Design of Perceptually Meaningful Quality in Robotic Motion

Lin Bai, Jon Bellona, Luke Dahl, Amy LaViers

Abstract—Robots that need to operate in human-facing environments will need complex options for modifying their movement to communicate changing state information. To that end, this paper builds on a method for creating variation in robotic movement and presents methods for improving this variation. In particular, a method using optimal control to modify the quality of robotic movements is updated to include generated sounds and a more expressive reference trajectory. The experimental design for finding the qualitative mapping between movement and sound, which leveraged expert musicians, and the experiment results are presented. Based on feedback from experiment participants, an improved method for generating movement variation is proposed. This method generates enhanced variations in robotic movement trajectories using the affinities between Effort and Space as described in Laban/Bartenieff Movement Studies (LBMS) to further improve people’s perception of the qualities of robotic movement.

I. INTRODUCTION

Robots are usually thought of as tools with functional movements that are meant to accomplish a task. The usefulness of robots can be increased with better control systems that enable a greater variety of movements, including movements which may be deemed the domain of performance artists – or are “expressive”. For example, robots that interact with people may require the expressive capacity to indicate caring in a hospital care setting, or to be authoritative in an emergency response setting. The same action, say an invitation to follow along, may need to be modulated to indicate the urgency of the request (in the latter setting) or to engender appropriate feelings (in the former).

This paper is motivated by improving the perception of qualitative robotic movement despite limited platform capabilities. Through a study of human movement and sound correspondences, the aim is to leverage the expertise of trained musicians to develop sonifications that give viewers additional cues to the intent of a robotic action. We increase the existing perceived variations in robotic movement by accompanying the movements with appropriate sounds. This paper documents two initial studies to this end.

Our position is that these goals are naturally informed by the body of knowledge in dance and choreography as codified in Laban/Bartenieff Movement Studies (LBMS)\(^1\).

Lin Bai is with the Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904, USA, Email: lb7ss@virginia.edu
Jon Bellona is with the Department of Music, University of Virginia, Charlottesville, VA 22904, USA, Email: jpbellona@virginia.edu
Luke Dahl is with the Department of Music, University of Virginia, Charlottesville, VA 22904, USA, Email: lsd5k@virginia.edu
Amy LaViers is with the Department of Mechanical Science and Engineering, University of Illinois-Urbana-Champaign, Urbana, IL 61801, USA, Email: alaviers@illinois.edu

\(^1\)Also known as Laban Movement Analysis (LMA).

This community has articulated that the expression and function of a movement are related to each other [1] and that their notion of movement quality or Effort is important in both of these contexts. For example, in [2], it is shown that by creating more variation and thoughtful choices in movement quality, or more specifically in Effort, workers in a manufacturing setting were able to improve their efficiency and comfort. Thus we suggest that a tool which can easily modify robotic movements along these same lines can improve the effectiveness of robotic co-workers in these settings. We inherit our notion of motion primitives and style from [3], [4], [5], [6]. A mapping between the components of Laban’s Effort theory to parameters, weights in an optimal control problem, is leveraged from [7]. This mapping is an alternative to the prior mappings in [8], [9] and the following mappings in [10], [11].

Humans communicate expressive intent through movement as well as through qualities of their vocalizations [12]. Adding appropriate sound to robotic movement may improve the interaction between robots and humans. Studies have been conducted to develop methods to vocalize an appropriate sound for the Effort factors in LBMS [13]. Vocalizations are often used in dance pedagogy to help dancers learn new choreography. A study in [14] shows that adding convergent auditory information can improve the accuracy of perception and reproduction of sports movement. In this paper, we try to add appropriate sound to robotic movement to improve the perception of the qualities of movement. We design a method to identify potential sound-movement correlations via vocalizations of trained musicians and composers. This study was used to suggest sound-design choices for a second study which will test people’s ability to select and distinguish movements based on varying qualities of movement and sound.

We next extend the prior mapping in [7] by increasing the variations in the movement trajectories. In LBMS, there are articulated relationships among the four components of movement: Body, Effort, Space, and Shape. We utilize the links between the qualities (in Effort) and the directions (in Space) of movement to improve the expression of a movement’s qualities utilizing the capabilities of a given platform, which cannot change the dynamics of each actuator or generate the speeds of motion of our simulation, but can alter a spatial pathway. Similar research of using the relationship between Effort and Shape are described in [8].

