Exp Brain Res (2011) 215:27–34
DOI 10.1007/s00221-011-2867-9

RESEARCH ARTICLE

Arousal, valence and their relative effects on postural control

Brian C. Horslen · Mark G. Carpenter

Received: 26 June 2011 / Accepted: 3 September 2011 / Published online: 27 September 2011

Abstract There is mounting evidence to suggest that emotional state can influence postural control. Emotions are often qualified using dimensions such as valence (pleasantness) and arousal. While affective pictures have been used to detail the effects of valence on postural control, the influence of arousal independently, or in combination with valence, has yet to be investigated. This is an important oversight because there are multiple sensory and neuromuscular mechanisms that are known to be sensitive to arousal and to contribute to postural control. As such, the current study is the first to independently manipulate valence and arousal through affective pictures and to examine their independent effects on postural control. Subjects stood quietly for 90 s long blocks while watching affective pictures, grouped by normative ratings of arousal (high and low) and valence (pleasant and unpleasant), and during which centre of pressure (COP) and electrodermal activity (EDA) were collected. EDA and anterior–posterior COP frequency were both increased with arousal, but not by valence. The postural effects observed in this study parallel those typically seen in other highly arousing situations, such as standing at the edge of an elevated platform or during performance evaluation. Therefore, we argue that arousal is a mediator of postural control and should be considered as a potential confound when testing or diagnosing subjects in clinical or experimental settings.

B. C. Horslen · M. G. Carpenter (✉)
School of Kinesiology, The University of British Columbia,
6108 Thunderbird Blvd., Vancouver, BC V6T 1Z4, Canada
e-mail: mark.carpenter@ubc.ca

Keywords Postural control · Centre of pressure · Arousal · Valence · Emotion

Introduction

It has been argued that all behaviours are governed by motivational circuits that are cued by either appetitive or aversive stimuli (Bonnet et al. 1995; Lang et al. 2000). Aversive stimuli are characterized as unpleasant and highly arousing. An animal's response to aversive stimuli depends on stimulus proximity and intensity; animals will respond with defensive aggression to close, intense aversive stimuli; and 'postural freezing' (i.e. immobility) to distal or less intense stimuli (Amorapanth et al. 1999; Blanchard et al. 1986; Lang et al. 2000).

There is some evidence to suggest that humans also demonstrate 'postural freezing' behaviours to aversive or threatening affective picture stimuli, based on subtle changes to postural control (Azevedo et al. 2005; Facchinetti et al. 2006). Studies that have contrasted unpleasant and pleasant affective pictures have demonstrated an effect of unpleasant valence on postural control during two-legged stance. However, the direction of, and variables involved in, this effect have been somewhat inconsistent across studies. For instance, Hillman et al. (2004) demonstrated that only women leaned significantly backwards while watching unpleasant pictures compared to pleasant pictures. In contrast, Stins and Beek (2007) found that subjects of both genders leaned slightly forward in response to unpleasant pictures compared to pleasant ones, although neutral and unpleasant pictures induced a comparable effect. Likewise, Azevedo et al. (2005) demonstrated increased centre of pressure (COP) frequency and decreased amplitude in the medial–lateral

(ML) plane in response to unpleasant pictures, compared to pleasant ones or neutral ones; yet Stins and Beek (2007), who used similar picture groups, did not see any significant change in ML sway amplitude during two-legged stance. In the anterior–posterior (AP) plane, Roelofs et al. (2010) demonstrated reduced COP amplitude to unpleasant pictures (angry faces), compared to pleasant ones (happy faces); and yet neither Azevedo et al. (2005) nor Facchinetti et al. (2006) found an effect of unpleasant pictures on COP amplitude in the AP plane. In sum, there is ample evidence to suggest that there is an effect of unpleasant pictures on postural control, yet the true extent of this effect is unclear.

The inconsistencies across these studies may be attributed to either methodological limitations concerning posturographic measures and/or a lack of control or consideration for the potential effects of arousal. For example, some studies (Hillman et al. 2004; Roelofs et al. 2010; Stins and Beek 2007) used sampling durations too short (<10 s) to accurately characterize the full spectrum of postural sway (Carpenter et al. 2001; van der Kooij et al. 2011). As a result, the short samples lead to under-representation of the lowest frequency components of the COP signal (thought to represent movement of the body) and over-representation of the higher-frequency oscillations of forces acting under the feet (thought to represent regulation of postural muscle tone; Winter et al. 1998). As such, it is not clear whether the unpleasant valence effects reported in these studies reflect sustained changes in whole-body leaning; or short duration, transient responses to the pictures.

