2.854 |
| *Modality* | *HRC* | 3.685 | -5.227 | -6.653 |
| *Pers_N* | - | 0.102 | 0.516 | -0.040 |
| *Pers_E* | - | 0.317 | -0.316 | 0.245 |
| *Pers_O* | - | 0.034 | -0.566 | 0.025 |
| *Pers_A* | - | -0.204 | 0.568 | -0.216 |
| *Pers_C* | - | 0.008 | -0.125 | 0.069 |
| *NARS_S1* | - | 0.308 | -0.728 | -0.004 |
| *NARS_S2* | - | 0.240 | 0.068 | 0.406 |
| *NARS_S3* | - | -0.329 | 0.654 | -1.499 |
| *Product · Modality* | *Tilecutter· HRC* | 0.899 | 0.160 | 1.501 |
| | *Pump · HRC* | 0.361 | -1.236 | 1.577 |
| *Product· Pers_N* | *Tilecutter· Pers_N* | -0.112 | -0.278 | 0.166 |
| | *Pump· Pers_N* | -0.141 | -0.267 | 0.122 |
| *Product· Pers_E* | *Tilecutter· Pers_E* | -0.213 | 0.423 | -0.378 |
| | *Pump· Pers_E* | -0.202 | 0.230 | -0.448 |
| *Product· Pers_O* | *Tilecutter· Pers_O* | 0.134 | 0.188 | 0.428 |
| | *Pump· Pers_O* | 0.260 | 0.240 | 0.438 |
| *Product· Pers_A* | *Tilecutter· Pers_A* | 0.256 | -0.086 | -0.348 |
| | *Pump· Pers_A* | 0.147 | -0.237 | -0.321 |
| *Product· Pers_C* | *Tilecutter· Pers_C* | -0.246 | -0.056 | 0.041 |
| | *Pump· Pers_C* | -0.119 | -0.141 | 0.206 |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | -0.026 | 0.334 | 0.185 |
| | *Pump· NARS_S1* | -0.091 | 0.670 | 0.081 |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | -0.216 | -0.017 | -0.379 |
| | *Pump· NARS_S2* | -0.020 | -0.346 | -0.370 |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | -0.119 | -0.275 | 0.865 |
| | *Pump· NARS_S3* | -0.055 | 0.102 | 0.854 |
| *Modality · Pers_N* | *HRC · Pers_N* | -0.141 | -0.060 | -0.022 |
| *Modality · Pers_E* | *HRC · Pers_E* | -0.110 | 0.251 | 0.091 |
| *Modality · Pers_O* | *HRC · Pers_O* | -0.223 | 0.093 | -0.175 |
| *Modality · Pers_A* | *HRC · Pers_A* | 0.275 | -0.222 | 0.269 |
| *Modality · Pers_C* | *HRC · Pers_C* | -0.007 | 0.124 | 0.059 |
| *Modality · NARS_S1* | *HRC · NARS_S1* | 0.100 | 0.207 | -0.242 |
| *Modality · NARS_S2* | *HRC · NARS_S2* | -0.159 | 0.137 | 0.023 |
| *Modality · NARS_S3* | *HRC · NARS_S3* | 0.598 | -0.666 | -0.277 |
| **Random effect** | - | **St. deviation** | | |
| | | ***Valence*** | ***Arousal*** | ***Dominance*** |
| *Participant* | - | 1.014 | 3.462 | 2.461 |

