Stress in Manual and Autonomous Modes of Collaboration with a Cobot

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Abstract

Working with collaborative robots (cobots) can be a potential source of stress for their operators. However, research on specific factors that affect users' stress levels when working with a cobot is still scarce. This study is the first to investigate the levels of psychological (primary and secondary stress appraisal) and physiological (heart rate) stress in human operators working in two different cobot modes (i.e., manual and autonomous). We applied an experimental within-subject repeated-measures design to 45 healthy adults (26 women, 19 men). The results show that the levels of secondary stress appraisal were lower and the heart rate levels were higher in the autonomous cobot mode. The results suggest that, when working with a cobot, control plays a key role in the emotional, cognitive, and physiological reactions during the human-robot collaboration. Implications for organizational practice are discussed.

Keywords: collaborative robot, cobot, stress, heart rate, primary appraisal, secondary appraisal

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1. Introduction

Collaborative robots (cobots) are increasingly being used at work. These systems work side by side with humans, often share their workspaces and tasks, and will be an indispensable tool in different future organizations (Fast-Berglund, Palmkvist, Nyqvist, Ekered, & Åkerman, 2016; Kildal, Tellaeche, Fernández, & Maurtua, 2018; Simões, Lucas Soares, & Barros, 2019), thus transforming work processes in the industry (Seriani, Gallina, Scalera, & Lughi, 2018). Due to their safety-centered design, cobots can be appealing companions for tedious, repetitive, or physically straining tasks because they help to improve ergonomics, reduce risk factors, and offload demands on robotic agents (Kildal et al., 2018; Safeea et al., 2019). They also create an opportunity for increased performance because they allow their human operators to focus on more value-added tasks (Safeea, Neto, & Béarée, 2019; Shah, Wiken, Williams, & Breazeal, 2011; Prewett, Johnson, Saboe, Elliott, & Coovert, 2010).

Although human-robot collaboration has been shown to be fruitful, achieving fluency and greater work safety in these teams has created some challenges (Baraglia, Cakmak, Nagai, Rao, & Asada, 2016). Because the human teammate plays a central role in the human-cobot partnership (Kildal et al., 2018), robots have to easily integrate with their human operators (Nikolaidis, Ramakrishnan, Gu, & Shah 2015), and it is essential for the individual to achieve optimal psychological states through this collaboration. Unfortunately, pan-European research indicates that attitudes towards autonomous robotic systems, including robots assisting workers, have declined over a five-year period (Gnambs & Appel, 2019). Along these lines, initial research suggests that the interaction with a cobot might be a source of negative cognitive-emotional reactions or mental strain for their human operators

(Arai, Kato, & Fujita, 2010; Gombolay, Bair, Huang, & Shah, 2017; Hoffman & Breazeal, 2007). However, research on specific factors that can contribute to operators' stress is still in its infancy.

In this experimental study, we show that different cobot modes (i.e., autonomous, manual) can have a differential effect on their operators' levels of psychological and physiological stress. To our knowledge, this is the first study to focus on both the psychological (primary and secondary appraisal) and physiological (heart rate, HR) stress response to different cobot modes in people operating with a cobot.

1.1. The Concept of Stress

Stress is a potential barrier to ensuring an optimal human-cobot collaboration because it can have detrimental consequences for the person (Wallace, Edwards, Arnold, Frazier, & Finch, 2009) and the organization (Podsakoff, LePine, & LePine, 2007). According to the transactional approach to stress, stress can be defined as "a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being" (Lazarus & Folkman, 1984, p.19), which means that the cognitive appraisal of a situation is essential in determining the stress experience. Lazarus and Folkman (1984) distinguish between two concurrent appraisals: primary appraisal and secondary appraisal. During primary appraisal, the demands are categorized as sources of threat, challenge (Lazarus & Folkman, 1984), or both (Folkman, 1997; Kozusznik, Peiró, Lloret, & Rodriguez, 2016). The appraisal of threat is defined as the perception that one might experience harm, whereas the appraisal of challenge is focused on potential gain or growth and accompanied by eagerness or excitement. The focus on these two types of appraisal reflects the interest in research on positive aspects of the stress process, in addition to the negative ones (Folkman and

Moskowitz, 2000). During the concurrent secondary appraisal, a complex evaluative process of "what might and can be done" (Lazarus & Folkman, 1984, p.35) about the demanding situation takes place. Secondary appraisal is influenced by the person’s beliefs about control (e.g., over environmental circumstances), related to feelings of confidence and mastery of the situation. It can be operationalized as two factors referring to the “self-concept of one’s own abilities” and “control expectancies” (Gaab, Rohleder, Nater, & Ehlert, 2005) when faced with the stressor.