Furthermore, despite the theoretical link between valence and arousal in emotion, none of the aforementioned studies have systematically manipulated arousal, independently from valence, to determine its effects on postural control. Some studies have grouped arousing and calming pictures together (Hillman et al. 2004; Stins and Beek 2007), others kept arousal constant while manipulating valence to study across valence conditions (Azevedo et al. 2005), and the remainder did not attempt to control arousal at all (Facchinetti et al. 2006; Roelofs et al. 2010). This is a very important limitation, because (a) there is evidence from other paradigms indicating that arousal alone may be associated with some postural changes (Maki and McIlroy 1996); (b) postural control and arousal both change in parallel when presented with a postural threat (Brown et al. 2006; Carpenter et al. 2006; Davis et al. 2009; Huffman et al. 2009); (c) transcranial magnetic stimulation studies suggest that corticospinal tract excitability is more heavily linked to arousal than valence (Baumgartner et al. 2007; Coombes et al. 2009); and finally, (d) the effects of valence on stretch reflexes in a postural muscle (soleus) have been shown to be dependent on arousal when both valence and arousal are manipulated independently (Bonnet et al. 1995). In particular, while stretch reflexes were significantly larger when subjects watched unpleasant pictures compared to pleasant ones in the low-arousal condition, there was no effect of valence in the high-arousal conditions. As such, there is considerable evidence to suggest that arousal may play a significant role in shaping postural responses to emotional stimuli.

Therefore, the aim of this study was to manipulate both arousal and valence, separately, to determine their potential independent and interactive effects on postural control. We used longer sampling durations to capture the full spectrum of postural sway characteristics. Based on the available literature concerning the effects of affective pictures on postural control, we predicted significant main effects between unpleasant and pleasant valence on AP COP mean position, frequency and amplitude, as well as ML frequency and amplitude. However, based on the work by Bonnet et al. (1995), we further predicted that the effects of valence would be dependent on arousal, such that significant differences between valence conditions would be apparent when arousal was low, and yet unpleasant and pleasant valence would be comparable when arousal was high.

Methods

Participants

Fifty-two subjects (mean age 24.3, range: 19–32 years; 26 women) participated in this study. Participants were excluded from the study if they had a known neurological, orthopaedic, vestibular, or uncorrected visual impairment that may have impeded them from standing quietly or viewing the picture stimuli. All participants were provided written informed consent, and the study was approved by the University of British Columbia Clinical Research Ethics Board.

Materials and procedure

Manipulation of valence and arousal

Affective pictures from the International Affective Picture System (IAPS) (Lang et al. 2008) were used to modify emotional valence and arousal. Four experimental picture groups consisting of 15 pictures each were assembled from the IAPS directory. Normative Self-Assessment Manikin (SAM) (Bradley and Lang 1994) values compiled through IAPS were used to divide pictures into four distinct groups: Unpleasant low-arousal, unpleasant high-arousal, pleasant

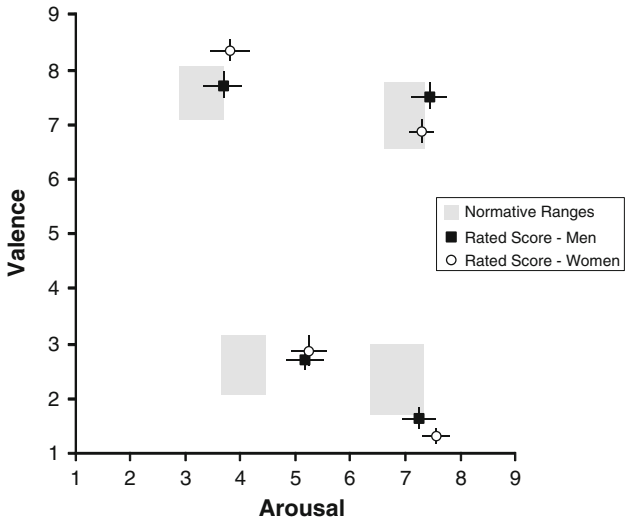

Fig. 1 *Shaded boxes* represent the normative valence and arousal ranges of the IAPS pictures used in the four experimental picture blocks. The overlaying points (women: *circles*; men: *squares*) represent the measured mean valence and arousal ratings for each of the experimental picture groups; *error bars* represent standard error measure

low-arousal, and pleasant high-arousal.[1] The normative scores for each block are graphed in Fig. 1, clearly demonstrating independence of groups.

Procedure

Participants performed a total of five standing trials. A common first trial with neutral valence and low-arousal pictures[2] was used to mitigate potential first trial effects (Adkin et al. 2000); this trial was not further analysed. After the neutral trial, participants performed each of the four experimental trials that were counterbalanced across participants to minimize potential order effects. In each trial, participants were required to stand quietly for 90 s with their feet side-by-side, approximately shoulder-width apart with arms hanging freely and eyes fixated on a 17-inch flat screen computer monitor adjusted to standing eye line located 130 cm in front of the subject. Foot position was marked on the forceplate to ensure consistent positioning across trials. A 2 min seated break was given between each trial, and subjects were required to stand in place for at least 30 s prior to initiation of each trial to allow autonomic responses associated with standing up (Olufsen et al. 2008) and transient COP components to stabilize (Carroll and Freedman 1993).

