GSTF Journal of Psychology (JPsych) Vol.2 No.1, August 2015

DOI 10.7603/s40790-015-0011-1

# Unstable Sense of Agency under Consistent Force Feedback

Nadiya Slobodenyuk

***Received 15 Jul 2015 Accepted 18 Aug 2015***

*Abstract*—**The present study undertakes an ecological approach to haptic interfaces grounded in the sense of agency that accompanies human action. The study had two aims. The first aim was to investigate the effect of two top-down cues (perceived initiation of action and presence of action options) on sense of agency in haptic interfaces. The second aim was to investigate the consistency of the sense of agency and answer the question whether consistent force feedback (bottom-up cue) is sufficient to grant stable experience of agency. The results of the study suggest that while high number of action options can be associated with stronger agency, low numbers of action options are unlikely to produce such effect, and that the cue of task completion might be critical for the sense of agency. The study also showed that sense of agency was relatively inconsistent, with the main source of uncertainty being computer-attributed agency. The discussion addresses issues of joint human-computer agency and the contribution of multiple sources of information to agency experience.**

***Keywords—sense of agency, motion control, joint human-computer action***

## I. INTRODUCTION

### A. Haptic Interfaces

Haptic human-computer interfaces offer a qualitatively new way of interacting with virtual environments. They have already become an indispensable learning means in some domains and a valuable tool for clinical practice. In the learning context, haptic interfaces have been primarily developed for surgery simulation and training [1, 2, 3], and driving simulation [4]. In the context of clinical practice, haptic interfaces are being developed for the therapeutic force feedback distortion for patients with motor restraints [5]. Due to the virtue of remote control, haptic systems have also found an application in motor rehabilitation that allows distant interaction with the therapist. In the case of such distant rehabilitation (telerehabilitation), the patient can sit in the haptic workstation and the therapist can remotely interact with the patient by giving instructions, controlling the exerted forces, and modifying other elements of the environment in real time, thereby driving the motor behavior of the patient in a way beneficial to the motor system [6].

Diversity in the application domains, functions, and interaction styles accounts for the large variety of haptic interfaces. The force feedback can be provided to the hand (see [7], for review), upper body (e.g., [6]), or lower body (e.g., [8]). Such feedback in some cases supports the possibility of distant interaction with real environment through teleoperation. In other cases, the design aids interaction with virtual reality exclusively, enabling the perception of shape and substance properties of virtual objects. Virtual haptically rendered objects and surfaces can be experienced as having a variety of properties including weight [9, 10], roughness [11, 12], and compliance [13] that conveys the related experiences of stiffness [14] and softness [15, 16, 17].

In essence, haptic human-computer interfaces are based on human ability to process force feedback provided by the haptic device; therefore, the design of the interface is innately linked to the limitations of vibrotactile stimuli processing by the human sensorimotor system. Such limitations of the human sensorimotor system are quite variable and depend on body part the measurement is taken from (e.g., differences in vibrotactile thresholds for wrist, elbow, and shoulder in [18]), rate of change of the stimulus [19], complexity of the generated movement [18], electrical and mechanical specifications of the device [20], and other factors. Considering that the detection limitations of the human sensorimotor system depend on multiple internal and external factors, in some cases it is possible to use generic knowledge about vibrotactile thresholds that represent such limitations of the sensorimotor processing; however, in most cases, a customized measure of the thresholds that allows testing the limitations for a specific type of setup or stimulus is employed. The measurement of the vibrotactile thresholds typically takes a form of explicit judgment of force differences (JND – just noticeable difference) [18, 21] and the obtained JND information is consequently used to render haptic stimuli and set the limits in the haptic system.

While vibrotactile thresholds are informative in general, the present study argues that threshold measurement can serve only as initial stage in rendering of haptic stimuli and that more complex experiential testing of haptic environment stimuli is necessary on the consequent stages of haptic interface design. This argument is based on the assumption that the performance on the threshold measurement tasks cannot be projected to the performance in haptic environment that has a task different from that of vibrotactile force feedback judgment. Such projection cannot be made because we normally do not explicitly evaluate the amount of experienced force, but rather sensorimotor feedback becomes implicitly interpreted through complex experience of sense of agency that relies on perceptual and motor cues as well as contextual top-down cues.

DOI: 10.5176/2345-7872_2.1_32

With regard to such ecological reasoning, the evaluation of JND is not representative of the force feedback perception in an actual haptic environment, and an efficient environment needs to be grounded in the human experience of agency characteristic to real interaction. The following section reviews the notion of the sense of agency and outlines the factors that determine the experience with haptically rendered stimuli.

### *B. Sense of Agency*

Sense of agency is an experience of control of own action that involves the perception of correspondence between intention and action and a causal attribution of the outcome of action to self. Sense of agency has been labeled "one of the most pervasive aspects of human consciousness" [22, p. 1]. A vastly supported account of the sense of agency indicates that agency depends on the bottom-up internal cues which pertain to motoric signal analysis and top-down cues which are quite diverse in nature and may include beliefs, task-related thoughts and expectations as well as external situational cues [23, 24, 25, 26]. The role of bottom-up cues in sense of agency has been explained well on the basis of the internal forward model that presumes the existence of two types of internal prediction mechanisms: the prediction of the outcome of the motor command and the prediction of the sensory consequences of movement. It was proposed [27] that three types of internal comparisons that employ these prediction mechanisms account for the normal experience of agency: 1) the comparison between predicted outcome and desired state of the motor system; 2) the comparison between the predicted sensory consequences and actual state; 3) the comparison between the desired state and the actual state. The model also postulates that only some internal representations are available to conscious awareness. For example, there seems to be limited awareness of the actual state of the motor system, but we are normally aware of the predicted consequences of movement. At the same time, as long as the desired state is achieved, we seem to be unaware of the results of the comparison between predicted outcome and desired outcome of the motor command [27]. Such comparator model that postulates that normal sense of agency is a result of the processes of comparison of representations that involve sensorimotor feedback and are partially outside our awareness has been used to explain a range of abnormal agency phenomena (e.g., delusions of control, anarchic hand sign); however, limitations of the explanatory power of the model have also been noted (see [28], for review).