Within this context, it is important to note that the use of solely subjective measures to assess stress may provide limited insight into the underlying psychobiological mechanisms involved. The Autonomic Nervous System (ANS) operates somewhat independently from subjective experiences and could provide crucial information about the actual activation of the stress system and the process of stress regulation (Allen, Kennedy, Cryan, Dinan, & Clarke, 2014). The ANS is rapidly activated by stressful situations, and one of the most important biomarkers is the cardiac response, measured with the heart rate (HR) (Allen et al., 2014; Pulopulos, Hidalgo, Puig-Perez, & Salvador, 2018). Importantly, previous research has shown that a stress-induced ANS response in general, and cardiac reactivity in particular, is associated with individual differences in cognitive stress appraisal (e.g., Quigley, Barrett, & Weinstein, 2002; Pulopulos, Baeken, & De Raedt, 2020; Zandara, Garcia-Lluch, Villada, Hidalgo, & Salvador, 2018). Therefore, in addition to psychological measures, investigating cardiovascular activity as a marker of ANS may provide crucial evidence about the stress response during interactions with cobots.

1.2. Stress in Human-Cobot Collaboration

In human-cobot interactions, stress factors may include the changes in the nature of the work (from physical to mental activities; Argote, Goodman, & Schkade, 1983), the proximity of the robot to the human operator and the robot’s movement (Arai et al., 2010), or the loss of control that can stem from the automation of robotic agents (Gaudiello, Zibetti, Lefort, Chetouani, & Ivaldi, 2015; Stein, Liebold, & Ohler, 2019). The first attempt to describe the subjective characteristics of working with a robot took place in the initial period of factory automation. In their research, Argote, Goodman, and Schkade (1983) showed that the implementation of robots in a workplace causes a shift in the work itself, from primarily manual to primarily mental activities, resulting in higher levels of employee stress. Furthermore, Elizur (1970 in Argote, Goodman, Schkade, 1983) and Mann and Hoffman (1956) revealed a difference between employees of automated and non-automated enterprises, in terms of their level of control and sense of responsibility. The introduction of autonomous robots caused their operators to experience less freedom in carrying out their tasks and perceive the results of their work as not depending on them. More recently, stress at work with a robot was analyzed in the context of legal restrictions, work safety, and well-being (Prewett et al., 2010; Złotowski, Yogeeswaran, Bartneck, 2017). These authors conclude that stress is an important indicator of the human operator’s well-being that stems from an adequate level of technical (e.g., automation and display) and social resources (Prewett et al., 2010) and is especially relevant in the domain of working with autonomous robots because they represent a realistic and symbolic threat to their operators´ safety and well-being (Złotowski et al., 2017).

Although the research on stress at work with cobots is limited, a noteworthy exception is the work by Arai, Kato, and Fujita (2010) who assessed physiological (i.e., skin conductance response) and psychological strain (conceptualized as a state of fear, surprise, and discomfort) in cobot users. They showed that less distance between a cobot and its human operator causes physiological strain, and that a greater motion speed of the cobot induces both physiological and psychological strain (i.e., fear and surprise) (Arai et al., 2010). Overall, this research indicates that working with a cobot may increase its operator's perception of stress, a factor that may have lasting negative health and economic consequences. However, more research is still needed to understand which factors in the work with cobots are critical to provoking stress in their human operators.