Each trial consisted of fifteen pictures from the same experimental picture group displayed for 6 s each for a continuous 90 s picture-viewing period. Participants were given specific instructions to watch the pictures, not look or turn away from the screen, and not speak during the trial.

Dependent measures

Posturography

Ground reaction forces and moments of force were measured with a forceplate (#K00407, Bertec, USA) and sampled at 100 Hz (Power 1401, CED, UK). The signal was low-pass filtered at 5 Hz with a 2nd order Butterworth filter, and COP was calculated over the 90 s picture-viewing period for each trial in both the AP and ML directions. From each trial, the AP COP mean position was calculated from the filtered signal; subsequently, the mean power frequency (MPF) and root mean square (RMS) from both the AP and ML directions were calculated from the unbiased COP signal.

Physiological arousal

Electrodermal activity (EDA) was measured from the thenar and hypothenar eminences of the non-dominant hand (model 2502, CED, UK). The EDA signal was sampled at 1,000 Hz and low-pass filtered at 5 Hz offline. The EDA signal was baseline corrected by subtracting the mean value of a 20 s period preceding picture onset then averaged over the same 90 s picture-viewing period from which posturographic measures were calculated.

SAM ratings

After each standing trial, subjects were asked to rate the picture block as a whole with the SAM valence and arousal scales. The SAM scales were designed to measure how pleasant and how emotionally arousing a stimulus is on a scale of 1–9 (Bradley and Lang 1994). Low scores indicate unpleasant or non-arousing pictures, and high scores indicate pleasant or arousing pictures (Fig. 1). For example, an extremely pleasant yet very calming picture

[1] IAPS pictures used:

Unpleasant low-arousal: 9220,9000,2750,9265,9280,9342,9331, 9290,9330,9291,9832,2455,9001,9471,2753

Unpleasant high-arousal: 3400,6230,2730,6563,3213,3030,6550, 6312,9908,8485,6540,9250,3212,6300,3150

Pleasant low-arousal: 2035,5760,1610,2370,5551,1620,5200, 5811,2360,5010,5891,2304,1604,5725,5779

Pleasant high-arousal: 8030,4681,8492,4668,5621,4659,8186, 4670,8370,4664,8490,4810,8080,4652,8185.

[2] Neutral: 2880,5510,5740,7000,7004,7233,7019,7160,7179,7187, 2038,2411,7035,7090,7235.

Table 1 Summary of results from statistical tests for effects of valence (V), arousal (A), and gender (G), as well as their interactions; statistically significant effects are bolded and italicized

Effect	Statistic	Main effects			Interactions			
		Valence	Arousal	Gender	V × A	V × A × G	V × G	A × G
SAM valence	*F* value	***955.88***	***53.84***	0.083	3.936	2.733	0.051	***8.935***
	P value	***≤0.001***	***≤0.001***	0.774	0.053	0.105	0.822	***0.004***
	η_p^2	***0.952***	***0.529***	0.002	0.076	0.054	≤0.001	***0.157***
SAM arousal	*F* value	***23.27***	***326.01***	0.069	***17.36***	0.582	0.501	0.004
	P value	***≤0.001***	***≤0.001***	0.794	***≤0.001***	0.449	0.483	0.951
	η_p^2	***0.326***	***0.872***	≤0.001	***0.266***	0.012	0.01	≤0.001
EDA	*F* value	1.467	***18.64***	0.426	0.06	0.343	0.675	2.564
	P value	0.232	***≤0.001***	0.517	0.808	0.561	0.416	0.116
	η_p^2	0.031	***0.288***	0.009	≤0.001	0.007	0.014	0.053
AP MPF	*F* value	0.131	***8.524***	1.579	0.034	0.945	1.753	0.125
	P value	0.719	***0.005***	0.215	0.854	0.336	0.192	0.725
	η_p^2	0.003	***0.151***	0.032	≤0.001	0.019	0.035	0.003
AP RMS	*F* value	0.003	2.671	0.295	1.222	1.271	0.504	2.192
	P value	0.956	0.109	0.589	0.274	0.265	0.481	0.145
	η_p^2	≤0.001	0.053	0.006	0.025	0.026	0.01	0.044
AP mean position	*F* value	0.017	1.442	1.355	0.072	0.116	0.227	0.818
	P value	0.897	0.236	0.25	0.789	0.735	0.636	0.37
	η_p^2	≤0.001	0.029	0.027	0.002	0.002	0.005	0.017
ML MPF	*F* value	1.112	0.944	2.579	0.407	0.071	0.286	0.216
	P value	0.297	0.336	0.115	0.526	0.791	0.596	0.644
	η_p^2	0.023	0.019	0.051	0.008	≤0.001	0.006	0.004
ML RMS	*F* value	0.201	1.173	1.389	1.009	≤0.001	0.206	0.308
	P value	0.656	0.284	0.244	0.32	0.989	0.652	0.582
	η_p^2	0.004	0.024	0.028	0.021	≤0.001	0.004	0.006

block would have a valence score of 9 and an arousal score of 1.