The role of top-down cues in sense of agency is understood less and no coherent theory exists up to date to explain at full how the top-down cues and the bottom-up cues are combined. This is partially due to the diversity of the top-down cues and the difference between the cues with regard to the time course of the action. Some are linked in time to action selection and generation others occur prior or after the action has been executed. Cognitive load, for example, could be considered a time-linked cue: as the performance on the task generates cognitive load, the cognitive load determines in an online manner the experience of agency in a target task. It was recently shown in [29] that sense of agency depends on cognitive load with greater working memory load being associated with lower ratings of agency.

A number of studies have shown that information prior to action can also influence the sense of agency. Most notably studies point to the effect of both subliminal and supraliminal priming on agency. In [30] participants were primed with words "left" and "right"; the priming stage was followed by left or right button presses that generated the tone. The results showed lower agency in incompatible primes. In [31] left- and right-pointing arrows were used to prime left and right index finger response. The results confirmed that sense of agency can be enhanced by compatible primes. Other studies have also shown the effect of priming on the sense of agency (e.g., [32]).

Finally, post hoc cognitive processing has been shown to influence the sense of agency as well. As an example, [33] describe a probable situation in which a golf player hits the ball and the trajectory of the ball is changed due to the wind which causes the ball to actually fall into the hole. In this case, the golf player might attribute the success to self even though the predicted flight trajectory was not expected to produce this result. Such attribution would be based on the positive evaluation of the action outcome. Such possibility has been proven experimentally as well. In [33] participants' movement was paired with pictures of positive, neutral, and negative affective content taken from the International Affective Picture System (IAPS). The results showed that the affective valence of the movement outcome influenced the judgment of the direction of movement by the participants with the movement being perceived as directed towards positive outcome and away from negative outcome.

Not only can top-down cues influence the sense of agency, but in cases when bottom-up cues are unavailable, top-down cues alone seem to be sufficient to grant the sense of agency. For example, [34] note that in daily life we, in fact, encounter situations when bottom-up cues are unavailable but the agency is still experienced due to beliefs and situational cues. For example, we might not remember performing an action due to its automatic nature, however, we would still experience agency over it because there might not be a better explanation of the event other than self-caused. What is even more interesting is that on the basis of top-down cues alone we can experience an absolutely illusory agency that pertains to the action that has not been performed by self at all. In [35] using a two-person paradigm that involved observing movements of hands of a different person positioned in a location of own hands, was shown that participants would report a greater sense of control over the movement of hands if the instruction pertaining to the movement was given prior to movement as opposed to after the movement, and if the instruction was congruent with movements as opposed to non-congruent. The study pointed to the role of anticipation of specific movement in the sense of agency experience. There are even more radical examples of the illusory agency on the basis of thoughts. It was shown in [36] that having thoughts about the event prior to it can create a sense of agency even though the causation itself would be quite "magical". For example, participants were more likely to believe that they inflicted harm to another person via a voodoo curse if they had thoughts about the event consistent with the harm. In a basketball game setting, participants were also more likely to perceive their causal role in the game performance if they had prior visualizations of success. Such “magical” agency is also based on top-down cues exclusively and is grounded in belief.

## II. PRESENT APPROACH

The present research builds on the argument that while for the purpose of haptic stimuli rendering participants are asked to explicitly evaluate the amount of experienced force, in the daily life we never explicitly evaluate sensorimotor feedback; such feedback becomes implicitly interpreted and coupled with other sources of information within the complex experience of agency that allows us to feel control over our actions. The implications of the discrepancy between the force evaluation in the context of haptic application design and real life experience would be in that the threshold measurements would not be representative of how the force feedback is perceived through the sense of agency during the performance on the tasks that are different from the task of force feedback evaluation. Accordingly, the present study has two aims.

First, taking into account the findings of the interaction between top-down cues and bottom-up cues, the aim is to investigate the sense of agency under consistent force feedback (bottom-up cue) while manipulating top-down cues of 1) perception of action options and 2) experience of initiation of action as opposed to continuation of action. The research on the above top-down cues is quite scarce and to our knowledge, up-to-date there has been only one study investigating the contribution of the action options to the sense of agency. In this sole study [22] that combined key pressing and tone presentation, participants were given one key to press, three keys to choose from and press, or seven keys. The results showed that the maximum number of alternatives was associated with the strongest degree of intentional binding. Intentional binding is a phenomenon of experienced time compression between an action and its perceived causal outcome in case of attribution of causal outcome to self. Intentional binding has been used as a reliable implicit measure of agency; hence, higher intentional binding in [22] is an indicator of the stronger sense of agency.