1.2.1. Manual vs. Autonomous Cobot Modes as Potential Sources of Stress

One of the factors that could explain why working with a cobot can be especially stressful is the cobot's operating mode. A cobot can work in either of two modes, i.e., autonomous (also called automatic) and manual (Fast-Berglund et al., 2016), which both result in a synchronous human-robot joint action (Gombolay, Huang, Shah, 2014). Choosing a specific mode depends on the need to eliminate nuisance and insecurity during a specific task (Cherubini, Passama, Crosnier, Lasnier, & Fraisse, 2016), and it determines the level of autonomy while working with a robot (Harriott, 2015), the operator's capacity to exert control over the robot's performance (Gombolay et al., 2014), and the constructive engagement of the human operator (Heyer, 2010).

In the autonomous mode, the cobot controls all the operations by itself. After initiating the cobot, the human operator performs his or her tasks synchronously with it (Gombolay & Shah, 2014; Shi, Jimmerson, Pearson, & Menassa, 2012). Successive sequences are implemented repetitively, until the cycle is interrupted when the sensor systems detect an intrusion into the cobot's work space. Although the operator of a cobot working in the autonomous cobot mode is able to disengage the system and take over its job, this only occurs in certain situations, such as the failure of the autonomous robotic system (Prewett et al., 2010).

In manual mode, each step in the human-cobot collaboration is initiated by the operator (Kruger, Lien, & Verl, 2009) by touching a button on the controller or one of the sensors installed on the cobot’s arm. Thus, the user operates the cobot (Shi et al., 2012) on tasks that require the flexibility and adaptability of the human operator (Charalambous, Fletcher, & Webb, 2016). A crucial question is whether the two different modes provoke different stress responses. In this domain, the cobot’s autonomy and, thus, the human’s limited possibility to exert control may be an important factor in explaining individual stress levels during the human-cobot interaction.

Following the occupational stress theory of demand-control (Karasek, 1979), limited control at work means a reduction in a job resource that employees need in order to deal with job demands. As a result, and in line with the principles of reactance theory (Brehm, 1966), limited control at work can have negative consequences for well-being (Kozusznik, Maricutoiu, Peiró, Virga, Soriano, Mateo-Cecilia, 2019; McCoy & Evans, 2005). Furthermore, in their Model of Autonomous Technology Threat, Stein, Liebold, and Ohler (2019) suggest that autonomous technology can be perceived as a source of stress for its users because it contributes to a general experience of threat to one’s control, safety, and identity. These researchers specifically describe this as a continuum of threat, ranging from physical harm to one's realization of the loss of human uniqueness. Following Gaudiello, Zibetti, Lefort, Chetouani, and Ivaldi (2015), autonomous robotic agents with decision-making capabilities can be perceived as having more intrusive consequences in our lives than other non-autonomous technologies. Accordingly, taking the decision-making authority away from the human teammate and giving it to the robotic counterpart may lead to workers’ negative emotional and cognitive reactions (Gombolay & Shah, 2014). Indeed, research shows that humans are not always willing to cede their control to the robots because they would rather be the decision-makers (Nikolaidis et al., 2015). This idea is consistent with the findings of Złotowski, Yogeeswaran, and Bartneck (2017), who show that people perceive autonomous robots to be significantly more threatening than non-autonomous agents. The researchers (Złotowski et al., 2017) explain user reactance to the robot based on the notion of the importance of power in social interactions. According to the authors, people share a general opinion that robots should be helpful and obedient. Therefore, when they meet a decisive autonomous robotic agent, they feel less certain about the outcome of their interaction and perceive a threat to their control. Despite the undeniable value of these results, they are based on the reports of participants who watched videos of robots, and the effect of a real collaboration with a cobot on its human user remains to be seen.

Taking all of the above into consideration, in this study we expect that the manual mode will be associated with less psychological and physiological stress in cobot operators compared to the autonomous mode. Specifically, we formulate the following hypotheses:

Hypothesis 1: The levels of primary appraisal will be lower in the manual cobot mode than in the autonomous cobot mode.

Hypothesis 2: The levels of secondary appraisal will be higher in the manual cobot mode than in the autonomous cobot mode.

Hypothesis 3: HR levels will be lower in the manual cobot mode than in the autonomous cobot mode.