Statistical analyses

Since there is evidence that men and women have different affective responses to IAPS pictures (Lang et al. 2008) and that these gender differences could potentially translate to different postural responses to these pictures (Hillman et al. 2004), we included gender as a between-subjects factor in our statistical analysis. Two (valence: low, high) by two (arousal: low, high) by two (gender: female, male) mixed model ANOVAs were used to test for significant differences across conditions for each dependent variable. Any interactions were explored post hoc with paired samples *t* tests. The criterion for statistical significance was set to $\alpha = 0.05$ for all statistical tests, and effect sizes are reported as partial eta squared (η_p^2); the results from all statistical tests are reported in Table 1.

Results

Subject exclusions

Two subjects (one woman) were excluded from the study because their COP signals were dominated by high-frequency components that were too high to have occurred in normal quiet sway (Carpenter et al. 2001) and were therefore considered to contain non-biological artefacts. As such, the total number of subjects included in the final analysis was 50 (25 women). Due to equipment malfunction, EDA data from two further subjects were not analysed, though these subjects were included in the remainder of the tests.

SAM ratings and physiological arousal

There was a significant arousal by gender interaction ($P = 0.004$) on rated SAM valence (Fig. 1). The difference in rated valence from low- to high-arousal picture conditions was greater for women than it was for men

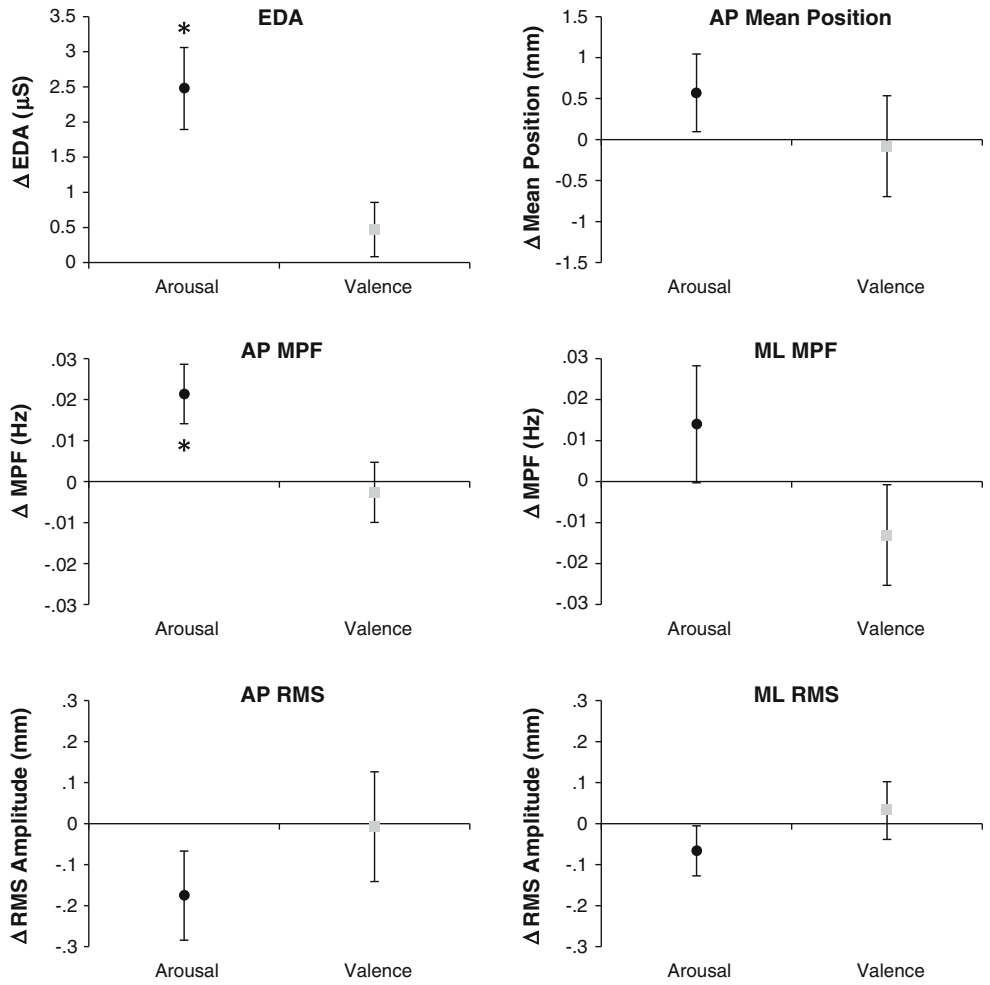

Fig. 2 Main effects of arousal and valence are demonstrated for EDA and COP-dependent measures with mean (±SE) change scores. Arousal effects were calculated as high-arousal minus low-arousal conditions (pooled across valence); positive values indicate larger values in the high-arousal conditions. Valence effects were calculated as pleasant minus unpleasant conditions (pooled across arousal); positive values indicate larger values in the pleasant conditions and negative values indicate larger scores in the unpleasant conditions. Note: *Asterisks* indicate statistical significance at $P > 0.05$; also, for mean position, larger scores indicate a backward lean