The second aim of the present study is to investigate consistency of agency judgment and answer the question whether consistent force feedback (bottom-up cue) is sufficient to grant stable experience of agency. This aim is grounded in the idea that human perceptual system should be evaluated in terms of stability and that such evaluation is particularly relevant to the contexts that deviate from common real-life experiences. Stability in haptic systems has so far been addressed systematically from technology-centered perspective. For example, it has been pointed out the fact that unlike other types of displays, haptic displays are fundamentally different as they involve bi-directional flow of physical energy and that “the human grasp may stabilize an otherwise unstable system by absorbing mechanical energy. Conversely, the human grasp may destabilize an otherwise stable system by reflecting energy back into the system. Since the haptic device actively generates physical energy, instabilities can damage hardware and even pose a physical threat to the human” [37, p. 465]. While the technology-centered perspective on stability is crucial, what is also true that human interaction with the haptic displays (e.g., human grasp that can destabilize the system in [37]) is based on the online perception, and the human perceptual system also has properties of noise and instability. The question of the joint stability of the human perceptual system and haptic hardware is beyond the scope of the current research and presents an area for future investigation. The present study intends to measure only the consistency of the sense of agency of human operator under the conditions of stable force feedback.

## III. EXPERIMENT

### A. *Method*

#### 1) *Participants*

Sixteen undergraduate students from the American University of Beirut took part in the study. All participants had normal or corrected-to-normal vision and did not report any sensory or motor impairment in the dominant hand. The study was approved by the Institutional Review Board of the American University of Beirut.

#### 2) *Task instructions and stimuli*

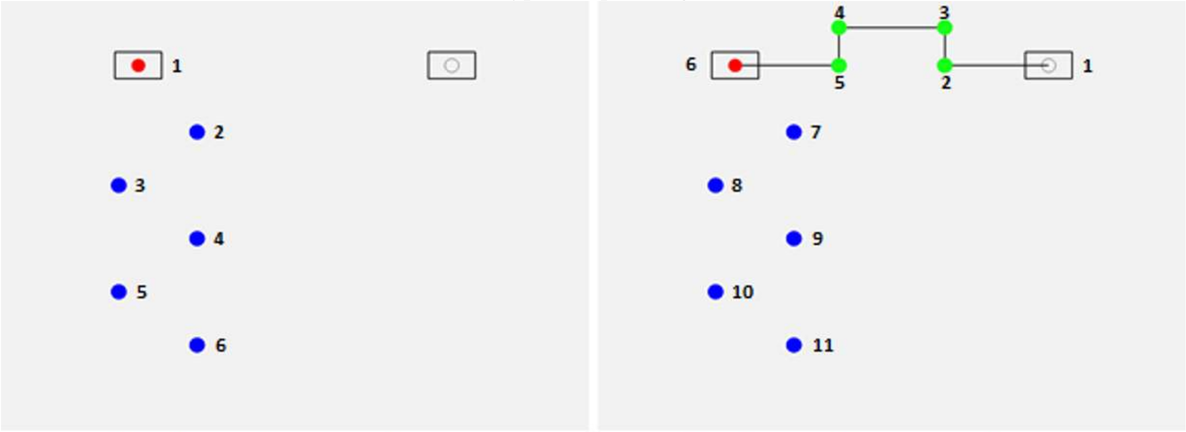
Participants were seated in front of the 15" computer screen that depicted a set of dots with assigned numbers. The task given to the participants was to connect the dots according to their numbers in a regular ascending sequence. The visual stimuli were two-dimensional, and the completion of the task required interaction with the display by the means of SensAble PHANTOM OMNI® haptic device. PHANTOM OMNI® haptic device is a system with 6 degrees of freedom and maximum exertable force of 3.3 N. The force feedback is provided on x, y and z planes. The device allows tactile interaction with virtual objects by employing the force and vibration feedback.

First, the participants had to place the stylus of the PHANTOM OMNI® haptic device in space in a way that the indicator of the spatial location of the tip of the stylus on the screen pointed at the first dot. Once the spatial location of the tip of the stylus was identified on the screen and the indicator placed at the target, the participants had to press the button on the stylus and move the stylus to the next dot in a sequence until all the dots were connected. As the participants moved from one dot to another, a line linking the dots appeared on the screen to indicate the connected sequence. Such visual indication of the connection ensured a clear experience of connecting the dots rather than moving in space from one location to another.

#### 3) *Task conditions*

Two types of dot sequencing were designed in the present study. Type I sequencing consisted of two tasks and type II sequencing consisted of six tasks, allowing the manipulation of the target top-down cues: 1) presence of action options and 2) perceived initiation of action (see Figure 1 for sample tasks). Two types of sequencing as opposed to one were used to ensure that the possible effect is unrelated to the sequence itself but rather to the manipulated variables. The cue of the presence of action options was manipulated by adding two dots with the