Namely, in this paper, we will present methods of generating various trajectories for robots to track. In Section II, the description of movement in Laban’s theory and the prior mapping to parameters in an optimal control problem are
given. In Section III, the experimental design is presented and the initial results are shown. In Section IV, our method of utilizing the affinities between Effort and Space in LBMS to improve the expressivity of robotic movement is presented. Finally, we give conclusions and future directions for incorporating artistic skills in robotic movement in Section V.

II. DESCRIBING AND GENERATING A MOVEMENT

The notion that the same ‘movement’ can be expressed in different ways is easy to see in our language. We separate action (verbs) and modifiers (adverbs) into distinct descriptors. We can, for example, ‘point’ or ‘paint’ in many different ways, with different functional and expressive objectives achieved in each. For example, to ask for a cookie, a child will point to the jar in a very different way than a mother who is angry about a messy room will point to a stray sock. These are two distinct examples where the action is expressive. On the other hand, the brush stroke required to cover an object with a desired paint is very different depending on the viscosity of the particular paint. This is an example that the focus of the movement variation is functional – yet relies on expressive quality to be achieved.

Furthermore, particular spatial pathways frequently correspond to these dynamic choices in Effort. These are articulated in the LBMS system as affinities. This theory explains that, for example, movements that happen toward the ground automatically appear to have a stronger sense of Strong Weight Effort by nature of the types of tasks which require this dynamic choice (i.e., chopping wood, digging in dirt, and lifting something heavy).

We look to an existing qualitative language in LBMS to articulate these differences and review a quantitative interpretation, which will be leveraged here. Both Laban’s system of Effort and prior work by the authors in generating trajectories endowed with a sense of Effort will be reviewed. Thus, in this section we provide a description of these prior methods of description and generation of movement, respectively.

A. Laban’s Description of Movement

We use the Effort system defined by Rudolf Laban [1], [2] to first qualitatively describe the execution of a known movement. In this Effort system, the qualitative characteristics of different movements are described by Laban with the four Motion Factors: Space Effort, Time Effort, Weight Effort, and Flow Effort. Note, we capitalize the terms in LBMS to avoid the possible confusion with the technical notions of space, weight, time and flow, as these technical meanings are different from those meant in LBMS.

Space Effort describes the attention a movement pays to the environment. A movement can be Direct or Flexible, which indicates whether the person is focusing his/her attention (as in the movements used for picking up an object) or diffusing it as he/she moves (as in spraying air freshener). Time Effort describes the attitude towards initiation and finish of a movement; it can be Sudden (like a sprinter) or Sustained (like an elderly person). Weight Effort describes the attitude towards the mover’s mass; it may be Condensed (like a track athlete) or Rarified (like a ballet dancer). Flow Effort describes the progression of a series of movements. It can be Free (as in a bungee jumper who cannot easily control what movement comes next) or Bound (as in a diver who exhibits great control over his/her fall).

B. Linear Quadratic Optimal Control Problem

We now review a mapping between an optimal control problem and the qualitative description of movement provided in [7], which we will leverage here. Consider a system with an input vector $u = [u_1, u_2, ..., u_m]^T$, a state vector $x = [x_1, x_2, ..., x_n]^T$, and an output vector $y = [y_1, y_2, ..., y_l]^T$, which tracks a reference signal $r = [r_1, r_2, ..., r_l]^T$. The quadratic cost function describing a total cost required to generate a movement is given as

$$J = \frac{1}{2} \int_0^{T_f} [(y - r)^T Q (y - r) + u^T R u + \dot{x}^T P \dot{x}] dt$$

$$+ \frac{1}{2} (y - r)^T S (y - r) \bigg|_{T_f}$$

where the four parameters $Q \in \mathbb{R}^{l \times l}, R \in \mathbb{R}^{m \times m}, P \in \mathbb{R}^{n \times n}, S \in \mathbb{R}^{l \times l}$ correspond to Space Effort, Weight Effort, Time Effort, and Flow Effort, respectively. These four parameters are not the standard control weights for an optimal control problem. Instead, they are redefined here to reflect the qualities of each Effort factor for varying the styles of the generated trajectories.