($t_{48} = 2.989$, $P = 0.004$, $\eta^2 = 0.157$). There were also significant main effects of valence ($P < 0.001$) and arousal ($P < 0.001$) on rated SAM valence. Higher (more pleasant) valence ratings were observed in the pleasant compared to unpleasant conditions and in the low compared to high-arousal conditions. Rated SAM arousal was significantly influenced by a valence by arousal interaction ($P < 0.001$). SAM arousal was consistently rated higher in the high compared to low-arousal conditions; however, the difference between arousal levels was greater for the pleasant picture groups ($t_{49} = -13.515$, $P < 0.001$, $\eta^2 = 0.788$) than for the unpleasant ones ($t_{49} = -11.478$, $P < 0.001$, $\eta^2 = 0.729$; Fig. 1). Note that this distinction across valence conditions coincides with the normative IAPS ratings of the pictures used in this study. There were no significant effects of gender on rated SAM arousal. Finally, there was a significant increase in EDA levels in the high compared to low-arousal conditions ($P < 0.001$; Fig. 2). There were no significant interactions or main effects of valence or gender on EDA.

Posturographic measures

There was a statistically significant main effect of arousal condition on AP MPF ($P = 0.005$). AP MPF was significantly higher in the high compared to low-arousal conditions (Fig. 2) Although AP RMS was on average lower in the high compared to low-arousal conditions, neither AP RMS nor AP mean position was significantly influenced by main effects of arousal. There were no significant main or interaction effects involving valence or gender on any of the AP postural measures. While ML MPF was on average higher in the high compared to low-arousal conditions and also in the unpleasant compared to pleasant conditions (Fig. 2), there were no statistically significant main effects

or interactions of arousal, valence, or gender on either ML MPF or RMS.

Discussion

Contrary to our original hypotheses, we did not observe any significant effects of valence or interaction effects between valence and arousal on postural control. The lack of agreement between the results of the current and prior studies in the ML plane may be attributed to methodological differences in the studies; subjects in the current study stood with their feet shoulder-width apart, whereas prior studies demonstrating an effect of unpleasant valence in the ML plane had subjects stand with their feet together (Azevedo et al. 2005; Facchinetti et al. 2006), or on one-leg only (Stins and Beek 2007). As such, our subjects, with their wide base-of-support, may have been too stable in the ML plane to demonstrate the characteristic postural responses to unpleasant pictures that have been previously observed with narrower, less stable, stance widths. Within the AP plane, where stance position was similar across all studies, the absence of valence effects on MPF and RMS amplitudes observed in the current study was in agreement with findings of Azevedo et al. (2005) and Facchinetti et al. (2006). While Roelofs et al. (2010) found decreased amplitudes with unpleasant pictures, the relatively short sampling duration used to calculate these measures (3 s) may have confounded these results and makes it difficult to compare with the other studies that have used longer sampling durations (Carpenter et al. 2001; Carroll and Freedman 1993; van der Kooij et al. 2011).

Previous studies have also suggested that unpleasant pictures induce a leaning effect in the AP plane; however, we cannot confirm this effect with these data. As discussed in the introduction, the studies that have demonstrated a leaning response to unpleasant pictures were not in agreement as to the direction of the effect. Stins and Beek (2007) observed forward leaning in response to unpleasant pictures, whereas Hillman et al. (2004) found that women leaned backwards. However, Hillman et al. (2004) also found that men tended to lean forward with unpleasant pictures, yet this effect was not statistically significant. Since we sampled equally across genders, it was possible for us to test the possibility that the direction of lean is dictated by gender. However, despite the fact that there were slight differences in how pleasantly men and women viewed the pictures, we found no main or interactive effects of gender on AP mean position, or any other postural measure. Therefore, we conclude that there was no significant leaning effect induced by the pictures used in this study. The difference between this and previous studies that have found a leaning effect might be attributed to their reliance on very short sampling durations (1 and 5 s) to characterize mean position. This may have biased their findings towards short, transient force fluctuations beneath the feet, as opposed to sustained, whole-body leaning. Alternatively, the lack of gender effects in leaning may be due to a failure to control background arousal state between subjects. Factors such as time of day, or time since waking or last meal (Silver and LeSauter 2008) can influence underlying arousal state yet were not controlled across subjects and may potentially have biased the results. However, the principle focus of this study was on within-subjects changes to postural control with changes in valence and/or arousal, which should not have been influenced by background arousal state.