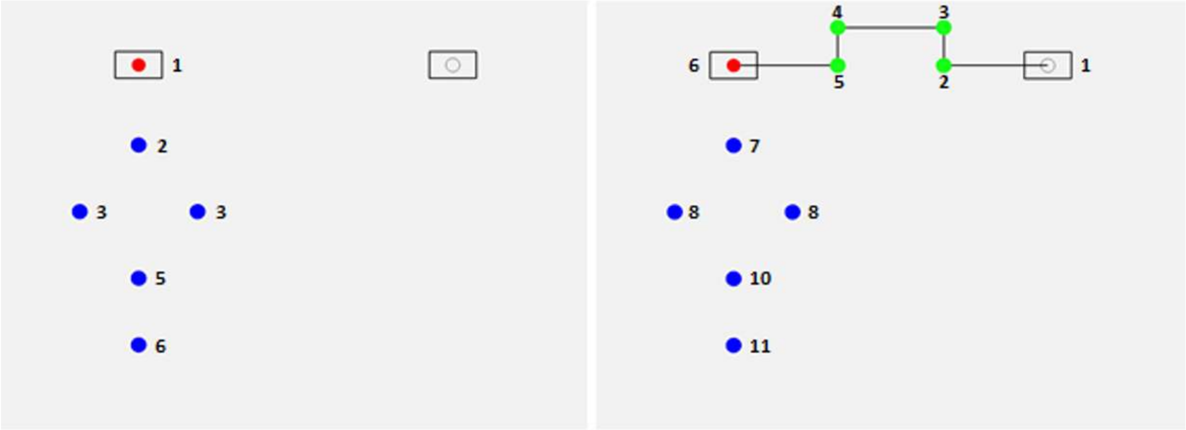
Type I sequencing



Non-decision / Initiation of action

Non-decision / Continuation of action

Type II sequencing



Decision / Initiation of action

Decision / Continuation of action

Figure 1. Sample tasks

same number equidistantly from the preceding dot resulting in an ambiguous situation where it is nonapparent to the participant which dot to connect next. The manipulation of the presence of action options cue resulted in two task conditions: 1) decision condition in which participants had to make a choice between two equally valid action options as two dots had the same number; 2) non-decision condition in which each dot had a unique number, and therefore, the necessary sequence of connection was unambiguous. The cue of perceived initiation of action was manipulated by creating tasks that were done jointly with the computer. The manipulation of the perceived initiation of action cue resulted in two task conditions: 1) initiation of action condition which represents a situation where the participant starts from dot with the number 1 and connects the rest of the dots according to their numbers, 2) continuation of action condition which represents a situation where the computer starts connecting the dots from dot 1 and the participant continues once the computer reaches a target red dot with the number 6. Computer's connection of the dots took the same visual form as participant's and the connecting line appeared between the dots. Regardless of the condition, participants connected six dots in all type I and type II tasks.

The experimental stage which followed the familiarization and practice stage consisted of 40 randomized trials: five trials of each of the eight tasks. The eight tasks with regard to sequencing and manipulated cues are following: task 1: type I sequencing non-decision/initiation of action; task 2: type I sequencing non-decision/continuation of action; task 3: type II sequencing decision/initiation of action; task 4: type II sequencing non-decision left/initiation of action; task 5: type II sequencing non-decision right/initiation of action; task 6: type II sequencing decision/continuation of action; task 7: type II sequencing non-decision right/continuation of action; task 8: type II sequencing non-decision left/continuation of action. Note that the difference in the number of tasks in type I sequencing and type II sequencing is due to the nature of the type I task which was a non-decision task by default and allowed manipulating only the cue of initiation / continuation of action. Type II sequencing, on the other hand, allowed manipulating both cues the initiation / continuation of action of action and the presence of action options. In this case, however, the design of the equidistant position of the dots at the decision level from the preceding dot placed the need to control the direction (left or right) of the movement under the non-decision condition resulting in larger number of type II sequencing tasks. The samples of type I sequencing tasks and type II sequencing tasks are given in figure 1.

### *4) Force feedback*

In all tasks and during the whole task duration, the force feedback applied to the hand of the participant through the haptic device once the participant started moving the hand in space, was pushing the hand upward. The movement from all dots to all following dots, except for the movement from the second to the third dot, was accompanied by force feedback of 0.9 N. The force feedback that accompanied the movement from the second to the third dot was 2N in all tasks. A sudden force change on the participant's hand was avoided by force acceleration by 3N/sec. and deceleration by 10N/sec. Such force feedback change that occurred in all tasks at the same dot-connection level, corresponded to the decision point in the decision tasks with two equally valid action options. This paradigm in which the bottom-up cues (force feedback change) were identical in all tasks, but the tasks were different with regard to top-down cues (presence of action options and perceived initiation of action) allowed testing 1) whether perceived initiation of action would override bottom up cues and influence sense of agency, and 2) whether the need for a decision would override bottom up cues and influence sense of agency.

### *5) Agency measure*

The sense of agency was measured using direct questions about the experience of control. After each of the 40 completed tasks, the participant had to indicate the perceived degree of own control (SELF agency) and the perceived degree of control induced by the computer (COMP agency). Considering that the change in the force feedback was introduced in the middle of the task, two separate agency questions referring to the experience of control exerted by self (SELF agency) and control provided by the computer (COMP agency) were used to account for bi-directionality of the haptic system and the joint nature of the task. The answers to two agency questions were given on a 7-point Likert scale.

## *B. Results*

### *1) Top-down cues and agency*

The main analysis was done on initiation vs. continuation of action and decision vs. non-decision conditions. Type I and type II tasks were analyzed separately which allowed eliminating the possible confounded top-down cue of the task difference perception. The results of the t-tests showed no significant difference in SELF agency between condition. There was also no significant difference in COMP agency between conditions (see Table 1).

### *2) Consistency of agency*

In order to identify how consistent were SELF agency and COMP agency across the trials of the individual tasks two measures were used: standard deviation and entropy. The analysis of conditions with regard to standard deviation revealed no significant differences in standard deviations for SELF agency or COMP agency between initiation vs. continuation conditions and decision vs. non-decision conditions. No significant differences between SD for SELF agency on individual tasks and overall SD for SELF agency were found either. On the other hand, SD for task 1 (M=0.99, SD=0.57) and SD for task 7 (M=0.73, SD=0.41) for COMP agency were significantly different from the average standard deviation for all COMP agency (M=0.85, SD=0.37). SD for task 1 was higher than the average, t(15)=2.14, p<0.05, while SD for task 7 was lower than the average, t(15)=-2.19, p<0.05.