The goal for the optimal control problem is to find an input $u$ which minimizes the cost function $J$ in (1) using the parameters $Q, R, P, S$ for generating trajectories with different styles. We minimize Equation (1) subject to a simple linear system dynamic constraint:

$$\dot{x} = Ax + Bu \quad (2)$$

$$y = Cx \quad (3)$$

where $A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m},$ and $C \in \mathbb{R}^{l \times n}$. Different solutions to this problem produce outputs of different Effort, or quality, according to this mapping. The solution of this problem has a closed algebraic form, as in [7].

C. Basic Effort Actions

Eight Basic Effort Actions (BEAs), dab, flick, float, glide, press, slash, thrust, wring, are formed with the pairing of eight motion factors (verbs) and modifiers (adverbs) into distinct descriptors. For example, to ask for a cookie, a child will point to the jar in a very different way than a mother who is angry about a messy room will point to a stray sock. These are two distinct examples where the action is expressive. On the other hand, the brush stroke required to cover an object with a desired paint is very different depending on the viscosity of the particular paint. This is an example that the focus of the movement variation is functional – yet relies on expressive quality to be achieved.

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The goal for the optimal control problem is to find an input $u$ which minimizes the cost function $J$ in (1) using the parameters $Q, R, P, S$ for generating trajectories with different styles. We minimize Equation (1) subject to a simple linear system dynamic constraint:

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C. Basic Effort Actions

Eight Basic Effort Actions (BEAs), dab, flick, float, glide, press, slash, thrust, wring, are formed with the pairing of three of the fundamental movement qualities: Space Effort, Weight Effort, and Time Effort [2], as shown in Table I.

<table>
<thead>
<tr>
<th>Movement</th>
<th>Time</th>
<th>Space</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gliding</td>
<td>Sustained</td>
<td>Direct</td>
<td>Light</td>
</tr>
<tr>
<td>Pressing</td>
<td>Sustained</td>
<td>Direct</td>
<td>Strong</td>
</tr>
<tr>
<td>Floating</td>
<td>Sustained</td>
<td>Indirect</td>
<td>Light</td>
</tr>
<tr>
<td>Wringing</td>
<td>Sustained</td>
<td>Indirect</td>
<td>Strong</td>
</tr>
<tr>
<td>Dabbing</td>
<td>Sudden</td>
<td>Direct</td>
<td>Light</td>
</tr>
<tr>
<td>Thrusting</td>
<td>Sudden</td>
<td>Direct</td>
<td>Strong</td>
</tr>
<tr>
<td>Flicking</td>
<td>Sudden</td>
<td>Indirect</td>
<td>Light</td>
</tr>
<tr>
<td>Slash</td>
<td>Sudden</td>
<td>Indirect</td>
<td>Strong</td>
</tr>
</tbody>
</table>
### III. Accompanying Movement with Sound

This section describes an experiment we designed to create sounds intended to accompany and improve the perception of expression in artificial motion. Expert musicians performed non-verbal vocal sounds in time to animations of the eight BEAs. These recorded sounds were then given qualitative labels by the team in order to gather initial broad correspondences between the Laban Effort factors and various sonic qualities. This analysis will inform the design of an automated sonification process that will be tested with a broader audience in later studies.

#### A. Experiment Design

Five graduate students in music composition at the University of Virginia and two music professionals took part in the study. They were recruited due to their significant experience in performing and improvising music. The participants ranged in age from 24 to 46, with a median age of 32.

We created animations of a stick figure (Figure 1) performing a gesture of extending its arms to the side and then bringing them back to the center. This simple gesture is intended to show the different qualities of the eight BEAs. We use the eight BEAs in our study because they span the extremes of three Motion Factors (Space Effort, Weight Effort, and Time Effort). By recording and analyzing sound vocalizations that mimic the qualities in these movements, we hope to isolate sound characteristics and accentuate how they vary according to movement qualities. The values of the parameters used in the cost function in Equation (1) for generating the eight BEAs are shown in Table II.