Addressing these hypotheses will make a contribution to the literature on the impact of cobot use on individuals in three ways. First, we conceptualize psychological stress as including both primary and secondary stress appraisal that explain the potential differences in stress levels when collaborating with a cobot. Second, we include both psychological and physiological stress measures to assess the effects of different cobot modes on the human users' outcomes. Finally, we show the robustness of the effects by applying a within-subject repeated-measures experimental design to a large sample of individuals collaborating with a cobot. Understanding the cobot mode-related stress relationship is necessary in order to improve the human-cobot interaction and prevent stress-related disorders in the workers. Gaining insight into the cobot operator's stress responses in different cobot modes has clear, practical implications for work design and training in industrial workplaces using cobots.

2. Method

2.1. Sample

Participants included 45 individuals (26 women, 19 men) aged 19-28 (*M* = 23.64, *SD* = 2.84) who had never had any experience working with a cobot. Eighty-seven percent of the respondents were undergraduate students, 9% were PhD students, and 4% were high school students. Moreover, 87% of all the participants were students engaged in technical studies (e.g., Biomedical engineering, Automatic Control and Robotics, and Architecture), and students from social and health sciences (i.e., Psychology) accounted for 9% of the sample[1]. We recruited all the participants through an online invitation posted on the university website. Upon completion of the study, each participant was debriefed and received a coupon worth approximately 10$ (50 Polish zloty) to use in the university gift shop as compensation.

2.2. Experimental setting and procedure

For each participant, the procedure began with brief information about the purpose of the experiment, which was described as being about modern forms of cooperation in

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[1] The majority of the participants (87%) were students with a technical background, whereas a much smaller part (9%) were students with a social and health science background. Because participants with a technical background might have different attitudes towards technology than students from social and health sciences, we conducted additional analyses including students' background variables (technical vs. social and health sciences) as covariate. The statistical conclusions of the study remained the same.

Industry 4.0, without revealing any information about the experimental task of cooperating with a cobot. Participants then gave their informed consent and were asked to fill out a baseline questionnaire containing sociodemographic data (i.e., sex, age, and field of study). Next, each participant was put on a telemetric heart rate monitor (Polar©V8000, Polar Electro, Kempele, Finland) that he or she had to wear during the entire experiment. Then they had a 15-minute habituation period. Subsequently, participants were invited to another room, where the human-cobot cooperation station had been set up. The station included a KUKA LBR iiwa 7 R800 cobot, a panel with a designed artificial pill holder, and a container with artificial 3D printed pills in 6 colors, half of which had the letter P printed on them.

We asked each participant to stand next to the cobot, and we gave them specific instructions about how to do the task. The task was designed to resemble that of a nurse working in a hospital. We told the participants to choose 36 artificial pills from the container and place them in the pill holder, one at a time, according to a list provided by the experimenter. We informed the participants that the order of the pills, their color, and the presence or absence of the letter P on them was significant. After each pill was placed in the holder on the panel, the cobot grabbed it and put it in a designated box that was out of the participant’s reach.

We asked the participants to do the same task twice, but in two different modes: manual and autonomous. In the manual mode, the participant’s task was to touch the robot in order to "wake it up" and continue with the task, so that the cobot would take the prepared pill from the holder. In the autonomous mode, the cobot worked autonomously at its own pace and needed no signal from the participant to work. If the participant did not place the pill in the holder on time, the cobot did not wait or respond by making any extra moves at the end of the task. In both cobot modes, the completion of the tasks by the human operator and by the cobot required following the same procedure of fetching and carrying the appropriate pills, working on the same panel. Furthermore, the tasks ended with the same outcome, and they had a similar degree of difficulty. The participants were randomly assigned to begin their task in the manual or autonomous mode.

Between the tasks, the experimenter reset the station and then repeated the instructions to the participant. In each mode, the sequence of the pills was altered, in order to minimize boredom or carryover effect. While the experimenter was resetting the station, the participants filled out the paper-pencil questionnaire. The task with the cobot lasted from 13.97 minutes to 16.59 minutes (*M* = 14.48, *SD* = .38), with the manual mode time span ranging from 6.75 to 9.22 minutes (*M* = 7.73, *SD* = .40) and the autonomous mode time span ranging from 6.66 to 7.74 minutes (*M* = 6.75, *SD* = .38). The time in the autonomous mode varied between subjects because the cobot was programmed to move in random trajectories within the space of the panel, which is a common practice.