The entropy measure for analysis of consistency of the sense of agency was also used. Entropy was calculated using:

$$H = \frac{1}{\ln t} \sum_{i=0}^{6} p_i \ln \frac{1}{p_i} \qquad (1)$$

where pi is the fraction of answers equal to i, for i =0,1,2,3,4,5,6, and t is the number of trials (t ⩽ 5). The measure was normalized by ln t resulting in the maximum entropy of 1 for all cases. This includes the cases where one or two trials were excluded from the analysis because they were not finished according to the instruction. The analysis of conditions with regard to entropy revealed no significant differences in entropy for SELF agency or COMP agency between initiation vs. continuation conditions and decision vs. non-decision conditions. Paired-samples t-tests also showed no significant differences between SELF agency entropy on individual tasks and the average entropy on all SLEF agency tasks. However, in the case of COMP agency entropy, task 4 entropy (M=0.55, SD=0.22) was significantly higher than the average entropy of all COMP agency tasks (M=0.49, SD=0.16), t(15)=2.20, p<0.05. Entropy averages on all tasks, except for average of SELF agency entropy for task 6 (H=0.36), fall within the range between 0.41 - 0.75, which, in this case, corresponds to entropy range representing cases when only 3 out 5 judgments were the same, and only 2 out of 4 judgments were the same in case of one invalid trial.

TABLE I. PAIRED SAMPLES T-TEST

| **SELF agency** | **t** | **df** |
|---|---|---|
| Initiation vs. continuation (Type I) | 0.87 | 15.00 |
| Initiation vs. continuation (Type II) | -1.07 | 15.00 |
| Decision vs. non-decision (Type II) | 1.26 | 15.00 |
| **COMP agency** | **t** | **df** |
| Initiation vs. continuation (Type I) | -.41 | 15.00 |
| Initiation vs. continuation (Type II) | 0.58 | 15.00 |
| Decision vs. non-decision (Type II) | -1.15 | 15.00 |

### *3) Serial position of tasks and agency*

In order to explain the discrepancy of agency on the identical trials of the same task, the possibility of the effect of serial position of the trials of individual tasks within the randomized sequence of 40 trails was considered. The measure of adjusted average distance between consecutive trials on individual tasks was used. Adjusted average distance was calculated using:

$$D = \left(\frac{1}{t-1}\sum\nolimits_{i=2}^{t}\sqrt{S_i - S_{i-1}}\right)^2 \qquad (2)$$

where S1, S2,…., St are the serial numbers of trials per task sorted in increasing order and t is the number of trials. The square-root adjustment was used to give more weight to medium intervals.

Further analysis comprised of several bivariate correlations to identify the relationship between SELF agency entropy, COMP agency entropy, standard deviations, and adjusted average distances was conducted. Significant correlations were found between adjusted average distances and standard deviations of SELF agency. There was a significant positive correlation between the standard deviation for task 2 and task 8 and adjusted average distances for task 6, r=0.5, p<0.05 and r=0.54, p<0.05 respectively. Both correlations had a large effect size of equal or above 0.50 indicating that these variables covary strongly. A negative correlation between the standard deviation for task 3 and adjusted average distance for task 2 was also found, r=-0.68, p<0.01. The effect size of this relationship is also large.

In the case of COMP agency, positive correlations were found between adjusted average distance for task 6 and entropy for task 7, r=0.54, p<0.05, adjusted average distance for task 1 and standard deviation for task 8, r=0.51, p<0.05. Negative correlations were found between adjusted average distance for task 6 and entropy for task 5, r=-0.55, p<0.05, adjusted average distance for task 5 and entropy for task 8, r=-0.51, p<0.05, and between adjusted average distance for task 5 and standard deviation for task 8, r=-0.50, p<0.05. All of the found relationships had large effect sizes with a correlation around 0.5.

The effect of training was checked by dividing the raw data into quartiles and comparing all possible pairs using a dependent t-test. No significant differences were found indicating no general effect of training on the performance.

## IV. DISCUSSION

The aim of the study was twofold. The first aim was to investigate the effect of two top-down cues (perceived initiation of action and presence of action options) on sense of agency in haptic interfaces. The second aim was to investigate the consistency of the sense of agency and answer the question whether consistent force feedback (bottom-up cue) is sufficient to grant stable experience of agency.

The results of the present study showed that the investigated top-down cues had no effect on sense of agency. In case of the presence of action options, the results are both inconsistent with but can be explained on the basis of the results obtained in [22]. They found that the maximum number of action options was associated with stronger intentional binding pointing to the stronger self-agency, and the difference in binding in 7-key condition (maximum choice) was significantly higher in comparison to 1-key condition (no choice), but the differences between 7-key condition and 3-key condition as well as the differences between the 3-key condition and 1-key condition were non-significant. It is reasonable to assume that the effects of action options and the experience of choice are observed only under the conditions of relatively large number of action choices. In the present study, the participants had two options to choose from or no choice options; therefore, the effect of choice options was not found.

With regard to the second top-down cue, the expectation was that the participants would experience more agency in the initiation of action condition because they performed the action on their own and they were the ones deciding when to start the task. In the case of continuation of action, not only did the participants continue the action initiated by the computer but they also could not decide on their own when to start as this was predetermined by the computer’s performance on the first part of the task. It is possible that the participants did not experience decreased agency because predetermined point of start was not perceived as a matter of less personal control but rather as an inherent element of the task being performed by two agents in which each agent has equal level of control. Therefore, a good framework to address these results would be joint agency. At this point we know very little about the dynamics of joint human-computer agency and the diversity of used paradigms makes it difficult to compare the results of the studies addressing the same issue; however, we do know that certain change in agency occurs when a computer partner is added. In their study on human-human and human-computer joint agency, [38] have noted that human-human performance was associated with immediate prereflective “we” agentic identify because intentional binding for action and its effect was present in human-human pairing regardless of who has generated an action. On the other hand, when a computer partner was added, implicit prereflective sense of agency, as measured by intentional binding, “broke down”, i.e. intentional binding did not occur in human-computer action even when explicit self-agency was present. In the present study, prereflective agency was not measured and, therefore, it is not known whether a similar dynamics of implicit/explicit agency occurred within the investigated case of joint human-computer agency; however, result from [38] give a convincing example of the possibility of change in the personal agency when the computer partner is added. Researchers [38] also propose that one of the criteria of forming ‘we’ identity for truly joint agency is the ability to represent the other agent’s task “in the same format as one’s own task and to comprehend that they have intentions to act that are similar to one’s own intentions” (p. 668). They also make a case for this criterion being met only in the human-human pairing condition in their experiment. If this criterion for joint agency to be accepted, it is possible that it was also met or partially met in the present case of human-computer pairing. This might be the case due to the joint nature of the task used. In the used paradigm, the participants had to finish the task initiated by the computer and the computer performed exactly the same kind of action as the participant which means the goal was shared and, therefore, the participants could have represented the task of the computer in the same format as own task. These give a good starting point for investigation of joint human-computer agency from perspective of shared goal representation.