#### TABLE II: The values of Q, R, P, and S utilized in the study

<table>
<thead>
<tr>
<th>Movement</th>
<th>Q</th>
<th>R</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gliding</td>
<td>1000</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Pressing</td>
<td>100</td>
<td>0.1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Floating</td>
<td>0.1</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Wringing</td>
<td>0.1</td>
<td>0.1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Dabbing</td>
<td>100</td>
<td>100</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>Thrusting</td>
<td>100</td>
<td>0.1</td>
<td>0.1</td>
<td>100</td>
</tr>
<tr>
<td>Flicking</td>
<td>0.1</td>
<td>100</td>
<td>0.1</td>
<td>1000</td>
</tr>
<tr>
<td>Slashing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>

To generate the animation of a stick figure moving its arms with different styles, we implemented in MATLAB the optimal control problem of minimizing the cost function (1) with different values of Q, R, P and S, subject to the system (2) and (3) in Section II. The stick figure is designed to have shoulders, elbows and wrists, so we consider a 6-dimensional system described in Equations (2) and (3) with the state \( x = [\theta_1, \theta_1, \theta_2, \theta_3, \theta_3] \) and the input \( u = [u_{\theta_1}, u_{\theta_2}, u_{\theta_3}] \). These are related by standard double integrator linear matrices \((A, B, C)\). The parameters \( \theta_1, \theta_2 \) and \( \theta_3 \) are the joint angles in the shoulder, elbow and wrist in each arm of the stick figure, shown in Figure 1.

Participants were shown each of the eight animations, as well as the name of the BEA for the animation (i.e. gliding, pressing, etc.). Then participants were asked to vocalize a sound for each animation, such that their vocalization began at the start of the movement, and lasted the duration of the movement. The videos have consistent durations and the recorded vocalizations were aligned with the videos in time. A three-second countdown was added before each movement to help with timing. Participants were allowed to practice before recording and record up to three takes, indicating the take that they felt best represented the movement.

We built a custom software interface with Max/MSPTM to display the animations and record the participants vocalizations. Participants were recorded in an isolated studio environment using a Neumann TLM103 microphone with pop filter and a Focusrite Scarlett 2i2 audio interface for microphone pre-amplification and analog-to-digital conversion. This set up provided a high-quality sound recording for analysis.

#### B. Analyzing Movement and Sound Correspondences

In order to begin to understand the sound-movement relationships embedded in the musicians’ vocalizations, we performed a qualitative encoding of various qualities in the audio recordings. Each of the authors listened to and applied labels to each of the 56 recordings (7 musicians × 8 BEAs).

These labels are used to describe the following qualities in each sound. The overall Pitch of the sound is described using the labels very low, low, medium, high, very high, none. The overall Amplitude of the sound uses the labels very soft, soft, medium, loud, very loud. The overall Timbre of the sound uses dark tone, dark noise, medium tone, medium noise, bright tone, bright noise. We also apply labels to the shape of how these qualities vary over the duration of the sound. The qualities of Pitch Curve, Amplitude Curve, and Timbre Curve are all described using the labels start emphasis, middle emphasis, end emphasis, linear increase, linear decrease, sustained, oscillating.

The movements and sounds are organized according to the BEAs. However we are interested in understanding how the sonic qualities vary with the Motion Factors. Thus we organized the labels according to the dimensions of Weight Effort, Time Effort, and Space Effort, and plotted the label counts for each factor in the form of bar graphs, as shown in Figures 2, 3, and 4. (I.e. the label counts for Sustained Time are the sum of the labels for the first four BEAs, and the label counts for Sudden Time are from the last four BEAs, as seen in Table I.)

1) Weight Effort: By examining Figure 2 we see interesting relationships between the movement quality of Weight Effort (Light vs. Strong), and the sonic qualities of amplitude...
and timbre. For example, sounds that corresponded to BEAs with Light Weight Effort were more often labeled with soft amplitude, whereas sounds corresponding to BEAs with Strong Weight Effort were more often labeled medium or loud, suggesting a Weight Effort to amplitude correlation.