2.3. Measures

2.3.1. Primary and secondary appraisal

Primary and secondary stress appraisal was measured by a 4-item self-report questionnaire, as used by Gaab et al. (2005), Klopp et al. (2012), or von Dawans et al. (2011) and adapted to the context of the experimental tasks. This measure is based on the PASA instrument (Gaab et al., 2005), which has been widely-employed in the field (Allen et al., 2014; Herhaus & Petrowski, 2018; Het et al., 2009; Kuebler et al., 2015; Nater et al., 2010; Skoluda et al., 2015; Wichmann et al., 2017). The scale is composed of primary appraisal and secondary appraisal subscales, which make up the global scale of stress appraisal. The primary appraisal subscale consists of two items that refer to a person's judgment of the event as significant, stressful, challenging, or irrelevant (Kuebler et al., 2015) (i.e., item "The past situation was stressful for me" for perceived stress and "I found the past situation to be a challenge" for challenge). The secondary appraisal scale consists of two items that refer to one’s available resources and options to cope with the stressor (Kuebler et al., 2015) (i.e., item "I knew what I had to do to influence the past situation" for self-concept and "I was able to do something to influence the course of the previous situation" for perceived control). Because in this study we were interested in measuring the levels of both primary and secondary appraisal, we considered these two factors in our analyses. The global scale of stress appraisal is computed using the following formula: primary appraisal (stress + challenge) - secondary appraisal (self-concept + perceived control). The response scale ranges from 1 (strongly disagree) to 6 (strongly agree), and higher scores indicate higher stress appraisal. Pearson inter-item correlations between the two items were .35 ($p = .01$) for primary appraisal and .58 ($p = .01$) for secondary appraisal, which is considered adequate for this two-item scale (Briggs & Cheek, 1986).

2.3.2. Heart Rate

HR data were continuously recorded throughout all the sessions using a telemetric heart rate monitor (Polar©V800) with a Polar H7 heart rate sensor and a prochest strap placed on the solar plexus. The Polar watch records HR with a sampling rate of 1000Hz. Previous studies have shown that the Polar is a valid and reliable method to assess HR at rest and HR changes during physical and psychological stress (e.g., Goodie et al., 2000; Giles et al., 2016; Caminal et al., 2018; Mishra et al., 2018; Gilgen-Ammann et al., 2019). Studies investigating the reliability of the Polar have shown significant correlations between HR measured by ECG and by Polar, with correlation coefficients ranging from 0.97 to 1.00 (e.g., Goodie et al., 2000; Terbizan et al., 2002; Engström et al., 2012). The mean HR score for each participant was obtained by calculating a mean score for the time range of HR data for each person, from the start of the task (i.e., the first move made by the cobot) until the moment of task completion (i.e., when the cobot returned to its starting position after placing the last pill in the container).

2.4. Analyses

Because age and sex have been related to the stress response (Pulopulos et al., 2018), we used unadjusted correlation analyses to investigate the relationships among primary appraisal, secondary appraisal, HR, and these variables. To test our hypotheses, we applied Linear Mixed Modelling (LMM) to our repeated-measures data nested in 45 participants, with the cobot mode (manual and autonomous mode) as a within-subject factor. Due to the similarity of the task in the autonomous and manual modes, we included the cobot mode order variable (first manual vs. first autonomous mode) as a between-subject factor in the LMM in order to control for a possible order or carryover effect. The LMM is a flexible approach to data structured in different levels, missing data, and/or more complex error structures (Heck, Thomas, & Tabata, 2010). To do so, we employed the MIXED package in SPSS v25 (IBM Corp., 2017). Three subjects were missing HR measurement values, and one subject in manual mode was missing primary and secondary stress values.

The effect sizes of the LMM were computed in R 3.5.0 (R Core Team, 2013) in conjunction with RStudio 1.1.453 (RStudio, 2012), using linear mixed-effects regression models fitted via the 'lmerTest' package (Kuznetsova et al., 2017) and the MuMIn package (Nakagawa et al., 2017). Using the MuMIn package, we derived the conditional r squared (R_c^2) values, a measure of the proportion of variance explained by both the fixed and random effects. Regarding the post hoc effects, there is no consensus about how LMM effect sizes should be calculated, due to the influence of the random effects. Therefore, in the current study, we calculated the Cohen´s *d* for the significant effects of interest on the post hoc tests. It is important to note that this effect size does not take into account the random effects, and, therefore, it only considers the effects of the independent variables, which are cobot modes (i.e., manual and autonomous), and the order of the cobot modes (first manual vs. first autonomous mode).