The considerations of the type of joint task in order to explain the agency results could be also extended to the assumption that some aspects of the joint task might affect agency more than other aspects. For example, if we assume that agency is a process of weighted contributions from multiple sources of information, there might be a difference in the weight of task initiation and the weight of task completion, with task completion being more crucial to sense of agency than initiation. This means that even though the task was in fact accomplished jointly by the computer and the human, because the computer was always the first one to start and the participants were always the ones to finish the task in the continuation of action condition, the participants experienced agency due to their contribution at the final stage of the task which allowed achieving the goal shared by two agents. This hypothesis could be addressed in the future research by looking at the agency effects in case of human continuation and completion of the task initiated by the computer and in case of human initiation of the task continued and completed by the computer partner. Regardless of whether the above explanations are adopted, future research on joint human-computer agency will need to take into consideration the types of joint tasks. In this study the participant needed to continue the task initiated by the computer. This case of human-computer pairing presents a qualitatively different case of joint agency than the case presented in [38]. In their study, participants performed a simple action of taping on the touch pad and had to judge the time of the action onset or the onset of the tone that followed the action with a delay. This task was paired with the feedback on whether the person has tapped on the touch pad first and caused the tone or the confederate did (another person in human-human pairing and computer software in human-computer pairing). On the other hand, in the present study the human agent and the computer agent completed one task together by each contributing to one part of that task. In fact, the paradigm proposed here might qualify better for a joint agency framework than the one used in [38].

The second aim of the study was to investigate consistency of the sense of agency and answer the question whether consistent force feedback (bottom-up cue) is sufficient to grant stable experience of agency. The overall experience of agency in this study was broken down into self-agency and computer-attributed agency to account for bi-directionality of the haptic system and the joint nature of the task. The findings show that self-agency was relatively consistent while computer-attributed agency was much less consistent. These findings likely indicate that the participants were relatively certain about the amount of haptic effort they applied; however, they were more likely to doubt the intensity of the force feedback induced by the computer during the task performance. The inconsistency of evaluation of force feedback could be due to poor force feedback tracking during the task, and therefore, poor encoding of force feedback cues. The assumption of poor online force feedback tracking means that the nature of the task could have lowered the attention to the force feedback and, therefore, the sensitivity to changes in force feedback at the critical point in each task was diminished. Such explanation is well supported by the studies on inattentional blindness, and tactile inattentional blindness in particular. Tactile inattentional blindness typically takes a form of change blindness and refers to inability to detect change in tactile stimulation as a function of attentional processes (e.g., [39]).

Alternatively, it is possible that online tracking of force feedback was accurate, however, relevant haptic representations faded quickly. Participants were given the task to connect the dots and were instructed and trained on how to do that using the haptic device; there was no task to keep a track of force feedback changes or the indication that this force feedback is important to the experiment. This was a crucial part of the used paradigm that allowed addressing the question of correspondence between the explicit force feedback judgment in JND experiments for haptic rendering and real experience with haptic displays that involves a task unrelated to explicit force evaluation. However, performance on the task unrelated to explicit force feedback evaluation might itself account for the fact that even if relevant force feedback representations were created in an online manner, the participants failed to achieve consistent agency due to fragile nature of these representations given participants' unawareness of the significance of this information. This assumption can also be reframed as a possibility that online feeling of agency might have been accurate and it is the post-factum judgment of agency that became biased. A larger framework to view this result could be the contribution of time-linked cues to agency as opposed to cues that occur prior and after the action. At this point we know that all three types of cues are essential; however, the weighted contribution of these cues and the biases associated with the time course of the action remain an area for future exploration.

The present study has also confirmed that information preceding the action, just as the time-linked cues, influences agency. The analysis showed that inconsistency of the perception of the force feedback can be partially explained by the position of trials of individual tasks within the sequence of 40 randomized trials. Randomized presentation of trials allowed dealing with the direct sequence effect; however, it did not eliminate the sequence effect entirely. The proximity of trials of some tasks was related to biased sense of agency on others supporting the previous findings that situational information prior to action generation can influence the sense of agency and in override the bottom-up sensorimotor feedback.

The above findings support the ecological approach to force feedback processing undertaken here, pointing to the fact that while explicit force feedback evaluation for haptic application design is informative in general, it, however, is not representative of the processing of such feedback in haptic interfaces that have a task other than force evaluation. Under the normal circumstances, the bottom-up cue of force feedback is coupled with a range of top-down cues that occur prior, at the time of and after the action has been generated. In the present study, the sequence of tasks was shown to have such effect, indicating that the information prior to action has influenced the interpretation of the force feedback. On the other hand, the effect of presence of action options and initiation vs. continuation of action did not have an effect on the sense of agency in the used paradigm. There is a possibility that other top-down cues not measured here could offer a full explanation for inconsistency of agency. Considering that previous research has pointed to the possibility that expectations can be a powerful top-down cue that can modify an overall agency experience [40], expectations regarding the similarity or difference of experience might have also contributed to the instability of agency in the present study.