For timbre, Strong Weight sounds contained more dark tone and dark noise labels, whereas Light Weight Effort sounds had more mid and bright tone labels.

In addition, from the three curves we see that Strong Weight Effort sounds seemed to have more end-emphasis, while Light Weight Effort sounds seemed to have more sustained and middle emphasis labels.

2) Time Effort: For the Motion Factor of Time Effort (Sudden vs. Sustained), a few qualitative correlations appeared. The vocalizations for Sustained Time Effort movements received more low and medium pitch labels, while Sudden Time Effort movement vocalizations received more labels for ‘none’ pitch, suggesting that sounds of Sudden Time Effort may be less pitched. This is corroborated by the timbre labels where we see that vocalizations for Sustained movements more often have mid tone, whereas Sudden movements are more often vocalized with bright noise.

For sound amplitude we see that Sudden movement vocalizations were more often labeled as loud, whereas Sustained movement vocalizations had a higher number of soft and medium amplitude labels. In addition, Sudden Time Effort movement vocalizations tend to have more end- or middle-emphasis labels whereas Sustained Time Effort movement vocalizations contained more sustained curve labels. See Figure 3.

3) Space Effort: We were not able to discern any clear differences between the sound labels for Direct and Indirect Space Effort movements. The results are plotted in Figure 4. These initial correspondences are being used to design a
system for parametrically generating sounds to accompany a movement according to its values for Time Effort, Space Effort, and Weight Effort. We will conduct a perceptual study on how these sounds affect viewer’s perception of quality in robotic movement.

Our initial experimental design was to use videos of an actual robot, the Baxter Research Robot. However, this platform has limits of maximum velocity and torque which can be used to generate quality of motion (and which the simulation does not suffer from). The torque limit, velocity limit and range of motion are listed in Table III. The “muted” quality visible on the physical platform, shown in Figure 5, was found to be not appropriate for the experiment described here. Thus, the following section describes an improvement to the method for generating movement; in particular, it creates more complex spatial pathways which may create more visible qualitative differences without requiring sharp dynamic changes to the robot joints.

TABLE III: Joint limits of Baxter Research Robot [15].

<table>
<thead>
<tr>
<th>Arm Joint</th>
<th>Torque Limit (N·m)</th>
<th>Velocity Limit (rad/s)</th>
<th>Range of Motion (rad): +limit,-limit: total movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>50</td>
<td>1.5</td>
<td>+0.909,-2.361/2.351</td>
</tr>
<tr>
<td>S1</td>
<td>100</td>
<td>1.5</td>
<td>+1.087,-2.147/3.194</td>
</tr>
<tr>
<td>E0</td>
<td>50</td>
<td>1.5</td>
<td>+3.028,-3.028/6.056</td>
</tr>
<tr>
<td>E1</td>
<td>50</td>
<td>1.5</td>
<td>+2.618,-0.052/2.67</td>
</tr>
<tr>
<td>W0</td>
<td>15</td>
<td>4</td>
<td>+3.059,-3.069/6.117</td>
</tr>
<tr>
<td>W1</td>
<td>15</td>
<td>4</td>
<td>+2.094,-1.571/3.665</td>
</tr>
<tr>
<td>W2</td>
<td>15</td>
<td>4</td>
<td>+2.094,-1.571/3.665</td>
</tr>
</tbody>
</table>

Light Weight Effort is usually linked with a high level in Space – imagine waving to a friend or lifting something off of a very high shelf, both of these examples typically require a rarefaction of Weight Effort. In this next section, the Space system and the affinities between the Effort and Space are discussed. These will be leveraged in an improved motion design, which is also described here.

The Space component of LBMS describes the direction, level and pathway of a particular movement. There are twenty six directions of the actions from Place Middle, which consist of combinations of three different levels (high, middle and low), three horizontal directions (left, middle and right) and three sagittal directions (forward, place and backward). The relationships between the qualities in Effort and the directions in Space are listed in Table IV.

TABLE IV: Affinities between Effort and Space [1].