3. Results

3.1. Preliminary analyses

Descriptive statistics and correlations between the study variables are shown in Table 1. Next, we analyzed whether age and sex (women = 0, men = 1)[2] were significantly associated with the variables of interest in our study. Covariate analyses showed that none of these variables were significantly associated with primary appraisal (*F* = 2.77, *p* = .11 and *F* = .48, *p* = .49, respectively), secondary appraisal (*F* = 3.04, *p* = .09 and *F* = .61, *p* = .44), or HR (*F* = .05, *p* = .83 and *F* = .01, *p* = .92, respectively). Therefore, we did not include age and sex in further analyses.

Table 1.
Descriptive statistics and correlations between study variables.

Variable	*M*	*SD*	Correlations				
			Sex	Age	HR	Primary appraisal	Secondary appraisal
Sex	.42	.50	1	-.08	.03	-.10	-.05
Age	23.64	2.84	-.08	1	-.01	.11	-.11
HR	97.64	12.64	.01	-.07	1	.09	.08

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[2] At the psychological level, several studies have suggested that women suffer more stress than men, and that they tend to perceive having inadequate resources for coping with a threatening situation more often than men do (e.g., Banyard & Graham-Bermann, 1993; Pilar et al., 2004). At the physiological level, although the current evidence suggests that men and women show a similar HR response to stressors, sex differences were observed in other stress markers, such as cortisol and blood pressure (for a review see Pulopulos et al., 2018). Therefore, although sex was not significantly related to the variables of interest, we carried out extra analyses to investigate sex differences in the stress response. We applied LMM to our repeated-measures data nested in 45 participants, with the cobot mode (manual and autonomous) as a within-subject factor and the order of the cobot mode (first manual vs. first autonomous) and sex as between-subject factors. These results show no differences between men and women in the psychological and physiological response to stress, and no interactions between sex and the other two factors (all *p*s > .323). Although these results indicate no differences between men and women in the psychological and physiological response to a collaboration with a cobot in manual and autonomous modes, these findings should be viewed with caution due to the sample size of men and women. Future research should include more participants to investigate sex differences.

Primary appraisal	6.31	2.42	-.14	.33*	-.12	1	.12
Secondary appraisal	10.08	1.74	-.11	-.35*	.25	-.09	1

Note. Correlations for the manual mode are below the diagonal; correlations for the autonomous mode are above the diagonal; *$p < .05$

3.2. Primary stress appraisal (H1)

In the next step, we investigated the hypothesized differences in the primary and secondary appraisal levels and the HR levels in the manual and autonomous modes, while including the task order as a factor. The direct effect of the cobot mode on primary stress appraisal was not significant (see Table 2). However, there was a significant interaction effect between the cobot mode and the task order on the level of primary stress appraisal ($F = 6.34$, $p = .016$). Specifically, in participants who first carried out an autonomous task, the level of primary stress appraisal was significantly lower in the manual mode (M=5.59, SD=2.42) than in the autonomous mode ($M = 6.68$, $SD = 2.40$), $F = 4.95$, $p = .032$, Cohen's d = .45. This difference was not statistically significant in the participants who first carried out the task in the manual mode ($M = 6.77$, $SD = 2.35$ and $M = 6.22$, $SD = 2.49$ in manual and autonomous modes, respectively ($F = 1.78$, $p = .19$). The R_c^2 of this model indicates that 57% of the variance is explained by both the fixed and random effects.

3.3. Secondary stress appraisal (H2)

There was a significant effect of the cobot mode on the level of secondary stress appraisal ($F = 5.46$, $p = .024$, Cohen's $d = .32$). Specifically, the level of secondary stress appraisal was significantly higher in the manual mode ($M = 10.36$, $SD = 1.59$) than in the autonomous mode ($M = 9.80$, $SD = 1.85$). The effect of the order and the interaction between the order and the cobot mode were not significant (p=.59). The R_c^2 of this model indicates that 60% of the variance is explained by both the fixed and random effects.