Some of the limitations of the present study to be noted pertain to the measurement of agency. While participants were not asked to evaluate force feedback explicitly in order to see how this feedback is interpreted through the sense of agency we experience in any action, it could be argued that the explicit measure of agency or the reflective feedback measure used here is also non-typical to daily functioning, and that in a typical situation we are likely to experience the feeling of agency without creating a judgment about it. An extension of this argument noted above could be that the feeling of agency might have been accurate while the judgment of agency became biased. Most recent accounts, however, show that we rely on both the feeling of agency and the judgment of agency and the dynamics of the two is situational. We might also consider that in a relatively artificial and novel situation such as the haptic display interaction, we are in fact more likely to be more introspective and reflective and rely on the explicit judgment than the implicit feeling of agency that is typical to familiar situations. The future research might address the issue of agency in haptic displays employing both reflective feedback measures of judgment of agency and implicit measures of feeling of agency (e.g., intentional binding).

## ACKNOWLEDGMENT

The data for this analysis was collected and processed in collaboration with Lama Ghanem, Jalal Awed, and Imad Elhajj.

## REFERENCES

[1] E. Burdet, R. Gassert, F. Mani, F. Wang, C.L. Teo, and H. Bleuler, “Design of a Haptic Forceps for Microsurgery Training,” In Proceedings of EuroHaptics 2004. Munich, Germany, 2004, pp. 74–81.

[2] E. Samur, L. Flaction, and H. Bleuler, “Design and Evaluation of a Novel Haptic Interface for Endoscopic Simulation,” IEEE T Hapt., vol. 5, no. 4, pp. 301–3011, Oct.-Dec. 2012.

[3] X. Shen, J. Zhou, A. Hamam, S. Nourian, N.R. El-Far, F. Malric, and N.D. Georganas, “Haptic-Enabled Telementoring Surgery Simulation,” IEEE Multimedia, vol. 15, no. 1, pp. 64–76, Jan.-Mar. 2008.

[4] M. Ambroz, I. Prebil, R. Kamnik, and M. Munih, “System for interactive scientific driving simulation with haptic information,” Adv Eng Softw., vol. 45, pp. 239–251, Mar. 2012.

[5] S. Allin, Y. Matsuoka, and R. Klatzky, “Measuring Just Noticeable Differences For Haptic Force Feedback: Implications for Rehabilitation,” In Proceedings of the 10th Symp. on Haptic Interfaces For Virtual Envir. & Teleoperator Systs. (HAPTICS.02). IEEE, Orlando, FL, USA, 2002, pp. 299–302.

[6] M. Gutierrez, P. Lemoine, D. Thalmann, and F. Vexo, “Telerehabilitation: Controlling haptic virtual environments through handheld interfaces,” In Proceedings of ACM Symposium on Virtual Reality Software and Technology (VRST 2004). ACM, New York, NY, 2004, pp. 195–200.

[7] A. Fisch, C. Mavroidis, J. Melli-Huber, and Y. Bar-Cohen, “Haptic Devices for Virtual Reality, Telepresence, and Human-Assistive Robotics,” In Biologically-Inspired Intelligent Robots. SPIE Press, 2003, pp. 73–101.

[8] H. Schmidt, S. Hesse, R.. Bernhardt, and J. Kruger, “HapticWalker—a novel haptic foot device,” ACM Trans App Perc., vol. 2, no. 2, pp. 166–180, Apr. 2005.

[9] J. Hummel, J. Dodiya, R. Wolff, A. Gerndt, and T. Kuhlen, “An Evaluation of Two Simple Methods for Representing Heaviness in Immersive Virtual Environments,” In Proceedings of the IEEE Symposium on 3D User Interfaces. Orlando, FL, USA, 2013, pp. 87–94.

[10] S. Scheggi, G. Salvietti, and D. Prattichizzo, “Shape and Weight Rendering for Haptic Augmented Reality,” In Proceedings of the 19th IEEE International Symposium on Robot and Human Interactive Communication, Principe di Piemonte - Viareggio, Italy, 2010, pp. 44–49.

[11] G. Campion and V. Hayward, “On the synthesis of haptic textures,” IEEE Trans Rob., vol. 24, no. 3, pp. 527–536, Jun. 2008.

[12] K. U. Kyung and D. S. Kwon, “Perceived roughness and correlation with frequency and amplitude of vibrotactile stimuli,” In Proceedings of EuroHaptics 2006. Paris, France, 2006, pp. 277–282.

[13] L. R. Kaim and K. Drewing, “Finger force of exploratory movements is adapted to the compliance of deformable objects,” In Proceedings of the Third Joint EuroHaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems. IEEE, Salt Lake City, UT, USA, 2009, pp. 565–569.

[14] F. Avanzini and P. Crosato, “Haptic-Auditory Rendering and Perception of Contact Stiffness,” In Proceedings of First Int. Conf. on Haptic and Audio Interaction Design (HAID'06). 4129, 2006, pp. 24–35.

[15] R. H. Lamotte, “Softness discrimination with a tool,” J Neurophysiol., vol. 83, no. 4, pp. 1777-1786, Apr. 2000.

[16] A. Bicchi, E. P. Scilingo, and D. De Rossi, “Haptic discrimination of softness in teleoperation: The role of the contact area spread rate,” IEEE Trans Robotic Autom., vol. 16, no. 5, pp. 496–504, Oct. 2000.