This study is the first to demonstrate that arousal, induced by affective pictures, can influence postural control, independent of valence. Specifically, we found that AP MPF was significantly higher in the high, compared to low, arousal conditions. This increased MPF observed across arousal conditions is similar to that reported in studies where subjects stood on an elevated surface height; a scenario that also elicits increases in physiological arousal (Brown et al. 2006; Carpenter et al. 2006; Davis et al. 2009; Huffman et al. 2009). Fear and anxiety, of which arousal is a significant component (Neiss 1988), have also been shown to increase COP frequency in individuals with phobic postural vertigo (Holmberg et al. 2003; Krafczyk et al. 1999), high trait anxiety (Wada et al. 2001), and state anxiety related to expert evaluation (Geh et al. 2011). There is a wide range of potential mechanisms through which arousal could influence postural control; yet the exact mechanisms through which arousal influences MPF are not clear. The most likely avenues for these effects are through neural projections from limbic areas to sensory modalities involved in postural control. For instance, the gain of the vestibulo-ocular response is known to be influenced by anxiety-inducing mental tasks (Collins and Guedry 1962; Yardley et al. 1995) and trait anxiety (Yardley et al. 1995); therefore, it would be reasonable to assume that descending vestibulospinal pathways involved in balance control may be similarly affected (Balaban and Jacob 2001; Balaban and Thayer 2001; Balaban 2002). Furthermore, arousal is also known to excite lower limb stretch reflexes (Bonnet et al. 1995; Both et al. 2005; Hjortskov et al. 2005; Kamibayashi et al. 2009) and improve ankle proprioceptive acuity (Matre and Knardahl 2003). It is thought that these changes reflect an arousal-driven increase in proprioceptive sensitivity. Finally, arousal has been linked to increased whole-body muscle stiffness (Fridlund et al. 1986). Such changes to proprioceptive acuity or vestibular gain could result in an increase in afferent input to spinal and/or supraspinal balance control centres. Such changes would allow the body to detect and correct for smaller amplitudes of sway and would therefore sway at a higher frequency. Alternatively,

these changes might lead to increased tonic muscle activation, which would change the passive stiffness properties of the ankle, and as a result change the frequency of sway (Winter et al. 1998). Unfortunately, at this time, further research is needed to establish how these potential mechanisms are influenced by arousal and how these changes influence postural sway.

Although the exact mechanisms through which arousal (and possibly valence in the ML plane) may influence postural control are currently unknown, the observed effect of emotion on postural control has important implications for future experimental and clinical practice. From a methodological perspective, the potential confounding effects of arousal on postural control characteristics must be controlled or accounted for (a) in future studies that examine the effects of valence or other affective dimensions on postural control; (b) in longitudinal studies in which arousal states may vary, such as over the duration of an intervention, training, or rehabilitation programme (Bolmont et al. 2002; Ohno et al. 2004); and (c) when comparing between populations with different underlying levels of arousal, perhaps due to fear or anxiety, such as older adults (Arfken et al. 1994), persons with Parkinson's disease (Bloem et al. 2001; Adkin et al. 2003), or vestibular disorders (Jacob and Furman 2001; Yardley and Redfern 2001). From a clinical point of view, there are important implications of this work as well. Firstly, older adults experience significantly more anxiety and fear and have poorer performance on clinical balance tests while performing for an expert evaluator (Geh et al. 2011). The concern is that this 'white coat effect', or context specific arousal, may potentially mask or mimic a balance deficit that is not normally present outside of the clinical setting. As such, we would argue that steps to reduce anxiety and arousal should be taken prior to clinical balance evaluations to maximize accuracy and external validity of such tests (Geh et al. 2011). A second clinical implication for these findings is that medications designed to suppress anxiety or arousal may have detrimental effects on postural control. Medications such as benzodiazepines, sedatives, hypnotics, and antidepressants are all associated with increased fall risk (Bloem et al. 2001; Leipzig et al. 1999; Woolcott et al. 2009). The exact mechanisms through which these medications increase fall risk are not clear; however, considering the impact of arousal on postural control in healthy subjects in this study, it would appear that the suppression of arousal through limbic inhibition would be a plausible route to investigate. In sum, we would advise that all studies of postural control take measures to monitor, and where possible control for, arousal as it may confound interpretation of experimental and/or clinical results.

We acknowledge the limitation that separating emotions into only valence and arousal is likely an oversimplification of emotion and motivation. Fontaine et al. (2007) argue that at least four dimensions (pleasantness, potency-control, arousal, and unpredictability) are required to define the emotional meanings of words. Furthermore, Harmon-Jones (2004) argues that anger and disgust, both unpleasant and arousing, activate different motivational regions of the cortex, one leading to approach and the other to withdrawal behaviour. With these points in mind, pictures in this study were chosen solely for their valence and arousal ratings and not for the emotions they are intended to invoke. We might have found more distinct contrasts between valence conditions on postural control if we used consistent emotional stimuli in each picture group. Yet, such a design would have restricted our ability to attribute our results to the broader dimensions of valence and arousal and limit us to making inferences about how specific emotional experiences influence postural control.