**Table 22** GLMM parameter estimates for each psychophysiological indicator

| Model term | Model parameter | Coefficient | |
|---|---|---|---|
| | | *Average SCR* | *RMSSD* |
| *Intercept* | - | 2.104 | 4.081 |
| *Product* | *Tilecutter* | -2.152 | -0.738 |
| | *Pump* | -0.302 | 0.261 |
| *Modality* | *HRC* | -0.784 | 1.310 |
| *Pers_N* | - | -0.029 | -0.014 |
| *Pers_E* | - | 0.001 | 0.010 |
| *Pers_O* | - | -0.183 | 0.046 |
| *Pers_A* | - | 0.146 | -0.054 |
| *Pers_C* | - | -0.042 | -0.009 |
| *NARS_S1* | - | -0.172 | 0.035 |
| *NARS_S2* | - | 0.266 | 0.006 |
| *NARS_S3* | - | -0.596 | 0.020 |
| *Product · Modality* | *Tilecutter· HRC* | -0.320 | -0.207 |
| | *Pump · HRC* | -0.430 | -0.339 |
| *Product· Pers_N* | *Tilecutter· Pers_N* | 0.036 | -0.017 |
| | *Pump· Pers_N* | -0.001 | 0.001 |
| *Product· Pers_E* | *Tilecutter· Pers_E* | 0.048 | 0.020 |
| | *Pump· Pers_E* | 0.058 | 0.027 |
| *Product· Pers_O* | *Tilecutter· Pers_O* | 0.001 | -0.032 |
| | *Pump· Pers_O* | -0.009 | -0.020 |
| *Product· Pers_A* | *Tilecutter· Pers_A* | -0.049 | 0.051 |
| | *Pump· Pers_A* | -0.015 | -0.007 |
| *Product· Pers_C* | *Tilecutter· Pers_C* | 0.012 | -0.019 |
| | *Pump· Pers_C* | -0.041 | 0.003 |
| *Product· NARS_S1* | *Tilecutter· NARS_S1* | 0.029 | 0.090 |
| | *Pump· NARS_S1* | 0.006 | 0.003 |
| *Product· NARS_S2* | *Tilecutter· NARS_S2* | 0.054 | -0.003 |
| | *Pump· NARS_S2* | 0.098 | 0.001 |
| *Product· NARS_S3* | *Tilecutter· NARS_S3* | 0.097 | 0.056 |
| | *Pump· NARS_S3* | -0.005 | -0.035 |
| *Modality · Pers_N* | *HRC · Pers_N* | 0.068 | -0.004 |
| *Modality · Pers_E* | *HRC · Pers_E* | -0.021 | 0.001 |
| *Modality · Pers_O* | *HRC · Pers_O* | 0.116 | -0.043 |
| *Modality · Pers_A* | *HRC · Pers_A* | -0.106 | 0.020 |
| *Modality · Pers_C* | *HRC · Pers_C* | -0.004 | 0.003 |
| *Modality · NARS_S1* | *HRC · NARS_S1* | -0.052 | 0.016 |
| *Modality · NARS_S2* | *HRC · NARS_S2* | 0.009 | -0.047 |
| *Modality · NARS_S3* | *HRC · NARS_S3* | -0.024 | 0.017 |
| **Random effect** | - | **St. deviation** | |
| | | ***Average SCR*** | ***RMSSD*** |
| *Participant* | - | 0.718 | 0.328 |

Operators with a negative attitude toward the social influence of robots (*NARS_S2*), during the assembly of more complex products ($\beta_{Product \bullet NARS\_S2}$), mitigated the perceived workload, but also reported a loss in *Dominance*. They perceived less *Workload* during HRC modality ($\beta_{Modality \bullet NARS\_S2}$). In particular, they reported an improvement in all constituent dimensions of workload except in *Frustration*. However, they felt a bit more stressed especially during the HRC modality according to the psychophysiological response (i.e., *RMSSD*). Since the study participants had never interacted with a cobot before, the actual experience with an emotionless cobot was appreciated by those who had more concerns about social influence of robots.

Operators with a negative attitude toward emotions in robot interaction (*NARS_S3*) perceived slightly less workload and more *Dominance* during the assembly of more complex products ($\beta_{Product \bullet NARS\_S3}$). They also experienced a slight decrease in perceived performance (*Performance*) in HRC modality ($\beta_{Modality \bullet NARS\_S3}$). However, they tended to feel slightly more pleasure (*Valence*) and less *Arousal* when working with the cobot. This may be due to the absence of emotional interaction with the cobot during the assembly process.