<table>
<thead>
<tr>
<th>Effort Element</th>
<th>Spatial Aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Weight</td>
<td>High</td>
</tr>
<tr>
<td>Strong Weight</td>
<td>Low</td>
</tr>
<tr>
<td>Sustained Time</td>
<td>Forward</td>
</tr>
<tr>
<td>Sudden Time</td>
<td>Backward</td>
</tr>
<tr>
<td>Indirect Space</td>
<td>Side Open</td>
</tr>
<tr>
<td>Direct Space</td>
<td>Side Across</td>
</tr>
</tbody>
</table>

In Equation (1), the reference trajectory \( r \) is simply the linear interpolation between the initial and final position. To further improve the variation created with the method described in Section II, we utilize the affinity relationships between the elements of Effort and Space in LBMS. For example, if the movement has Light Weight Effort, we may adjust the trajectory by making it higher in Space to enhance the perception of this quality.

The interpolation equations we use to generate a new \( r \) for Equation (1) are as follows, demonstrated in Figure 6 and 7.

Acceleration interpolation:

\[
f = y_0 - k(y_0 + y_1)t + (k - 1)y_0t^2 + (k + 1)y_1t^2 \tag{4}\]

where \( y_0 \) is the initial position of the trajectory, \( y_1 \) is the final position of the trajectory, and \( k \) is the coefficient that is associated with the quality in Effort. For example, bigger \( R \) in Equation (1) gives Lighter Weight Effort, which corresponds to higher vertical position in Space, that needs bigger \( k \) in Equation (4).

Deceleration interpolation:

\[
f = y_0 - k(y_0 + y_1)t + (k - 1)y_0[1 - (1 - t)^2] + (k + 1)y_1[1 - (1 - t)^2] \tag{5}\]

where \( y_0 \) is the initial position of the trajectory, \( y_1 \) is the final position of the trajectory, and \( k \) is the coefficient that is associated with the quality in Effort.

Figure 8 shows trajectories of the reference signal \( r(t) \) with different choices of parameter \( k \). We can see that with larger \( k \), the reference trajectory has exaggerated spatial differences. Future work will evaluate if this difference is enough to be perceived by human viewers.
In this paper we discussed the idea that increasing the expressivity of robotic movement inherently improves the functionality of robots in human-facing environments. We investigated correspondences between movement and sound to increase the perceived variation in robotic movement. We presented initial findings that will guide the design of a mapping between the qualities of movement and sound. Finally, we tackled the problem of increasing expressive variation through newly designed robotic behavior where affinities between Effort and Space were leveraged to create more exaggerated differences, which favorably do not introduce greater dynamic variation but instead rely on spatial pathway.

This work is part of a larger effort to design automatically generated behavior – motion and sound – that will communicate intent to human viewers. Planned extensions to this work include quantitative analysis of musician vocalization, a larger user study on a broad population, and control methods to preserve more dynamism in the robotic movement. These extensions will leverage the data-driven approach to understanding human perception of motion and endow robotic agents with an artificial artistic skill that will help integrate them into human-facing scenarios.

V. CONCLUSIONS

In this paper we discussed the idea that increasing the expressivity of robotic movement inherently improves the functionality of robots in human-facing environments. We investigated correspondences between movement and sound to increase the perceived variation in robotic movement. We presented initial findings that will guide the design of a mapping between the qualities of movement and sound. Finally, we tackled the problem of increasing expressive variation through newly designed robotic behavior where affinities between Effort and Space were leveraged to create more exaggerated differences, which favorably do not introduce greater dynamic variation but instead rely on spatial pathway.

This work is part of a larger effort to design automatically generated behavior – motion and sound – that will communicate intent to human viewers. Planned extensions to this work include quantitative analysis of musician vocalization, a larger user study on a broad population, and control methods to preserve more dynamism in the robotic movement. These extensions will leverage the data-driven approach to understanding human perception of motion and endow robotic agents with an artificial artistic skill that will help integrate them into human-facing scenarios.

ACKNOWLEDGMENT

The study was made possible in part by the University of Virginia Data Science Institute, Office of the President, and the University of Virginia VPR Office of Graduate and Postdoctoral Affairs. The experiments with human subjects were governed by UVA IRB 2015047100.

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