In conclusion, this study is the first to classify the effects of arousal, induced by affective pictures, on postural control. Furthermore, we have progressed the field by contributing data that reliably represent the full spectrum of postural sway. While our results demonstrate that arousal influences the frequency of COP displacements in the AP plane, these data do not necessarily contradict prior observations that suggest that valence can alter postural control in the ML plane if subjects are allowed to stand in narrower, less stable, stance positions. Finally, we suggest that future investigations explore the role of postural stability in emotional changes to postural control and also the mechanisms through which arousal induces changes to postural control.

Acknowledgments The authors are grateful for financial support from the Natural Sciences and Engineering Research Council of Canada to BCH and MGC as well as The University of British Columbia University Graduate Fellowship program to BCH.

References

Adkin AL, Frank JS, Carpenter MG, Peysar GW (2000) Postural control is scaled to level of postural threat. Gait Posture 12(2):87–93

Adkin AL, Frank JS, Jog MS (2003) Fear of falling and postural control in Parkinson's disease. Mov Disord 18(5):496–502

Amorapanth P, Nader K, LeDoux JE (1999) Lesions of periaqueductal gray dissociate-conditioned freezing from conditioned suppression behavior in rats. Learn Mem 6(5):491–499

Arfken CL, Lach HW, Birge SJ, Miller JP (1994) The prevalence and correlates of fear of falling in elderly persons living in the community. Am J Public Health 84(4):565–570

Azevedo TM et al (2005) A freezing-like posture to pictures of mutilation. Psychophysiology 42(3):255–260

Balaban CD (2002) Neural substrates linking balance control and anxiety. Physiol Behav 77(4–5):469–475

Balaban CD, Jacob RG (2001) Background and history of the interface between anxiety and vertigo. J Anxiety Disord 15(1–2):27–51

Balaban CD, Thayer JF (2001) Neurological bases for balance—anxiety links. J Anxiety Disord 15(1–2):53–79

Baumgartner T, Willi M, Jancke L (2007) Modulation of corticospinal activity by strong emotions evoked by pictures and classical music: a transcranial magnetic stimulation study. Neuroreport 18(3):261–265

Blanchard RJ, Flannelly KJ, Blanchard DC (1986) Defensive behavior of laboratory and wild rattus norvegicus. J Comp Psychol 100(2):101–107

Bloem BR, Grimbergen YA, Cramer M, Willemsen M, Zwinderman AH (2001) Prospective assessment of falls in Parkinson's disease. J Neurol 248(11):950–958

Bolmont B, Gangloff P, Vouriot A, Perrin PP (2002) Mood states and anxiety influence abilities to maintain balance control in healthy human subjects. Neurosci Lett 329(1):96–100

Bonnet M, Bradley MM, Lang PJ, Requin J (1995) Modulation of spinal reflexes: arousal, pleasure, action. Psychophysiology 32(4):367–372

Both S, Boxtel G, Stekelenburg J, Everaerd W, Laan E (2005) Modulation of spinal reflexes by sexual films of increasing intensity. Psychophysiology 42(6):726–731

Bradley MM, Lang PJ (1994) Measuring emotion: the self-assessment manikin and the semantic differential. J Behav Ther Exp Psychiatry 25(1):49–59

Brown LA, Polych MA, Doan JB (2006) The effect of anxiety on the regulation of upright standing among younger and older adults. Gait Posture 24:397–405

Carpenter MG, Frank JS, Winter DA, Peysar GW (2001) Sampling duration effects on centre of pressure summary measures. Gait Posture 13(1):35–40

Carpenter MG, Adkin AL, Brawley LR, Frank JS (2006) Postural, physiological and psychological reactions to challenging balance: does age make a difference? Age Ageing 35(3):298–303

Carroll JP, Freedman W (1993) Nonstationary properties of postural sway. J Biomech 26(4–5):409–416

Collins WE, Guedry FE, Jr. (1962) Arousal effects and nystagmus during prolonged constant angular acceleration. Acta Otolaryngol 54:349–362

Coombes SA, Tandonnet C, Fujiyama H, Janelle CM, Cauraugh JH, Summers JJ (2009) Emotion and motor preparation: a transcranial magnetic stimulation study of corticospinal motor tract excitability. Cogn Affect Behav Neurosci 9(4):380–388

Davis JR, Campbell AD, Adkin AL, Carpenter MG (2009) The relationship between fear of falling and human postural control. Gait Posture 29(2):275–279

Facchinetti LD, Imbiriba LA, Azevedo TM, Vargas CD, Volchan E (2006) Postural modulation induced by pictures depicting prosocial or dangerous contexts. Neurosci Lett 410(1):52–56