3.4. Heart rate (H3)

There was a significant effect of the cobot mode on the HR level (*F* = 4.74, *p* = .035, Cohen's *d* = .16). Specifically, HR was significantly lower in the manual mode (*M* = 96.63, *SD* = 11.85) than in the autonomous mode (*M* = 98.65, *SD* = 13.46). The effect of the order and the interaction between the order and the cobot mode were not significant (*p*=.60). The R_c^2 of this model indicates that 89% of the variance is explained by both the fixed and random effects.

Table 2.
Differences in Heart Rate, and primary and secondary stress appraisal in manual and autonomous cobot mode.

Dimension	Manual			Autonomous			*F*	*p*
	M	*SD*	*N*	*M*	*SD*	*N*		
HR	96.63	11.85	42	98.65	13.46	42	4.74	.035
Primary appraisal[a]	6.18	2.43	44	6.44	2.43	45	4.10	.527
Secondary appraisal[a]	10.36	1.59	44	9.80	1.85	45	5.46	.024

Note. [a]range: 2-12.

4. Discussion

The aim of this research was to study the levels of psychological and physiological stress of cobot operators in different cobot modes (i.e., manual and autonomous). To our knowledge, the present study is the first to assess psychological and physiological stress reactions to collaboration with a real cobot in two different cobot modes (autonomous vs manual).

The results show that the participants had higher levels of secondary stress appraisal in the manual mode than in the autonomous mode, yielding support for Hypothesis 2. This means that the cobot users perceived themselves as more capable of coping with and controlling the situation. This result emphasizes the importance of the perception of having control over the robotic system, and it coincides with the occupational stress theory of demand-control (Karasek, 1979), which considers control at work to be a key job resource in dealing with job demands. Indeed, the essential feature of the manual mode is the operator's prerogative to initiate each step of the task (Kruger et al., 2009), in contrast to the autonomous mode, where the cobot controls all the operations, leaving the human counterpart to merely perform his/her tasks synchronously with it (Gombolay & Shah, 2014; Shi et al., 2012). This finding supports the results showing that autonomous robotic agents with decision-making capabilities can be perceived as more intrusive than other non-autonomous technologies (Gaudiello et al., 2015), and that humans may not be willing to cede control to them (Nikolaidis et al., 2015). Particularly, giving decision-making authority to robots may lead to negative individual emotional and cognitive reactions (Gombolay & Shah, 2014). Furthermore, our results are consistent with reactance theory (Brehm, 1966) and related empirical studies (Kozusznik et al., 2019; McCoy & Evans, 2005) showing that limited control at work has negative consequences for wellbeing. More specifically, in the domain of human-robot collaboration, researchers (Złotowski et al., 2017) explain that user reactance to autonomous robots is based on the notion of the importance of power in social interactions. This reactance stems from the fact that, when people's expectations about the robot's obedience in human-robot interactions are not met, they can feel less certain about the interaction and perceive a threat to their control (Złotowski et al., 2017).

We observed that HR levels were higher in the autonomous mode than in the manual mode, which supports Hypothesis 3. This is a noteworthy result because it indicates that the autonomous mode not only affects stress appraisal, but it also provokes a significant physiological reaction. Although the effect size of the difference in HR is relatively small, it is relevant to highlight that the participants in the manual mode were required to carry out more movements (i.e., touch the cobot in order to initiate its actions) than those in the autonomous mode. Despite this increased physical activity in the manual mode, which should translate into an increased HR, the HR levels in the manual mode remained significantly lower than in the autonomous mode. Previous research has shown that a higher physiological reaction to daily stressors is related to important psychological and physical health problems (e.g., Lundberg 2005; Morris, Ciesla, & Garber, 2010; Monroe & Harkness, 2005). Importantly, based on the Neurocognitive framework for Regulation Expectations (De Raedt and Hooley, 2016), recent research has shown that individuals with low expectations - understood as the perception of being able to deal with a stressful situation - show worse physiological stress regulation (Pulopulos et al., 2020). Along these lines, our secondary appraisal results suggest that the higher physiological response in our participants may have been due to the fact that they felt less confident about coping with the situation and perceived that they had less control over the situation. Together, workers may benefit from training strategies focused on increasing the perception of control and the ability to deal with their work with the cobot.