[17] E. P. Scilingo, M. Bianchi, G. Grioli, and A. Bicchi, “Rendering softness: Integration of kinaesthetic andcutaneous information in haptic devices,” IEEE T Hapt., vol. 3, no. 2, pp. 109–118, Apr.-Jun. 2010.

[18] S. Feyzabadi, S. Straube, M. Folgheraiter, E.A. Kirchner, S.K. Kim, and J.C. Albiez, “Human Force Discrimination during Active Arm Motion for Force Feedback Design,” IEEE T Hapt., vol. 6, no. 3, pp. 309–319, July-Sept. 2013.

[19] A. Bhardwaj and S. Chaudhuri, “Does Just Noticeable Difference Depend on the Rate of Change of Kinesthetic Force Stimulus?” In EuroHaptics 2014. LNCS 8618, 2014, pp. 40–47.

[20] C. Salisbury, R.B. Gillespie, H. Tan, F. Barbagli, and J.K. Salisbury, “Effects of Haptic Device Attributes on Vibration Detection Thresholds,” In Proceedings of the Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. Salt Lake City, UT, USA, 2009, pp. 115–120.

[21] K. U. Kyung, M. Ahn, D.-S. Kwon, and M. A. Srinivasan, “Perceptual and Biomechanical Frequency Response of Human Skin: Implication for Design of Tactile Displays,” Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. IEEE Computer Society Washington, DC, USA, 2005, pp. 96–101.

[22] Z. Berlas and S.S. Obhi, “Freedom, choice, and the sense of agency,” Front Hum Neurosci., vol. 7, pp. 1–7, Aug. 2013.

[23] C. Farrer, G. Valentin, and J.M. Hupé, “The time windows of the sense of agency,” Conscious Cogn., vol. 22, pp. 1431–1441, Dec. 2013.

[24] N. David, A. Newen, and K. Vogeley, “The “sense of agency” and its underlying cognitive and neural mechanisms,” Conscious Cogn., vol. 17, pp. 523–534, Jun. 2008.

[25] F. De Vignemont and P. Fourneret, “The sense of agency: A philosophical and empirical review of the ‘‘who” system,” Conscious Cogn., vol. 13, no. 1, pp. 1–19, Mar. 2004.

[26] J. W. Moore and P. C. Fletcher, “Sense of agency in health and disease: a review of cue integration approaches,” Conscious Cogn., vol. 21, pp. 59–68, Mar. 2012.

[27] S. J. Blakemore, D. M. Wolpert, and C. D. Frith, “Abnormalities in the awareness of action,” Trends Cogn Sci., vol. 6, no. 6, pp. 237–242, Jun. 2002.

[28] G. Carruthers, “The case for the comparator model as an explanation of the sense of agency and its breakdowns,” Conscious Cogn., vol. 21, no. 1, pp. 30–45, Mar. 2012.

[29] N. Hon, J-H. Poh, and C-S. Soon, “Preoccupied minds feel less control: Sense of agency is modulated by cognitive load,” Conscious Cogn., vol. 22, pp. 556–561, Jun. 2013.

[30] T.G.E. Damen, R. B. van Baaren, and A. Dijksterhuis, “You should read this! Perceiving and acting upon action primes influences one's sense of agency,” J Exp Soc Psychol., vol. 50, pp. 21–26, Jan. 2014.

[31] V. Chambon and P. Haggard, “Sense of control depends on fluency of action selection, not motor performance,” Cognition, vol. 125, pp. 441–451, Dec. 2012.

[32] H. Aarts, R. Custers, and D. M. Wegner, “On the inference of personal authorship: Enhancing experienced agency by priming effect information,” Conscious Cogn., vol. 14, pp. 439–458, Sep. 2005.

[33] C. Wilke, M. Synofzik, and A. Lindner, “The valence of action outcomes modulates the perception of one’s actions,” Conscious Cogn., vol. 21, pp. 18–29, Mar. 2012.

[34] M. Synofzik, G. Vosgerau, and A. Newen, “Beyond the comparator model: A multifactorial two-step account of agency,” Conscious Cogn., vol. 17, pp. 219–239, Mar. 2008.

[35] D. M. Wegner, B. Sparrow, and L. Winerman, “Vicarious agency: Experiencing control over the movements of others,” J Pers Soc Psychol., vol. 86, pp. 838–848, Jun. 2004.

[36] E. Pronin, D. M. Wegner, K. McCarthy, and S. Rodriguez, “Everyday magical powers: The role of apparent mental causation in the overestimation of personal influence,” J Pers Soc Psychol., vol. 91, pp. 218–231, Aug. 2006.

[37] R.J. Adams and B. Hannaford, “Stable Haptic Interaction with Virtual Environments,” IEEE T Robotic Autom., vol. 15, no. 3, pp. 465–474, 1999.

[38] S. S. Obhi and P. Hall, “Sense of agency in joint action: influence of human and computer co-actors,” Exp Brain Res., vol. 211, pp. 663–670, Jun. 2011.

[39] M. Auvray, A. Gallace, J. Hartcher-O'Brien, H. Z. Tan, and C. Spence, “Tactile and visual distractors induce change blindness for tactile stimuli presented on the fingertips,” Brain Res., vol. 1213, no. 5, pp. 111–119, Jun. 2008.

[40] G. Knoblich and B.H. Repp, “Inferring agency from sound,” Cognition, vol. 111, pp. 248–262, May 2009.

## AUTHOR’S PROFILE

**Dr. Nadiya Slobodenyuk,** is an Assistant Professor in Psychology at the American University of Beirut. She received a doctoral degree in psychology from Maria Curie-Sklodowska University, Poland in 2008. Her present research concerns sense of agency and motor cognition in haptic virtual environments and gaze-controlled interfaces.