Fontaine JR, Scherer KR, Roesch EB, Ellsworth PC (2007) The world of emotions is not two-dimensional. Psychol Sci 18(12):1050–1057

Fridlund AJ, Hatfield ME, Cottam GL, Fowler SC (1986) Anxiety and striate-muscle activation: evidence from electromyographic pattern analysis. J Abnorm Psychol 95(3):228–236

Geh CLM, Beauchamp MR, Crocker PRE, Carpenter MG (2011) Assessed and distressed: white-coat effects on clinical balance performance. J Psychosom Res 70(1):45–51

Harmon-Jones E (2004) Contributions from research on anger and cognitive dissonance to understanding the motivational functions of asymmetrical frontal brain activity. Biol Psychol 67(1–2):51–76

Hillman CH, Rosengren KS, Smith DP (2004) Emotion and motivated behavior: postural adjustments to affective picture viewing. Biol Psychol 66(1):51–62

Hjortskov N, Skotte J, Hye-Knudsen C, Fallentin N (2005) Sympathetic outflow enhances the stretch reflex response in the relaxed soleus muscle in humans. J Appl Physiol 98(4):1366–1370

Holmberg J, Karlberg M, Fransson PA, Magnusson M (2003) Phobic postural vertigo: body sway during vibratory proprioceptive stimulation. Neuroreport 14(7):1007–1011

Huffman JL, Horslen BC, Carpenter MG, Adkin AL (2009) Does increased postural threat lead to more conscious control of posture? Gait Posture 30(4):528–532

Jacob RG, Furman JM (2001) Psychiatric consequences of vestibular dysfunction. Curr Opin Neurol 14(1):41–46

Kamibayashi K, Nakazawa K, Ogata H, Obata H, Akai M, Shinohara M (2009) Invariable H-reflex and sustained facilitation of stretch reflex with heightened sympathetic outflow. J Electromyogr Kinesiol 19(6):1053–1060

Krafczyk S, Schlamp V, Dieterich M, Haberhauer P, Brandt T (1999) Increased body sway at 3.5–8 Hz in patients with phobic postural vertigo. Neurosci Lett 259(3):149–152

Lang PJ, Davis M, Öhman A (2000) Fear and anxiety: animal models and human cognitive psychophysiology. J Affect Disord 61(3):137–159

Lang PJ, Bradley MM, Cuthbert BN (2008) International affective picture system (IAPS): affective ratings of pictures and instruction manual. Technical report A-8. Unpublished manuscript

Leipzig RM, Cumming RG, Tinetti ME (1999) Drugs and falls in older people: a systematic review and meta-analysis: I. Psychotropic drugs. J Am Geriatr Soc 47(1):30–39

Maki BE, McIlroy WE (1996) Influence of arousal and attention on the control of postural sway. J Vestib Res 6(1):53–59

Matre D, Knardahl S (2003) Sympathetic nerve activity does not reduce proprioceptive acuity in humans. Acta Physiol Scand 178(3):261–268

Neiss R (1988) Reconceptualizing arousal: psychobiological states in motor performance. Psychol Bull 103(3):345–366

Ohno H, Wada M, Saitoh J, Sunaga N, Nagai M (2004) The effect of anxiety on postural control in humans depends on visual information processing. Neurosci Lett 364(1):37–39

Olufsen MS, Alston AV, Tran HT, Ottesen JT, Novak V (2008) Modeling heart rate regulation—part I: sit-to-stand versus head-up tilt. Cardiovasc Eng 8(2):73–87

Roelofs K, Hagenaars MA, Stins JF (2010) Facing freeze: social threat induces bodily freeze in humans. Psychol Sci 21(11):1575–1581

Silver R, LeSauter J (2008) Circadian and homeostatic factors in arousal. Ann NY Acad Sci 1129:263–274

Stins JF, Beek PJ (2007) Effects of affective picture viewing on postural control. BMC Neurosci 8:83

van der Kooij H, Campbell AD, Carpenter MG (2011) Sampling duration effects on centre of pressure descriptive measures. Gait Posture 34(1):19–24

Wada M, Sunaga N, Nagai M (2001) Anxiety affects the postural sway of the antero-posterior axis in college students. Neurosci Lett 302(2–3):157–159

Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K (1998) Stiffness control of balance in quiet standing. J Neurophysiol 80(3):1211–1221

Woolcott JC et al (2009) Meta-analysis of the impact of 9 medication classes on falls in elderly persons. Arch Intern Med 169(21): 1952–1960

Yardley L, Redfern MS (2001) Psychological factors influencing recovery from balance disorders. J Anxiety Disord 15(1–2):107–119

Yardley L, Watson S, Britton J, Lear S, Bird J (1995) Effects of anxiety arousal and mental stress on the vestibulo-ocular reflex. Acta Otolaryngol 115(5):597–602