Therefore, H5 was partially supported, due to the absence of emotional or social influence during the assembly process.

## 5 Conclusions

The presented study aimed at exploring the influence of individual characteristics on user experience during HRC assembly in the manufacturing context. In general, findings suggested that the cobot support was mostly appreciated when assembling complex product. In addition, preliminary experimental results support the significant influence of personality traits and attitude toward robots in moderating the user experience of HRC, identifying candidate moderators of operator's user experience that may provide insights for optimal design and human-centered adaptation strategies in industrial HRC. The practical relevance of these findings lies in how they can inform the introduction and configuration of industrial HRC systems. The results suggest that personalization in HRC should focus primarily on adaptive onboarding, transparency of robot behavior, clarity of role allocation, and adjustable levels of support. For example, operators showing a less positive response to HRC may benefit from longer familiarization, clearer timing cues, more predictable robot actions, and more explicit feedback on task progress. By contrast, operators showing a more positive response to HRC may be suitable for earlier deployment of shared-task strategies. In this sense, the contribution of the present study is to provide preliminary evidence for human-centered adaptation strategies in manufacturing. Operators with high levels of *Extraversion* or *Agreeableness* showed greater appreciation and found more benefit in working with a cobot. Whereas, on the other hand, more caution is needed in implementing HRC with operators who have a high level of *Neuroticism*, *Openness*, and *Conscientiousness*, requiring specific customization in order to fully exploit the benefits of collaborative robotics. Furthermore, it emerged that operators with high levels of *Openness* tend to appreciate more complex (i.e., more challenging) assemblies, while operators with high levels of *Extraversion* would particularly benefit from the support of a collaborative system in such situations.

It is important to note that discussed implications should be interpreted as preliminary design hypotheses rather than definitive guidelines for personalization rules. The influence of personal characteristics in industrial HRC processes will require further investigation in future works, including replication studies on larger and more varied samples. Longitudinal research, in real industrial settings and with online adaptation algorithms, will be also necessary to verify the evolution of user experience for different operators and refine customized strategies for promoting human-centricity in manufacturing.

## Appendix A

In this section, the sequence of operations for each product (Fig. 4) is reported in Table 16, showing also the task allocation among the manual and HRC modalities.

To evaluate assembly complexity of the three products the method of Samy and ElMarghy [30] was used:

$$C_{product} = \left[\frac{n_p}{N_p} + CI_{product}\right][\log_2(N_p + 1)] + \left[\frac{n_s}{N_s}\right][\log_2(N_s + 1) \tag{A1}$$

where $n_p$ is the number of unique parts while $N_p$ is the related total, $n_s$ is the number of unique fasteners, while $N_s$ the related total. $CI_{product}$ is a complexity index ranging from 0 to 1 that takes into account the geometric and dimensional characteristics of the parts which can be determined using the difficulty factors of manual handling and joining from "Design for Assembly" [30, 31]. Table 17 reports the obtained assembly complexity scores for each product, with the mechanical equipment and the diaphragm water pump being the least and most complex product, respectively.

## Appendix B

In this section, the implemented questionnaires are illustrated. Table 18 reports some example items of the NEO-FFI-3 questionnaire for each scale, Table 19 reports the NARS questionnaire, Fig. 5 contains the NASA-TLX, and Fig. 6 shows the SAM.

## Appendix C

In this section, the estimated parameters for the fitted models are reported. Table 20, 21, and 22 contain the estimated parameters of the models for NASA-TLX dimensions, SAM dimensions, and physiological signals, respectively. Note that the mechanical equipment and the manual modality are the reference category for the variables *Product* and *Modality*, respectively.

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**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Ethics Approval** The authors respect the Ethical Guidelines of the Journal.

**Consent to Participate** Informed consent was obtained from all individual participants included in the study.

**Consent for Publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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