Finally, our results show that primary stress appraisal was higher in the autonomous mode, but only in those participants who carried out the task in the autonomous mode first and then worked in the manual mode, yielding partial support for Hypothesis 1. These results may be due to a possible effect of the elimination of a threat on perception. In this case, the shift from autonomous cobot mode, where the user has little or no control over the collaboration, to manual mode, may have produced relief that can stem from “a distressing goal-incongruent condition that has changed for the better or gone away” (Lazarus, 1993, p. 13) and "occurs when a threat is removed or avoided” (Carver, 2009, p. 125). Future research should further study the role of relief and other positive emotions as potentially affecting individual perceptions of stress in the collaboration with a cobot.

Despite the novel results and the methodological strengths of this well-powered within-subject study, some limitations have to be acknowledged. First, because the aim of this experiment was to study within-subject differences in the levels of primary appraisal, secondary appraisal, and HR in two cobot modes, we did not take other stress-related variables into account, such as the role of social support (e.g., emotional, instrumental), coping, or personality. In everyday work, however, workers can seek help from their co-workers or supervisors or employ different coping strategies (e.g., problem-focused, emotion focused) in order to deal with a difficult situation. Hence, future studies on human-robot collaboration should take these factors into account and study their potential mitigating effects on the levels of cobot-induced stress. They should also involve employees who work with cobots on a daily basis and for longer periods of time in order to study the dynamics and long-term consequences of stress when working with a cobot. Moreover, researchers should explore different outcomes of stress (e.g., anxiety, burnout) in order to understand the effects of collaboration with a cobot and yield relevant recommendations for practice. Second, in this study we included young participants. Studies have shown that there are age-related differences in the stress response (for a review see Pulopulos, et al., 2018). Therefore, future studies should investigate the impact of cobot modes on stress in different age groups. Third, the majority of the sample was composed of students with a technical background, whereas a smaller part were students with social and health science backgrounds. Because students with different backgrounds might have different attitudes towards technology, these results should be replicated with different populations. Finally, to draw broad conclusions about human-robot interactions, future studies should take into consideration the changes stemming from the use of social robots. Specifically, future studies could focus on the role of their expression of social behavior (e.g., smiling or gazing) in the stress levels of their human counterparts.

5. Conclusion

In recent years, the number of cobots implemented in the industrial environment has grown significantly. The impetus for the introduction of autonomous automatic devices is the desire to make work less demanding and safer for their human counterparts. Although successful in many areas, the collaboration between cobots and their operators presents a challenge in terms of control distribution, which, if not managed appropriately, can have serious individual (e.g., stress-related health problems) and organizational consequences (e.g., absenteeism, counterproductive behavior towards robots). The present study makes a noteworthy contribution to the literature on the human-robot interaction because it is the first one to show that the cobot's operating mode is important in the cobot operator's stress levels. It also points to the key role of cobot users' personal control over the outcomes of the human-robot collaboration in their well-being. In line with the present findings, people responsible for designing human-robot interaction stations and processes should pay close attention to giving the human operator the opportunity to switch the robot into manual mode. This could be an attractive feature because the manual mode gives the worker the necessary control to cope with a demanding task or situation, thus impacting his or her well-being. However, if the process does not allow the human worker to make decisions, it is essential to provide the employee with a significant amount of training, coaching, and time to gain experience in working with the robot. This training or coaching should be especially targeted at increasing operators' confidence in coping with the situation and the perception of control in their work with the cobot. All these opportunities can help the operator to learn how to cooperate with the robot, become convinced of its reliability in the interaction, and contribute to a successful cobot-human integration that ensures optimal individual psychological states.

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Highlights:

- Secondary stress appraisal is higher in the manual cobot mode than in the autonomous mode
- Heart rate is higher in the autonomous cobot mode than in the manual mode
- Control when working with the cobot improves the outcomes of the human-cobot collaboration